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Façade Refurbishment Toolbox

Supporting the Design of Residential Energy Upgrades

Thaleia Konstantinou

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Contents (concise)

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Abstract

The starting point of the research is the need to refurbish existing residential building stock, in order to reduce its energy demand, which accounts for over one fourth of the energy consumption in the European Union. Refurbishment is a necessary step to reach the ambitious energy and decarbonisation targets for 2020 and 2050 that require an eventual reduction up to 90% in CO_2 emissions. In this context, the rate and depth of refurbishment need to grow. The number of building to be renovated every year should increase, while the energy savings in renovated buildings should be over 60% reduction to current energy demand. To achieve that, not only is it necessary to find politics and incentives, but also to enable the building industry to design and construct effective refurbishment strategies. This research focuses on refurbishment of the building envelope, as it is very influential with regard to energy reduction.

The early design phases are particularly important, as decisions taken during this stage can determine the success or failure of the design. Even though the design decisions made earlier can have bigger impact with lower cost and effort, most existing tools focus on post-design evaluation. The integration of all aspects during the early design phases is complex, particularly as far as energy efficient design is concerned. At this stage, architects are in search for a design direction to make an informed decision. If the designer is provided with an indication of how efficient refurbishment options are, it is possible to apply them as part of an integrated strategy rather than trying to add measures at later stages, after the strategy has been developed.

Therefore, taking into account the need to refurbish residential buildings and the importance of integrated design of façade refurbishment strategies, the thesis aims at answering the following question.

How can the energy upgrade potential of residential façade refurbishment strategies be integrated in the early design phase, in order to support decision-making?

The objective of the research is to enable the design of refurbishment strategies that acknowledge the potential of energy savings. Having available an assessment of the energy performance results in informed decisions that improve the efficiency of the strategy and the final refurbished building.

The answer to the research question is given by the Façade Refurbishment Toolbox (FRT) approach. It consists of three different types of information that can support the decision-making of residential façade refurbishment strategies. Firstly, the building envelope components that need to be addressed in an integrated refurbishment strategy are identified and different retrofitting measures for each one are proposed,

composing the façade refurbishment toolbox. Secondly, the measures are quantified in terms of energy upgrade potential, expressed by the simulated energy demand reduction after the application of the measure. Finally, a roadmap to the key decision aspects in the refurbishment strategy development indicates when the toolbox information can be used.

The methodology used to develop the FRT approach includes organising and calculating information about component retrofitting measures. The steps of the methodology were developed in the different chapters of the thesis. The first three chapters (Chapters 2-4) comprise the theoretical background that shapes the research question, discussion of the residential building stock, energy performance and refurbishment practice. Chapters 5 and 6 describe the process of the composition of the toolbox. Finally, Chapters 7 and 8 are concerned with its further applicability, regarding the approach validation and usability.

This thesis concludes with an approach to enable informed and energy-efficiency conscious decisions in the early stage of the design of refurbishment strategies. To improve the design process, the Façade Refurbishment Toolbox facilitates the development of strategies in different cases and for different specifications, without limiting or dictating designers' choices.

Designing is deciding. Knowledge and information can lead to better understanding of a decision consequent and, therefore, result in better design solutions. Different buildings have different energy saving potential. They also have different specifications, performance requirements and design ambitions. All these parameters result in different refurbishment strategies. The aim of the proposed approach is not replacing the design process and generating a solution, but supporting it by providing information to lead into responsible and knowledgeable decisions. In this way, refurbishment strategies that take into account the building improvement, occupants' comfort and efficient energy use can be designed, contributing to the greater society's goals of CO_2 emissions reduction and sustainable development.

Samenvatting

Dit onderzoek richt zich op de noodzaak van het renoveren van bestaand woningvoorraad om het energieverbruik te reduceren. Het energieverbruik beslaat op het moment een kwart van het totale energieverbruik in Europa. Het renoveren van de bestaande woningen is een belangrijke stap in het behalen van de ambitieuze energie- en CO_2 reductie doelen voor 2020 en 2050, waarbij een reductie van 90% CO_2 uitstoot nodig is. Om deze doelen te behalen moet zowel de snelheid als de hoeveelheid gerenoveerde gebouwen aanzienlijk verhoogd worden. Hierbij dient een energiebesparing van 60% in vergelijking met het huidige verbruik behaald te worden. Het is daarbij niet alleen belangrijk om politieke veranderingen en stimulans te reguleren, maar ook voor de bouwindustrie zelf is een belangrijke taak weggelegd voor het ontwerp en ontwikkeling van effectieve renovatiestrategieën. Dit onderzoek richt zich voornamelijk op de renovatie van de gebouwschil, omdat op het gebied van energiereductie met name hier veel winst te behalen is.

De beslissingen die in de beginfase van het ontwerp van een renovatiestrategie gemaakt worden kunnen het succes of falen van het ontwerp bepalen. Daarom is voor een succesvolle renovatiestrategie de vroege ontwerpfases van groot belang. Ondanks dat de vroege ontwerpbeslissingen een grotere impact hebben op de reductie van de kosten en inspanning, focussen de meeste bestaande 'tools' op de post-ontwerp evaluatie. De integratie van alle aspecten tijdens de beginfase van het ontwerp is complex, vooral daar waar het energie-efficiënt ontwerpen betreft. Architecten zoeken in deze fase naar ontwerpaanwijzingen die helpen bij het maken van onderbouwde beslissingen. Als de ontwerper in deze fase wordt geïnformeerd over de energie efficiëntie van de ontwerpopties, is het eenvoudiger om deze opties toe te passen als onderdeel van een geïntegreerde strategie.

De noodzaak tot energie renovatie van bestaande woningen en het daaraan gekoppelde belang van een geïntegreerde ontwerpstrategie voor gevelrenovatie, leidt tot de volgende onderzoeksvraag:
Hoe kan de energieverbeteringspotentie van gevelrenovatie strategieën van woningen worden geïntegreerd in de beginfase van het ontwerpproces, zodat dit het besluitvormingsproces kan ondersteunen?

De doelstelling van dit onderzoek is het tijdens de vroege ontwerpfases ondersteunen van renovatiestrategieën die zich volledig richten op de potentie van energiebesparing. Als er een evaluatie beschikbaar is om de resultaten aangaande energiebesparing te analyseren, is het mogelijk om een weloverwogen beslissing te maken, die de efficiëntie van de strategie en de uiteindelijk gerealiseerde energieprestatie van het gerenoveerde gebouw verbeteren.

Als antwoord op deze onderzoeksvraag wordt gegeven door deis een 'Gevelrenovatie Toolbox' (FRT-Façade Refurbishment Toolbox) aanpak ontwikkeld. Deze aanpak bestaat uit drie verschillende informatietypes die het besluitvormingsproces van gevelrenovatie strategieën voor woningen kan ondersteunen. Binnen de FRT methode worden allereerst de componenten in de gebouwschil gedefinieerd die van belang zijn voor een geïntegreerde renovatiestrategie, waarbij de verschillende mogelijke renovatie maatregelen voor elke component worden vastgesteld. Deze bepalen vervolgens de Gevelrenovatie Toolbox. Vervolgens worden de maatregelen gekwantificeerd door de specifieke energieverbeteringspotentie. Na de keuzes voor de toe te passen maatregelen, worden door middel van simulatie de uiteindelijke resultaten van de gebruikte toegepaste maatregelingen verkregen. Ten slotte wordt een roadmap opgesteld voor de belangrijkste beslissingsaspecten voor de ontwikkeling van de renovatiestrategie. Deze roadmap bepaald wanneer de toolbox informatie gebruikt kan worden.

De methode die gebruikt wordt om de FRT te ontwikkelen omvat informatie over de organisatie en berekening van de renovatiemaatregelen van de gevelcomponenten. De onderscheiden stappen van de methode zijn beschreven in de verschillende hoofdstukken. De eerste drie hoofdstukken (hoofdstuk 2-4) bevatten de theoretische achtergrond voor de onderzoeksvraag en bediscussiëren gerelateerde aspecten, zoals de samenstelling van de woningvoorraad, energieprestaties en de stand van zaken van de renovatiemarkt. In hoofdstuk 5 en 6 wordt de ontwikkeling van de FRT behandeld. Hoofdstuk 7 en 8 gaan over de verdere toepassingsmogelijkheden en bruikbaarheid van de toolbox, en deze verder gevalideerd.

Dit Het proefschrift concludeert met de aanpak om een bewuste- en dus onderbouwde besluitvorming omtrent energie-efficiëntie verbeteringene mogelijk te maken in de beginfase van het ontwerp van een renovatiestrategie. De FRT ondersteunt de ontwikkeling van strategieën voor verschillende situaties en specifieke omstandigheden, zonder dat de ontwerpkeuzes worden beperkt of bepaald. Dit leidt tot een optimalisatie van het ontwerpproces.

Ontwerpen is beslissen. Kennis en informatie kan kunnen tijdens de ontwerpfases leiden tot een beter begrip van de consequenties van beslissingen en resulteren in betere ontwerp oplossingen. Verschillende gebouwen hebben andere energiebesparende potenties, verschillende specificaties, prestatie eisen en ontwerpambities. Deze aspecten onderbouwen de noodzaak om voor elk gebouw een ander renovatiestrategie toe te passen. Het doel van de voorgestelde methode is niet om het ontwerpproces te vervangen en kant-en-klare oplossingen te generen, maar om het ontwerpproces te ondersteunen en informatie te verschaffen die leidt tot deskundige beslissingen. Op deze manier kunnen renovatiestrategieën ontworpen worden die rekening houden met de verbetering van het gebouw, gebruikerscomfort en efficiënt energiegebruik, waarbij deze bijdragen aan de hogere maatschappelijke doelen van CO_2 reductie en duurzame ontwikkeling.

Περίληψη

Αφετηρία της έρευνας αυτής αποτελεί η ανάγκη για αναβάθμιση των υφιστάμενων κτιρίων κατοικιών, προκειμένου να μειωθούν οι ενεργειακές τους απαιτήσεις, οι οποίες αντιπροσωπεύουν πάνω από το ένα τέταρτο της κατανάλωσης ενέργειας στην Ευρωπαϊκή Ένωση. Πρόκειται για ένα απαραίτητο βήμα προς την επίτευξη των φιλόδοξων στόχων της ΕΕ μέχρι το 2020 και το 2050, όπου απαιτείται μια συνολική μείωση των εκπομπών CO_2 έως 90%. Στο πλαίσιο αυτό, πρέπει να αυξηθεί τόσο ο αριθμός των κτιρίων που αναβαθμίζονται κάθε χρόνο, όσο και το ποσοστό εξοικονόμησης ενέργειας, που στα ανακαινισμένα κτίρια πρέπει να κυμαίνεται πάνω από το 60% των υπαρχόντων ενεργειακών αναγκών. Για το σκοπό αυτό, δεν αρκεί να βρεθούν τα απαραίτητα πολιτικά και οικονομικά κίνητρα, αλλά πρέπει και ο κατασκευαστικός κλάδος να έχει τη δυνατότητα να σχεδιάσει και να πραγματοποιήσει αποτελεσματικά την αναβάθμιση του κτιριακού αποθέματος. Η παρούσα έρευνα εστιάζει στο κτιριακό κέλυφος, καθώς έχει μεγάλη επιρροή στην εξοικονόμηση ενέργειας.

Τα πρώτα στάδια του σχεδιασμού είναι ιδιαίτερα σημαντικά καθώς οι αποφάσεις που λαμβάνονται σε αυτά καθορίζουν την επιτυχία ή την αποτυχία του σχεδιασμού και έχουν μεγαλύτερο αντίκτυπο με χαμηλότερο κόστος και προσπάθεια. Παρ’ όλα αυτά, τα περισσότερα εργαλεία σχεδιασμού επικεντρώνονται στην εκ των υστέρων αξιολόγηση της λύσης. Οι διαφορετικές παράμετροι που λαμβάνονται υπ’ όψιν κατά τα πρώτα στάδια του σχεδιασμού καθιστούν τη διαδικασία ιδιαίτερα πολύπλοκη, ιδίως όσον αφορά την ενεργειακή απόδοση του κτιρίου. Σε αυτό το στάδιο , οι αρχιτέκτονες αναζητούν πληροφορίες ώστε να μπορέσουν να λάβουν τεκμηριωμένες αποφάσεις για τη σχεδιαστική τους κατεύθυνση. Εάν ο σχεδιαστής γνωρίζει έστω και ενδεικτικά την αποτελεσματικότητα των διαφόρων μέτρων ανακαίνισης, έχει τη δυνατότητα να τα εφαρμόσει ως μέρος μιας ολοκληρωμένης στρατηγικής αναβάθμισης, αντί να τα προσθέσει σε μεταγενέστερα στάδια και αφού ο σχεδιασμός της στρατηγικής έχει ολοκληρωθεί.

Ως εκ τούτου και λαμβάνοντας υπ’ όψιν την ανάγκη αναβάθμισης των κτιρίων κατοικιών, καθώς και την σημασία ενός ολοκληρωμένου σχεδιασμού, η εργασία αυτή στοχεύει να απαντήσει στο παρακάτω ερευνητικό ερώτημα:

Πώς μπορεί η δυνατότητα ενεργειακής αναβάθμισης των προσόψεων κτιρίων κατοικιών να ενσωματωθεί στη πρώιμη φάση του σχεδιασμού, ώστε να υποστηρίξει τη λήψη αποφάσεων;

Ο στόχος της έρευνας είναι να συνεισφέρει στο σχεδιασμό στρατηγικών αναβάθμισης που αναγνωρίζουν τη δυνατότητα εξοικονόμησης ενέργειας. Η εκτίμηση της ενεργειακής απόδοσης θα έχει ως αποτέλεσμα τεκμηριωμένες αποφάσεις που βελτιώνουν τον σχεδιασμό και, κατά συνέπεια, την αποδοτικότητα του ανακαινισμένου κτιρίου.

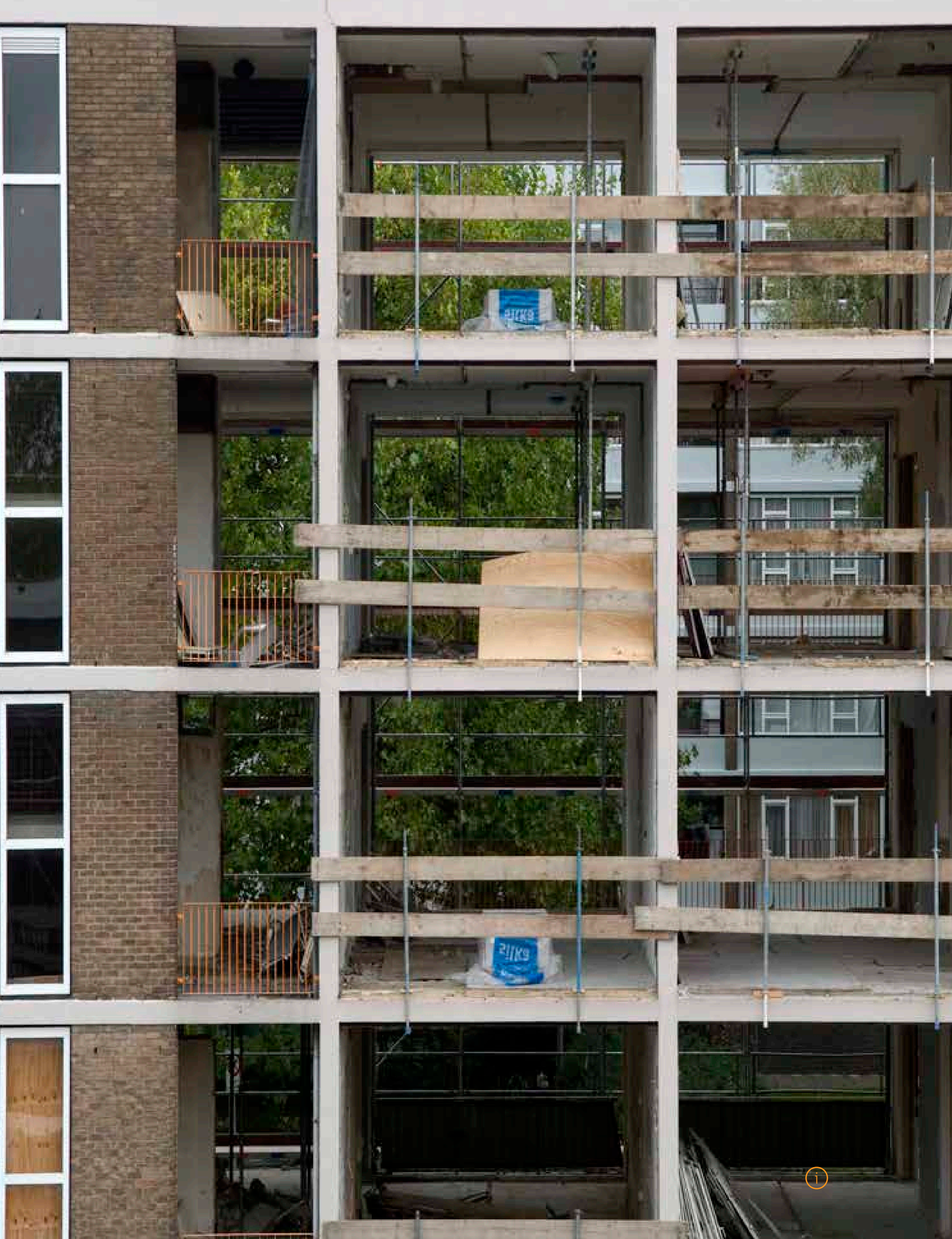
Η απάντηση στο ερευνητικό ερώτημα δίνεται μέσω της «Εργαλειοθήκης για την Αναβάθμιση Προσόψεων» (FRT- Façade Refurbishment Toolbox). Η προσέγγιση αυτή αποτελείται από τρία διαφορετικά είδη πληροφορίας που μπορούν να υποστηρίξουν τη λήψη αποφάσεων σχετικά με την στρατηγική αναβάθμισης. Αρχικά, ορίζονται τα στοιχεία του κτιριακού κελύφους που πρέπει να συμπεριληφθούν στον σχεδιασμό και προτείνονται διάφορα μέτρα αναβάθμισης για το κάθε στοιχείο, δημιουργώντας έτσι μία εργαλειοθήκη για την αναβάθμιση των προσόψεων. Στη συνέχεια, τα μέτρα ποσοτικοποιούνται ως προς τη δυνατότητα ενεργειακής αναβάθμισης, όπως αυτή εκφράζεται μέσω της μείωσης των ενεργειακών απαιτήσεων μετά την εφαρμογή των μέτρων. Τέλος, ένας οδικός χάρτης για τις βασικές πτυχές κατά την ανάπτυξη της στρατηγικής αναβάθμισης υποδεικνύει το πότε οι πληροφορίες της εργαλειοθήκης μπορούν να χρησιμοποιηθούν στη λήψη αποφάσεων.

Η μεθοδολογία που χρησιμοποιήθηκε για την ανάπτυξη της παρούσας προσέγγισης συμπεριλαμβάνει την οργάνωση και τον υπολογισμό των πληροφοριών σχετικά με τα μέτρα αναβάθμισης του κτιριακού κελύφους. Τα μεθοδολογικά βήματα αναλύονται στα αντίστοιχα κεφάλαια της παρούσας διατριβής. Τα τρία πρώτα κεφάλαια (Κεφάλαια 2-4) αποτελούν το θεωρητικό υπόβαθρο το οποίο διαμορφώνει το ερευνητικό ερώτημα. Στα κεφάλαια αυτά συζητούνται αντίστοιχα το κτιριακό απόθεμα κατοικιών, η ενεργειακή απόδοση, και οι τρέχουσες πρακτικές αναβάθμισης. Τα Κεφάλαια 5 και 6 περιγράφουν την ανάπτυξη της FRT προσέγγισης. Τέλος, τα Κεφάλαια 7 και 8 ασχολούνται με την αξιολόγηση και την χρηστικότητά της.

Η παρούσα έρευνα καταλήγει σε μια προσέγγιση που καθιστά δυνατή τη λήψη τεκμηριωμένων και συνειδητών σε σχέση με την ενεργειακή απόδοση αποφάσεων κατά το πρώιμο στάδιο του σχεδιασμού. Προκειμένου να βελτιωθεί η διαδικασία αυτή, η FRT διευκολύνει την ανάπτυξη στρατηγικών σε διαφορετικές περιπτώσεις και με διαφορετικές προδιαγραφές, χωρίς να επιβάλλει τις σχεδιαστικές επιλογές.

Σχεδιασμός σημαίνει λήψη αποφάσεων. Η γνώση και η πληροφορία μπορούν να οδηγήσουν στη καλύτερη κατανόηση των συνεπειών που έχει μια απόφαση και άρα να έχουν ως αποτέλεσμα μια καλύτερη σχεδιαστική λύση. Διαφορετικά κτίρια έχουν διαφορετικές δυνατότητες εξοικονόμησης ενέργειας, αλλά και διαφορετικές προδιαγραφές απόδοσης και σχεδιασμού. Όλες αυτές οι παράμετροι καταλήγουν σε διαφορετικές στρατηγικές αναβάθμισης. Ο σκοπός της προτεινόμενης προσέγγισης δεν είναι η υποκατάσταση της διαδικασίας σχεδιασμού και η αυτόματη παραγωγή μιας λύσης, αλλά η υποστήριξή του σχεδιασμού μέσω της παροχής πληροφοριών που οδηγούν σε υπεύθυνες και τεκμηριωμένες αποφάσεις. Κατά αυτόν τον τρόπο μπορούν να σχεδιαστούν στρατηγικές αναβάθμισης οι οποίες λαμβάνουν υπ' όψιν τη βελτίωση του κτιρίου, την άνεση των κατοίκων, και την αποδοτική χρήση της ενέργειας, συνεισφέροντας έτσι στον ευρύτερο στόχο της κοινωνίας για αειφόρο ανάπτυξη.

Contents (extensive)



1 Introduction

§ 1.1 Background: The need to reduce energy demand in the building sector

The motivation to reconsider and improve the existing building stock lies in society's efforts towards sustainable development. In this context, the building sector, comprising of the household and service sector, has a considerable role to play. Accounting for approximately 40% of the energy consumed in EU, it is the biggest energy user, bigger than industry and road transport. Energy is one of the eight key issues to ensure sustainable development, as the use of energy is largely connected with the depletion of fossil fuels and climate change.

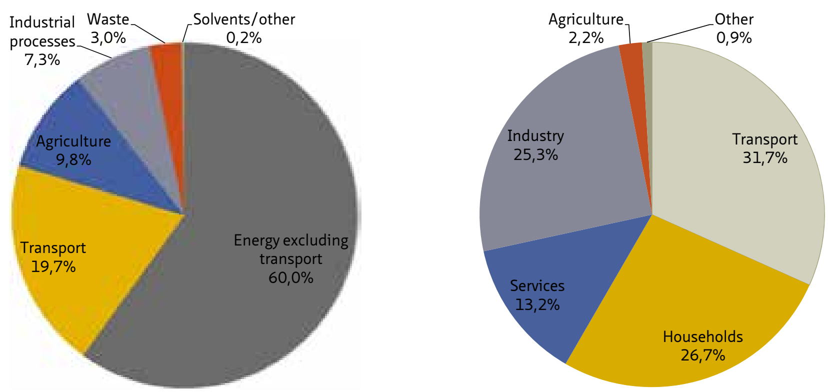


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Figure 1.1
(a) Greenhouse gas emissions by sector, EU-27, 2010 (source: Eurostat, 2012 © European Union, 1995-2013) and (b) Final energy consumption, EU-27, 2010 (Eurostat, 2013a, fig. 11.20 © European Union, 1995-2013)

Based on the scientific and social consensus, an international policy framework to underpin global efforts to tackle climate change has been developed in the last few decades. The European Commission has adopted an energy policy for Europe (European Commission 2007), endorsing targets for 2020, such as reducing greenhouse gas emissions by at least 20 % to1990 levels, increasing the share of renewable energy to 20% and making a 20% improvement in energy efficiency (Eurostat, 2009). The European Parliament has continuously supported these goals.

The European Council has also made a long term commitment to the decarbonisation path with a target for the EU and other industrialised countries of an 80 to 95% cuts in emissions by 2050 (European Commission, 2010).

Being the biggest energy user, the importance of residential and services buildings has been addressed by national and international legislative parties and institutions. Moreover, the building sector is explicitly mentioned as a key sector in the roadmap to the 2050 targets, issued by the European Commission in March 2011. The expected reduction in CO_2 emissions reaches up to 88 - 91% by 2050 (European Commission, 2011). This reduction is larger than in other sectors such as transport, agriculture and industry, indicating the importance of the building sector and the urgency of the measures to be taken.

Residential buildings in particular provide considerable potential for energy conservation and further sustainable benefits. The household sector is one of the largest energy consumers, accounting for approximately 1/4 of the final energy use in the European Union. The domestic sector could potentially make a significant contribution to the reduction of energy consumption (Gaterell & McEvoy, 2005). Additional studies have shown that households have larger energy saving potential and benefit than other sectors, along with the necessary higher investment (Rademaekers et al., 2012). Moreover, residential buildings account for 2/3 of building floor area, while the condition and efficiency of a large part of the residential stock still needs attention.

The recognition of the building sector's importance has led to the European Directive on the Energy Performance of Buildings (EPBD), adopted in 2002. According to the directive, an energy performance certificate is required when buildings are constructed, sold or rented out. In general the objective of the EPBD is to 'promote the improvement of the energy performance of buildings within the community taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness'. In order to achieve significant reductions in CO_2 emissions, the directive was updated in 2010, requiring new buildings to be low- or zero-energy buildings (DIRECTIVE 2010/31/EU).

However, a greater challenge that must be faced, in order to tackle the energy demand of the building sector and to effectively implement the Energy Performance Building Directive (EPBD) is the proper refurbishment of existing buildings. The analysis in the European Commission's roadmap projects that over the next decade investments in energy-saving building components and equipment will need to be increased by up to € 200 billion (European Commission, 2011), together with a substantial increase in the rate and depth of renovations (BPIE, 2011a). An increase in building energy performance could constitute an important instrument in the efforts toward alleviating the EU's energy import dependency and reach national and international targets for the reduction of carbon dioxide emissions.

The importance of the existing residential buildings is firstly due to the fact that they are already there. The renewal rate of the stock is very slow. It is estimated that every year only 1% at most is added to the existing stock, which means that in a period of 10 years only 10% of the stock will be at least at the level demanded by the current building regulations for newly built dwellings. Still, the condition of the existing stock is problematic. Not only do buildings suffer from a variety of physical problems, but also most of the existing buildings were built under far lower energy and sustainability standards. About 70% of the existing buildings are over 30 years old and about 35% are more than 50 years old. This is an important observation given that most national building regulations that mandate thermal insulation of building envelopes were introduced after the 1970s following the energy crisis (Poel et al, 2007, p.394).

On the other hand, demolition is not the solution for the aging buildings. Regarding materials and waste, studies have shown that the environmental impact of life cycle extension of a building is definitely less than demolition and reconstruction (Thomsen and Van der Flier,2008, p.5). The energy consumed during the production and transport of materials is stored in the construction itself and demolition means throwing this energy away. Along with embodied energy, buildings are also stored capital. Thus, demolition would not only waste energy but also capital.

Therefore, the answer to the increasing requirements for lower energy use and high living standards is refurbishing the residential stock, in order to improve its condition and increase energy efficiency. The existing buildings need to be upgraded to use minimum non-renewable energy, while providing comfort, health and safety and lower operating costs. Refurbishment constitutes a necessary action to meet the energy targets for the coming decades. Not only does it provide huge potentials for energy savings, but also it is economically and socially relevant. Technical problems, operational costs and internal conditions can be improved, resulting in more favourable living and working conditions, as well as, increased property value.

§ 1.2 Scientific Problem

The potential of refurbishment to upgrade the energy efficiency of the building stock and the resulting cuts in CO_2 emissions has been addressed by both the building industry and research. Deep renovation, in particular, achieving savings over 60% to current energy demand, has the potential to be the preferred solution from an ecological and economic point of view and that superficial renovations significantly increase the risk of missing the climate targets and leaving huge absolute savings untapped (Hermelink & Müller, 2011).

Although the potential has been identified, guidelines come in the form of general suggestion that fail to address the diversity of each project. The directives and regulations provide benchmarks for thermal performance and energy consumptions, but not specific information about how these requirements can be implemented in the design. In practice, the detailed implementation of the measures has to suit the individual project (Nemry et al., 2010), in terms of the building's existing condition, location, project specifications, budget and the client's ambition and, of course, architect's decisions.

Refurbishment of aging residential buildings is a complicated task encompassing a number of parameters such as the architectural design and construction, energy efficiency along with political support and incentives, socio-financial effects, users' behaviour and, of course, the available investment. The design process needs to address all the different specifications. All these parameters define the decisions taken. Moreover, there are often many parties involved, from the end-user to the real estate company and from the architect to the constructor. Throughout this process and the various constraints to be considered, energy performance is often not one of the main consideration. It is calculated towards the end of the design process, for example in the form of an energy label regarding the final strategy, mostly to be used for official and marketing purposes. In this way, the performance evaluation comes after the strategy has been developed, without influencing the decisions made.

The integration of all design aspects during the early design phases is extremely complex, particularly as far as energy efficient design is concerned. At this stage, the architects are in search for a design direction to make an informed decision (Attia et al., 2012). Decisions taken during this stage can determine the success or failure of the design, as a decision made earlier can have a bigger impact with less effort. If the designer is provided with an indication of how efficient refurbishment options are, it is possible to apply them as part of an integrated strategy rather than try to add measures at later stages, after the strategy has been developed.

In order to be able to assess the energy performance of the refurbished building at the early stages of the design phase, we first need to address the building component that is the most influential with regard to energy consumption. This is the building façade, or rather the building envelope. The building envelope is the space enclosure element and it consists of components such as external wall, windows, roof and ground floor. Not only is the façade the main element of the architectural expression and the key feature of the building's existence, but, most importantly, it also regulated the energy use and the indoor condition. The energy consumption for heating and cooling of buildings is directly related to heat losses through building envelope components, ventilation and air infiltration and inversely related to heat gains in the building through solar radiation, all parameters that depend on the design, quality and function of the external envelope of the building.

Therefore, taking into account the need to refurbish residential buildings and the importance of integrated design of façade refurbishment strategies, this research aims at answering the following question.

How can the energy upgrade potential of residential façade refurbishment strategies be integrated in the early design phase, in order to support decision-making?

The objective of the research is to enable the design of refurbishment strategies that acknowledge the potential of energy saving. Having an assessment of the energy performance results in informed decisions at the early stages of the design, which improve the efficiency of the strategy and the final refurbished building.

To be able to answer the research question, several sub-questions need to be investigated. The sub-questions include the following:

1. What are the condition and construction of existing residential building stock?
2. What is the role of the building stock refurbishment in the context of sustainable development?
3. What are the design principles to improve the energy performance of existing buildings?
4. What strategies and retrofitting measures are currently applied in refurbishment practice?
5. When are decisions made during the design process of refurbishment strategies and how can it be supported?
6. How can the different measures be organised and quantified?
7. What are the key points during the design to consider the energy saving potential?
8. What type of information do refurbishment stakeholders find useful to support the decision-making?

§ 1.3 Methodology

To answer the research question and to support the design of refurbishment strategies, the present thesis proposes an approach to provide an indication of the energy saving potential of different retrofitting measures. The methodology used to develop the approach includes organising and calculating information about component retrofitting measures. Thus, it consists of different steps, as explained below:

1. Systematically organise different refurbishment measures.
2. Quantify retrofitting measures.
3. Create a roadmap to use the data during the design, based on case-study refurbishment strategies design.
4. Validate the approach and combine all findings in the final database.

The developed approach is also referred as a "toolbox approach". The different retrofitting measures are the "tools" that constitute the refurbishment strategy. In this sense, the organisation of the different measures compiles a "Façade Refurbishment Toolbox" (FRT), from which the refurbishment designer selects the tools to use to upgrade the building envelope.

1 Systematically organise different refurbishment measures: Toolbox compilation

The first step to enable the evaluation of the different measures is to systematically compile and organise them, according to the building envelope component they address. When it comes to integrated refurbishment, all the key aspects of the building envelope need to be considered and included in the refurbishment measures. The key components of the building envelope are where heat losses occur, compromising the thermal envelope. Depending on the design and function of the occupied spaces, they are the exterior wall, windows, balcony ceiling or ground floor, roof or top floor ceiling, balcony slab, etc. Building services should not be neglected, as they can be connected to the envelope as well, for example in the case of distribution systems or solar panels.

Depending on the objectives of each project, different strategies can be found. They can range from the basic thermal update of the envelope to meet energy efficiency standards to more sophisticated solutions, in which extra space is added and advanced options for energy upgrade (e.g. renewable energy sources) are available. Integrated strategies are the result of combining measures for each building component. That is why refurbishment options are systematically organised according to the component they address. The options presented are based on a literature review on the existing building stock, principles of improve the buildings energy performance and current refurbishment practice, as investigated through best practice examples, industry overview and experience with refurbishment specialists.

2 Quantify toolbox options

After defining the different possible retrofitting measures, it is essential to assess how the measures contribute to the energy efficiency upgrade. The quantification of the energy efficiency upgrade is expressed as the reduction in energy demand prior to and after their application.

For the comparison to be possible, the performance of existing buildings is first simulated, to provide a number for the energy demand. As the approach aims at supporting future refurbishment projects and it is not limited to specific case studies, the options calculated need to cover a wide range of buildings. To assist this process, we need to identify the key parameters that can be used to categorise refurbishment projects. The location, orientation and existing construction are parameters that define the performance and, thus, the choice of measures. These parameters are given for any existing buildings and depend on neither the refurbishment scenario nor the design process.

Following the assessment of existing buildings' performance, each refurbishment option is individually simulated. This process results in the quantification of the toolbox, as we can provide numerical data on the potential energy reduction that results from the implementation of each separate tool.

3 Create a roadmap to use the toolbox data

For the toolbox approach, it is crucial to understand what the parameters that shape decisions are and when the information of the possible energy reduction is useful for the designer. Important as the compilation of options provided by the toolbox might be, not all of them are applicable to every case. Furthermore, the designer needs to know at which points throughout the process the information is needed and what are the available options at that time.

To address these issues, the approach investigates how refurbishment strategies are developed, identifies the decision-making points and determines what the input of the toolbox can be. Refurbishment strategies for case-study buildings have been developed with the support of the toolbox. Each project has different design process, as the parameters that affect decisions differ. Combining these processes creates a roadmap to refurbishment strategy design process.

The roadmap addressed each building envelope component separately. In reality, the process is iterative and not necessarily linear, as some decisions affect other components as well. However, the roadmap and the toolbox aim at simplifying this complex process, in order to underline the impact of the toolbox information of the design decisions.

4 **Validate the Approach and combine all findings in the final toolbox database.**

As a final step in the methodology, all the data are combined and a guideline on how to use them to support the decision-making is provided. An important step in the methodology is the approach validation. Since the approach aims at supporting refurbishment strategy design, it should be validated by designers and building industry professionals involved in the decision-making process for refurbishment projects, which can potentially use the toolbox information. These professionals are primarily architects working on refurbishment projects, but could also be housing association and constructors who are responsible for maintaining the estates and making decision regarding refurbishment. Therefore, validation will be conducted through interviews with refurbishment experts and stakeholders. They are presented with the approach and the relevant information and are asked to give feedback on its usability and suggest improvements.

§ 1.4 Scope of the research

This thesis deals with the refurbishment of residential building stock and aims at giving an indication of the energy performance of refurbishment measures at the early stages of the design. However, the subject of the research is very broad and, thus, certain boundary conditions need to be set.

The present research is focused on investigating refurbishment at the European level. European countries share similarities that render them comparable. On the other hand, there are differences in climate, topography, building methods, etc. Even though it is important to identify key parameters, addressing all of them adds to the toolbox complexity, making it very difficult to organise. Therefore the parameter of climate is excluded by focusing on one climate, the north-west European climate. Nevertheless, the proposed methodology does not exclude its applicability in other geographical areas with different climates. The numerical output of the toolbox calculations would be different but the approach would still be valid.

The focus area was selected based on the intention to address large markets that share certain similarities in terms of climate, architecture, construction methods etc. The countries of Central Europe, such as the UK, Germany and the Netherlands, fulfil these conditions. Not only do they have similar climate type, as shown in Figure 1.2, but they also account for the largest proportion of floor area in Europe. According to a study of the BPIE (2011a) half of the total estimated floor area is located in North and West Europe, with Germany, France and the UK having the highest amount of residential floor area, occupying approximately 7.5 billion m^2.

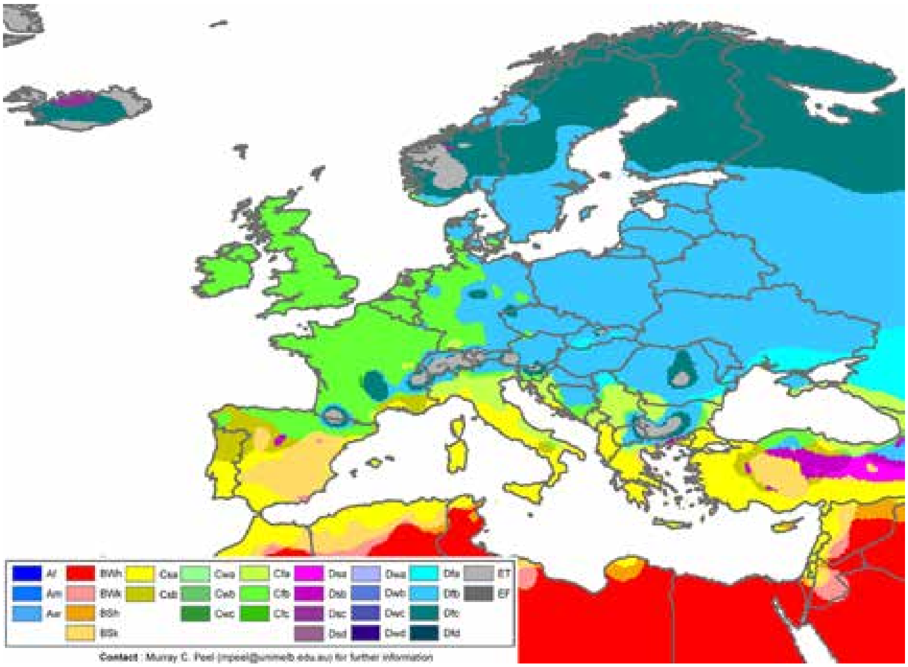


Figure 1.2
Koppen-Geiger climate type map of Europe (source: adapted from Peel et al., 2007, fig. 8). The research focuses on Cfb climate type (moist mid-latitude climate, with adequate precipitation in all months and no dry season, warm summer with the warmest month below 22°C)

Case-study buildings are investigated as part of the methodology. As the European residential building stock is very diverse, in terms of building types, size and construction, the research needed to focus on one case-study building type, so that refurbishment strategies would be comparable. The applicability of the research can be extended to other building types, as will be explained in chapter 8 of the thesis. The target group selected is multi-family residential buildings, constructed between the years 1945 and 1975, after the Second World War and before the oil crisis. The selection of the group was based on many criteria, including the size and the possibilities of the particular building type.

The buildings of that period account for a large proportion of total stock, around one third (Itard & Meijer, 2008). This dwelling stock is not very homogenous, varying from traditional to modern construction techniques. A common characteristic, however, is that the buildings were generally poorly insulated at the time of construction and that there is a need for renovation. Moreover, being 50 years old, the building envelope is approaching the end of its life while the structure is normally still active. Multi-family houses are of significant importance, as according to Eurostat (2011) 41.8% of the EU population lived in flats. Even though, the proportion varies from country to country, it is still a considerable part.

Last but not least, this building type better serves the purpose of the research to investigate several refurbishment measures. Compared to building from earlier periods, which in many cases have been declared as monuments and have load-bearing walls, the building types in question provide less limitation and more possibilities for building envelope interventions. Nevertheless, the results of the proposed methodology are applicable to other types as well.

Since the research aims at integrating the energy performance into the design process, the performance needs to be quantified. The research focuses on operational energy which is one fragment of the environmental impact of buildings (EN15643-1, 2010). Other parameters important for the environmental performance of buildings are the thermal comfort of occupants, energy conservation features, solar energy utilization, incorporation of recycled materials, reduced building construction waste etc. In the present study the building performance is assessed in terms of energy efficiency. The comfort of the users, with regard to adequate ventilation rates and comfort temperatures is a precondition in calculation.

The indicator for energy efficiency is heating demand, as it accounts for the largest percentage of energy consumption in residential buildings. Namely, more than half of the final energy consumption of residential buildings in the EU is used for space heating, reaching up to 70% (BPIE, 2011a). Water heating also plays a major role (25%). Even though the importance of water heating is also addressed by the toolbox, e.g. with the use of solar panels, it is not considered in the energy efficiency calculation in the current study. The usage patterns prior to and after the refurbishment are assumed to be comparable, thus, no significant change in the use of appliances, for example, is expected.

§ 1.5 Relevance

Scientific Relevance

The present thesis adds to knowledge on refurbishing and improving the energy efficiency of the building stock. It approaches the design process differently compared to hot it is usually approached in practice. The design process of refurbishment projects is a complicated task and depends on a large number of parameters. The decisions taken in the early stages of the design determine the final result; however, the assessment of the environmental performance only happens at the end of the design process. The proposed approach aims at reversing this process, by giving information regarding the energy upgrade in the early stages of the design. This could be an asset to designers, the building industry and stakeholders, who do not have specialised knowledge on energy performance. Based on existing methodologies, such as Building Performance Simulation (BPS) and research projects providing information for effective evaluation, the focus of the proposed approach is the architect of a refurbishment strategy who makes decisions on the design quality.

The research presents an integrated approach to the energy efficiency upgrade and gives specific answers to key parameters of refurbishment, resulting in improved energy performance. The importance of this approach is that it recognises the diversity of each project, as well as the designer freedom to his decisions, in contrast to existing refurbishment guidelines, which mostly comes in form of general suggestions. With respect to the specific requirements of each case, the research results constitute a starting point for refurbishment projects, assisting designers, clients and users to make efficient choices.

Societal Relevance

Refurbishment of aging and neglected multi-residential buildings is a particularly socially sensitive topic. The results are expected to have a big impact on society. Apart from the resulting savings on energy and the consequent effect on climate change, a direct effect will be better comfort (Hong et al., 2009), housing quality and lower energy bills for the people living in the dwellings in question. With 10-25% of the total EU population estimated to be fuel poor, energy upgrade of residential buildings can provide the means whereby homes can be "fuel poverty proofed" as a result of the lower energy bills that arise from such a renovation (BPIE, 2013b).

Moreover, refurbishment serves to preserve the societal value of existing buildings, while also improving the living conditions. Furthermore, technical decay in the estates is connected with social decay. Groups of users with higher socio-economic strength leave the estate and are replaced by weaker groups. This mechanism often results in high turnover, vacancy, lack of control and in general unfavourable living conditions. Hence, refurbishment can reverse this problematic social environment, as the building meets today's demands and provide a functional and attractive contribution to society.

§ 1.6 Research outline

These questions can be answered in steps that make up the separate thesis chapters. The first part of the thesis, which consists of three chapters, will set the theoretical framework that is necessary to be able to support the proposed approach. To achieve the purpose of the research, which is to support refurbishment design process and enable effective choices, it is necessary to combine the existing practice of the building industry with specialised knowledge on upgrading the efficiency of the building stock.

Chapter 2 deals with the context of refurbishment, which is the residential building stock. In addition, construction principles of residential facades and standard problems are reviewed. In this way, refurbishment objectives are defined, as well as the key components that need to be addressed. Once the objectives of refurbishment are identified, Chapter 3 gives an overview of design principles that help the building to adapt to weather conditions and achieve occupants' comfort with minimum support from auxiliary energy sources. The parameters that are critical to measures adequacy in refurbishment projects are also discussed. Chapter 4 completes the theoretical framework that leads to the proposed approach to support the design of refurbishment projects, by examining the state-of-the-art of refurbishment practice.

Once the theoretical frame is composed, Chapter 5 introduces an approach that addresses refurbishment as a design question. After having extensively discussed refurbishment in the previous chapters, in terms of existing stock, possible strategies to enhance building performance and current refurbishment methods, Chapter 5 aims at explaining the bottlenecks in the design process of refurbishment projects and proposing an approach to support the decision-making process and improve the design's effectiveness. In order to enable effective choices, we need information of the diverse options and their impact on the energy efficiency of the refurbished building. This knowledge is provided through systematic organisation of the possible options and quantification of their impact. In this way not only is the process organised, but the different options are also made comparable, facilitating the decision-making. This can be made possible through the systematic organisation of refurbishment options and the quantification of their efficiency in a toolbox, which is a database of options organised according to the key components of an integrated refurbishment.

Chapter 6 includes the roadmap composition. The toolbox quantification has resulted in a large amount of data related to potential energy reduction in refurbished buildings. To demonstrate how the data are used in the decision-making process for refurbishment strategies, case study buildings are examined. First the existing situation of the buildings is presented, along with any specific problems or requirements for the refurbishment, then solutions for each building envelope component are chosen accordingly, supported by toolbox information. Based on the design process of the case studies, we can highlight the decision point where the refurbishment options performance, provided by the toolbox, is used. As a result, a roadmap to the toolbox data is composed. Moreover, different combined solutions are simulated, demonstrating relevant combinations of tools.

The approach is validated in chapter 7, through interviews with experts. The experts from the building industry are chosen and the topics and layout of interviews are explained. The results draw conclusions regarding the usability of the toolbox information and the roadmap to support the design process and suggested improvements.

The final result of the thesis, presented in Chapter 8, is the FRT database, along with a guideline on how the information can be implemented in the future, detailed information of how to categorise each refurbishment project and an assessment of the effect of diverse options, in order to support the decision-making process.

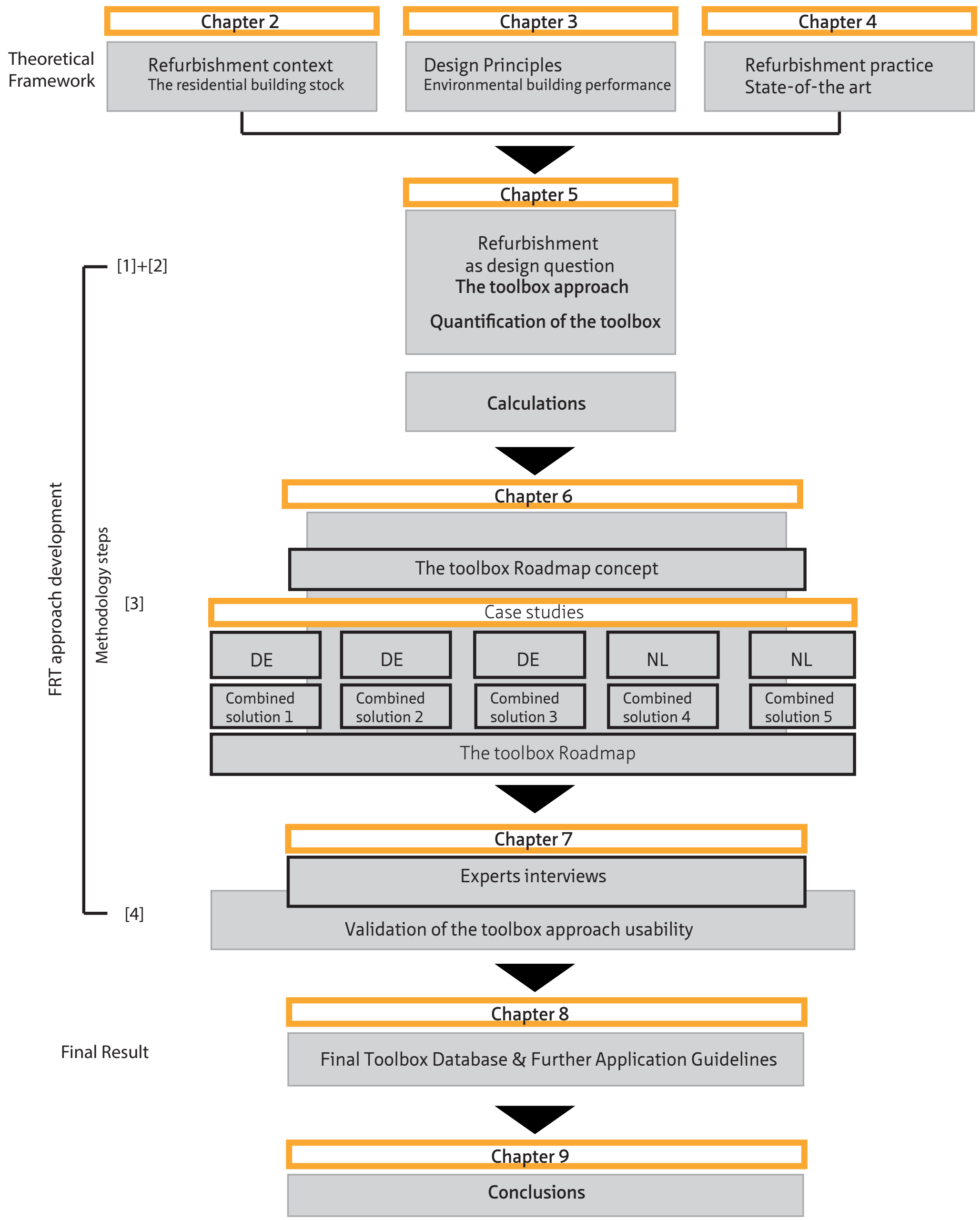


Figure 1.3
Research outline scheme .

2 Refurbishment Context: The Residential Building Stock in Europe

Given the task of refurbishing the existing residential buildings, the first necessary step is to identify and understand the target of this action, which are the old buildings that are or will be considered for refurbishment. Therefore, this chapter sets off to study the existing residential buildings stock. The goal is not only to define the context of refurbishment, but also set the theoretical framework and starting point for the research approach developed in chapters 5 and 6.
In the first section of this chapter, the residential building stock in Europe is discussed, in terms of amount, age and ownership status. The post war residential stock is highlighted in section 2.2.4, as it is a particularly interesting part of the stock for the present thesis, and the refurbishment discussion in general. Following that, in section 2.3, an overview of residential façade types is presented, since the façade is one of the most important components addressed by refurbishment and the focus of the present research. The current conditions and standard problems that refurbishment needs to tackle are reviewed in section 2.4. Finally, section 2.5 starts the refurbishment discussion, with definitions, motivation, and barriers.

§ 2.1 Introduction

In every refurbishment project, the first step is examining and analysing the existing building. In order to be able to propose successful solutions and respond appropriately to the refurbishment needs, we must be familiar or at least understand the typical forms of construction of the past years (Giebeler, 2009). The objective is not strictly to document the complete history of each building's creation, but to gather information relevant to its original construction, current condition and future prospects (Zijlstra, 2009). Hence, we should look at the buildings stock at three levels: past, present, future. The past refers to building construction, as it was realised in the past technological and historical circumstances, present is the existing condition and its problems, and future is the refurbishment strategy. The development of refurbishment strategy in particular is the objective of the present research. To answer the research question, first we need to investigate the past and present state of the building. For this purpose, our discussion on refurbishment gives an overview of the building stock and identifies the decisive factors for refurbishment.

The importance of investigating the existing construction and condition of the building stock has been recognised by various studies that aim at researching refurbishment potential and methodologies to evaluate and implement it. There is an extensive record of reports and publications that survey the residential building stock on a national and international level. They are mostly result of European funded projects with a number of different countries involved, such as the European project EPIQR (energy performance, indoor air quality, retrofit) (Balaras et al., 2000), C16 (2011) on the topic of "Improving the quality of existing urban building envelopes" and TABULA (2012) that aims at creating a harmonised structure for European building typologies. Publications also come from research institutes, such as the Building Performance institute Europe (BPIE (2011a) the International Energy Agency (Waide et al., 2006; Zimmermann, 2011), and other research projects about refurbishment solutions (TES Energy Façade, 2011; Itard et al., 2008; Nemry et al., 2010). Further discussion on these research projects and their relationship with our research approach will follow in Chapter 5.

Chapter 2 of this thesis sets off to investigate the European residential building stock, which is being considered for refurbishment. The analysis is based on literature review on residential building stock and it is organised with focus on the building envelope construction, which serves the purpose of the research. The chapter aims at analysing and classifying characteristics of the building stock. The analysis is not meant to be historical and does not strictly follow time periods, even though the time frame of construction type's development is indicatively mentioned.

Firstly general characteristics of the stock, such as the building type, age and ownership status, are mentioned. These characteristics are important for shaping the refurbishment context. The post-war housing stock is discussed separately, not only because it is the target group of the research, but also it is very interesting in the refurbishment discussion in general, due to its large numbers and quality. Subsequently, the building typologies are organised in terms of construction. The investigation of existing construction is essential to answer the research question of integrating the energy saving potential into the design of refurbishment strategies, because the potential savings are related with the existing construction and current energy use. To conclude the stock investigation, common problems of the buildings, both physical and energy-efficiency related, are highlighted.

Finally, at the end of the chapter the refurbishment discussion begins, which is regarded as the future of the building stock. Definitions of refurbishment and relevant actions are given, as well as motivation and barriers. Understanding the building stock, which is to be the subject of refurbishment, is an essential step, before moving to the next chapters, where sustainability aspect and current practice of refurbishment are discussed.

§ 2.2 The Residential Building Stock in Europe

The building stock consists of a variety of building types such as offices, commercial buildings, schools, hospitals, apartment buildings, terraced or detached houses etc. The different building types share certain similarities in the parameters that affect the refurbishment strategies. Groups with considerable differences in terms of size, constructional features, function, decision-making and market processes etc. can be identified and, thus, they need to be addressed separately. There are two general categories that the building stock can be divided into, residential (houses and apartments) and non-residential.

In the European Union, it is estimated that there are 24 billion m² of usable floor space, which increases at a rate of 1% (BPIE, 2011a). According to the 'Europarc-Survey', which estimates the building stock in the five biggest Western European Countries - Germany, France, Italy, Spain and Great Britain, the total stock excluding agricultural constructions in the five countries mentioned above sums up to 16 to 17 billion m² net occupiable floor area (NOA) (Ebbert, 2010). Residential buildings represent the largest amount of floor area, accounting for 70-75% (BPIE, 2011a; Ebbert, 2010; Itard & Meijer, 2008). Moreover, the energy demand of residential buildings accounts for more than one fourth of total energy consumption in the EU. Therefore, their impact is considerably important.

To investigate the possibilities of refurbishment, it is essential to understand the parameters that formulate the refurbishment scenario. The construction time and the market are important parameters. Depending on the different time each building exhibits typical characteristics and shortcomings according to the material used, the requirements and regulations, the design and the construction techniques applied in that specific period. The market, on the other hand, in terms of ownership and tenure status, is particularly significant with regard to renovation, as it determines the decision-making and the profit of the investment.

§ 2.2.1 Age

Data on the age of the building stock give a good indication of the physical characteristics of buildings. The Figure 2.1 shows the breakdown of the residential building stock into the different construction periods in different European countries.

The pre-war residential building stock accounts for 20% to 39% of the total residential building stock. The pre-war building stock is relatively homogenous in terms of construction characteristics. Dwellings built after World War II and before the oil crisis account on average for 29%. This is an important observation given that most national building regulations that mandate thermal insulation of building envelopes were introduced after the 1970s following the energy crisis (Poel et al, 2007, p.394).

In most countries, the dwellings built between 1970 and 1990 account for 21% to 27% of the total stock. In general, the dwellings built during this period are reasonably well insulated, but already need some kind of renovation, especially the older ones. The percentage of newly built dwellings (since 1990) appears to be almost 14% on average, varying from 8% to 22% (Itard and Meijer, 2009, p. 34).

The BPIE survey (BPIE, 2011a) has classified the stock according to age into three bands; before 1960, between 1961-1990, and after 1991. The survey includes 23 European countries and it makes a distinction between south, north- west, and central-east Europe. Since different age bands are used the results are not directly comparable with the data in Figure 2.1. In this study, the buildings built in the period 1961-1990 are 40-50% of the stock. This does not contradict the previous study, which showed approximately 55% to be built between 1945 and 1990. The data on recent buildings (>1991) agree in both studies to be approximately 15%, suggesting the 85% of the European building stock is older than 20 years.

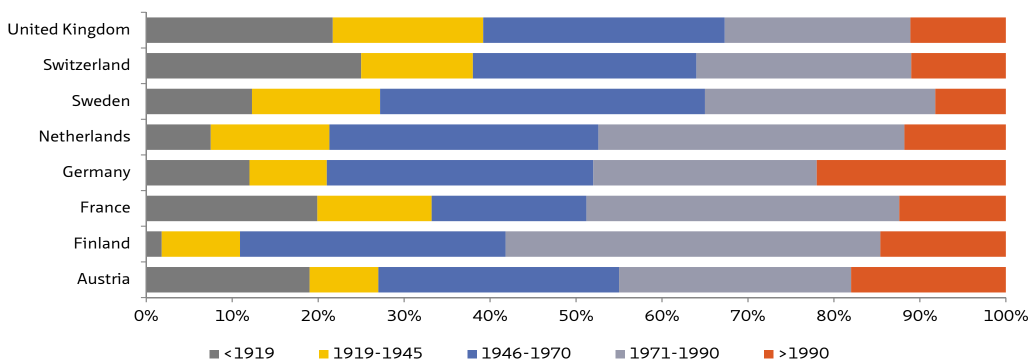


Figure 2.1
Age distribution of the residential building stock (source: Itard and Meijer, 2009, p. 35)

§ 2.2.2 Housing types

Within the residential building stock, different housing types are encountered, according to the number of dwellings accommodated in one building and their relation to neighbouring dwellings. The housing type is important not only for the current performance of the building – for example detached houses have higher energy demand because they have more external walls-, but also for the refurbishment decision-making and measures. Residential buildings can be classified into single-family houses, terraced houses and multi-family houses.

A single-family or detached house is a house that is separated from its neighbours on all sides. It is the archetype house, the shelter of the family. Furthermore, it is the most desirable type of housing (Schittich & Geisel, 2000), as it realises the need for privacy and personal freedom and also symbolises a roof over the head, a piece of land that we can claim our own. The detached house has open spaces around it and gives the possibility for on all sides, allowing greater flexibility in floor plans. The variation in the size and design of the building and surrounding spaces are endless.

Terraced or row houses are single-family houses built in a row, with their side exterior walls to be shared, separated with a small cavity or adjacent to each other. They have private entrances to dwellings within the narrow street façade. It is mostly an urban housing type, due to space limitations in the urban environment. They are also referred to as townhouses (Chandler, 2005). Rural row houses can also be found, especially in clustered developments. Built closely together, terraced houses make efficient use of the land, allowing higher densities and preserving outside space. Moreover, the shared wall conserves materials and reduced heat losses. Terraced houses are often as collective residential complexes and have similar floor plans and some exterior visual connection. On the other hand, it possible to encounter greater variation in row houses when they are not the result of the same design. Separate single-family houses built in adjacent plots and making use of the whole plot width become terrace houses. This is particularly common in city centres due to high density and small plots width.

Multi-family houses consist of several self-contained housing units, referred to as apartments or flats. They can be perceived as detached or terrace houses, but in this case the street entrance gives access to a number of dwellings. As cities have grown and land values have risen, residential buildings become taller to accommodate more dwellings and provide higher density. Often, building intended for single families have been converted into multiple dwelling units (Chandler, 2005). A common form of multi-family houses is apartment blocks. They existed since earlier years, but became particular popular after the Second World War, due to the extreme housing shortage and the need for higher densities. In those circumstances, traditional building methods became less importance, as developers sought for fast and economical construction techniques to cover the demand. Apartment blocks range from middle-rise (3-4 storeys) to high-rise.

Figure 2.2 shows the housing types distribution in different counties. The data show that in 2011 41.5 % of the EU-27 population lived in flats, just over one third (34.4 %) in detached houses and 23.3 % in semi-detached houses. The share of persons living in flats was highest among the EU Member States in Latvia (65.3 %), Spain (64.9 %)

and Estonia (64.5 %). The share of people living in detached houses peaked in Slovenia (66.8 %), Hungary (64.7 %), Romania (60.8 %) and Denmark (59.2 %), while the highest propensity to live in semi-detached houses was reported in the Netherlands (61.2 %) and in the United Kingdom (59.3 %) (Eurostat, 2013b). It is then obvious that all housing types share comparable parts of the stock and they should all be subject to refurbishment.

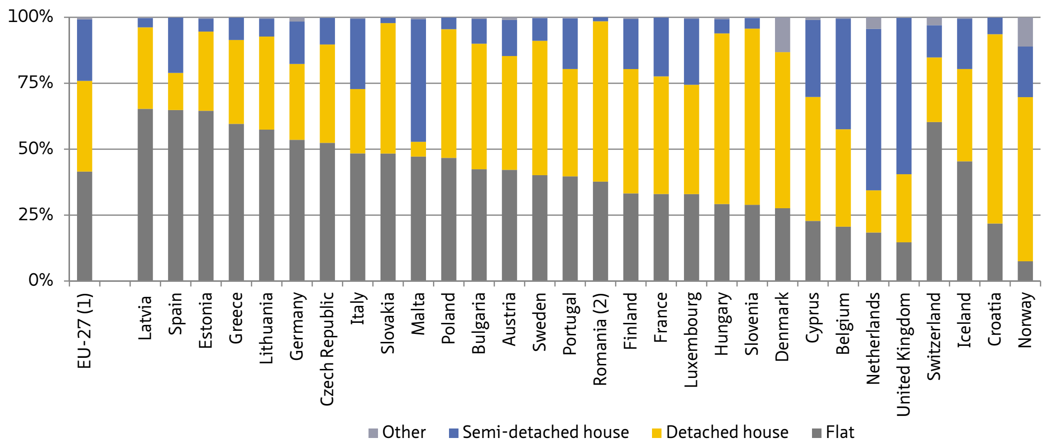


Figure 2.2
Households broken down by type of dwelling in the EU 2011 (source: Eurostat, 2011© European Union, 1995-2013).

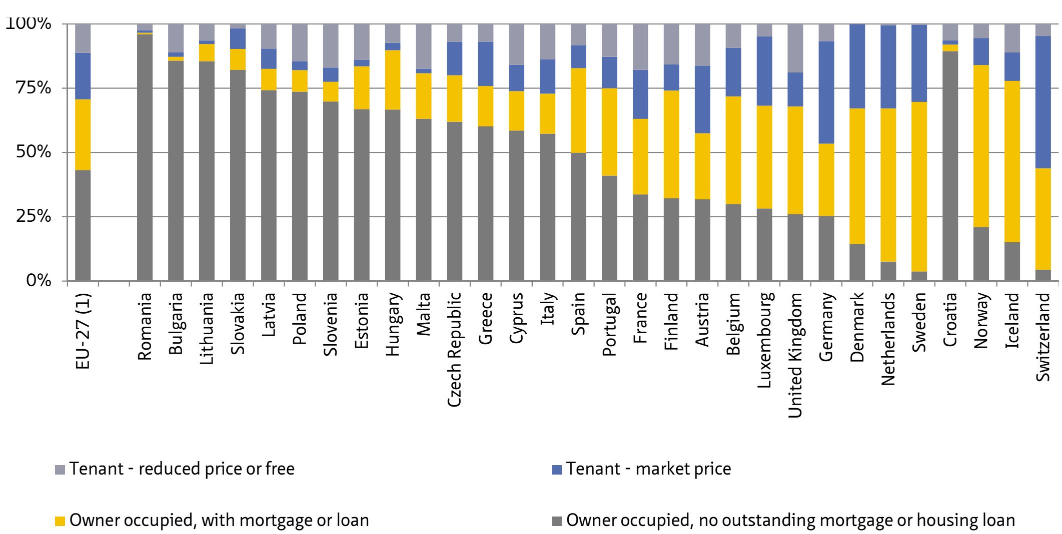


Figure 2.3
Households broken down by type of tenure in the EU 2011 (source:Eurostat, 2013b© European Union, 1995-2013)

§ 2.2.3 Ownership

In terms of ownership status, the residential building stock is divided into three main categories: owner-occupied, social rented, and private rented. Roughly stated, the ratio of the owner-occupied to the rented sector is 2 to 1. However it may vary significantly in the different countries (Figure 2.3). Eurostat (2013b) subdivides owner occupied houses with or without outstanding mortgage. In 2011, over one quarter (27.6 %) of the EU-27 population lived in an owner-occupied home for which there was an outstanding loan or mortgage, while more than two fifths (43.1 %) of the population lived in an owner-occupied home without a loan or mortgage. Overall, seven out of every ten (70.7 %) persons in the EU-27 lived in owner-occupied dwellings, while 18.1 % were tenants with a market price rent (private rented), and 11.2 % tenants in reduced-rent or free accommodation (socially rented). In few countries, such as Switzerland and Germany, the owner occupancy and rented sector share similar parts of the housing market.

There is a relationship between the type of tenure and the type of dwelling. In general, a very large share of single-family houses is owner-occupied. For multi-family houses the shares vary a lot. In Sweden, for instance 68% of the multifamily houses are social rented, while this percentage is only 6% in Switzerland. In a country like Switzerland, it may be more difficult to implement the renovation of apartment buildings because the ownership – and therefore the responsibility – is shared between several households. (Itard et al., 2008).

The owner-occupied and the rented sector both share parts of the market and they are both important to achieve sustainable renovation. However, the characteristics of both sectors differ a lot. In the owner-occupied market, the investor is also the one who profits from the investment. However, there is often a lack of financial means to invest. A major barrier of the rented sector is that the owner has to invest, whereas the occupant profits from the investment, known as the split incentives barrier (see also section 2.5.4). In the private rented sector, increasing the rent may solve this barrier, insofar as it is desirable and possible within the existing regulations. In the social rented sector, this would be more difficult, therefore specific financial solutions and regulations will be necessary (Itard & Meijer, 2008).

§ 2.2.4 Overview of the Post-war multi-family housing stock

The post-war period is particularly interesting for the present research and the refurbishment discussion in general, as it was a turning point in the development of the residential building stock. There has been a shift away from traditional construction methods to enable the production of large numbers of housing units, as quick and economical possible.

After the World War II, most European countries experienced a large housing shortage, due to war devastation, population increase and economic growth. This shortage was anticipated with a high level of building activities, focusing on quantity rather than quality (Andeweg et al., 2007). As a result, the European housing stock originated from this period accounts for a considerable share of the total stock, while it lacks technical and functional performance. A second benchmark for the housing stock is the oil crisis in 1970s. The increasing awareness of fossil fuels deficiency brought concerns on the energy efficiency of the building stock, resulting in legislation related with building insulation and material.

This particular part of the stock, which represents almost one third of residential buildings, is not very homogenous. A varied mix of construction types exists, from traditional to modern, from low rise to high-rise. A common characteristic, however, is that the buildings were generally poorly insulated at the time of construction and that there is a need for renovation (Itard & Meijer, 2008). Moreover, being 50 years old, the building envelope has reached end of life while structure is in general sound (Andeweg et al., 2007). Due to the circumstances of its development, the post-war housing stock has specific characteristics in terms of neighbourhood design, construction and problems.

Housing policy and the new neighbourhoods

After 1945, a series of developments led to the emergence of a field of action that we may refer to as international housing policy. There are noticeable similarities in different European countries concerning housing policy during the first decades after the WW II. Most countries created legislative frameworks to facilitate and encourage large scale production of housing (Andeweg et al., 2007). The aim of these policies was to increase the total supply, raise and equalise housing and urban standards and help the economy (Power, 1997). Housing policies came in the following form; public housing – estates constructed or managed by the state with low or subsidised rent-; promoting owner-occupancy, by financial and technical assistance to privately built homes; and enabling the building industry to become more efficient at delivering decent, affordable housing. The latter involved better building materials and methods, the training of tradesmen and entrepreneurs, assistance to small savings and mortgage lending institutions, and efforts toward guaranteeing secure tenure (Harris & Giles, 2003).

The result of these policies was the development of large housing estates. A housing estate is the result of urban planning, not of the organic growth of cities. Estates contain thousands of dwellings, depending on the local context. The new neighbourhoods were based on CIAM ideas of constructing free standing, well oriented building blocks that allowed air, light and sunshine into every apartment (Andeweg et al., 2007). The estates were mostly constructed in the periphery of cities, were the land was cheap and easy to develop, without urban restrictions. Some of these once peripheral spots become central within cities, while others remain in isolated locations.

Housing estates vary from single-family developments to large-scale housing constructions, like high-rise blocks (Wassenberg, 2012). At a time with great housing shortage and overcrowded inner slums, these developments transformed urban living conditions. They offered mass population improvement in living conditions, providing affordable, spacious, better equipped, airy and day-lit houses. These gains became elusive when problems started to appear, but in the end they validated the estates rescue efforts that took and are currently taken place (Power, 1997).

Construction -The Non-traditional building systems

During the development of post-war housing stock, there has been a significant change in construction techniques, which were looking to achieve quicker and cheaper housing production. The new systems are in general characterised as "non-traditional" and they are dominated by industrialisation in the construction. The idea of industrialised building systems has been developed since the interwar years and the Modern movement (Moe & Smith, 2012). The social and economic conditions after the WWII helped to realise these systems in a large scale.

Throughout Western Europe housing shortage was great. An increase in housing production was required, utilized also to promote economic growth. Building capacity of the traditional construction was not enough. In many countries industrial building methods were sought, to solve the shortage of skilled building trade operatives. The answer was sought above all in labour-saving concrete constructions, mostly in element building methods or cast in-situ methods. Element building means that large concrete wall and floor elements are made in the factory, transported to the building site on large trucks and assembled on the spot with a large building crane. In cast-in-situ methods, a formwork (often of steel) is used in which the concrete is poured. Such systems cost less than traditional building methods if the series are large ones. The pressure to increase the size of orders and to apply high-rise (in which these methods specialized) was great, partly because of the strong market position of the building firms (Priemus, 1986).

The technology used for non–traditional buildings in Europe seems to be geographically defined. Prefabricated systems became the norm in many central, east and north European countries. They were already in the early years of their application well documented, as the same system was used almost identically of the construction of different building, throughout the country. The system often was named after the construction company that implemented it. Literature with details on the manufacturing and construction of the systems can be found (Diamant, 1964, 1965, 1968; Kjeldsen & Simonsen, 1965; Priemus & Elk, 1971). In the eastern part of Europe, as well as in Sweden and Denmark, large panel building is the prevailing technology. In France and the Netherlands, there are a wider variety of techniques, including and some more experimental made of stacked concrete blocks (e.g. MUWI system in the Netherlands). Industrialised, prefabricated systems were not used in a large scale in southern European countries, where the stone and brick tradition was still strong (Andeweg et al., 2007).

Problems of the post war housing

Problems in the particular part of the housing stock are not a new issue. Even though the post-was multi-family houses started with ambition to be a spacious, comfortable, well designed, and often suitably located alternative to the city-centre dwellings (Wassenberg, 2012), problems manifested themselves in the early decades after their construction. Already in the 1980s, serious operating problems and high vacancy have been observed, in many countries including the United States, Great Britain, France, Sweden, Norway, The Netherlands and Denmark. The terms "difficult-to-let" in the UK or "distressed neighbourhoods" in France, with regard to the post-war housing estates, reflected the growing problems (Power, 1997). International conferences, such as "Post-war public housing in trouble" (Prak & Priemus, 1984) and World Congress of the International Federation for Housing and Planning, 'Improvement of post-war housing estates', came to bring the issue into attention and try to find solutions. The study of Power (1997), initiated in 1987 by 5 European institutions, analysed the problems and the actions to be taken and evaluated examples of interventions in estates.

According to Priemus (1986) operating problems on post-war housing estates are characterized by three processes of decay that are usually interrelated: technical decay, social decay and financial decay. Technical decay frequently already begun with an inadequate initial quality, due to small construction times, poor material and lack of experience of the non-traditional construction. Lack of proper management and maintenance came to add to the problematic technical condition. As a result, groups of residents with greater socio-economic strength leave the estate, to be replaced by socio-economically weaker groups (young people, ethnic minorities, etc.). Because of high turnover on the estate social control is limited. The estate gets a bad name. The 'living climate' is generally regarded as unfavourable. The third negative spiral is financial decay. As a result of vacancy, often tenants' turnover and technical problems, income is lower than estimated, while expenses for repairs grow, causing financial issues to landlords. Even though mass housing was adopted as an economical method to housing production, due to the cheap land and industrialised systems that enable large scale repetition, in the long-run they proved to have unforeseen costs. The sites outside the cities required infrastructure and facilities. In many cases the infrastructures came too late, sharpening social problems and isolation. Moreover, the properties lost their predicted value, while the subsidies related with the housing policy of these estates were not properly forecast (Power, 1997).

Technical, social and financial decay often prove to reinforce one another, in a vicious cycle. Once the social decay has spread, the turnover of tenants' increases and excessive vacancy looms. The subsequent loss of income intensified the lack of maintenance, deteriorating the technical problems. The complex interconnected problems pressed governments of the European countries in the 1980's to re-engage in the estates. The rescue programmes included three main phases; physical reinvestment, resident consultation and management change, and social and economic priorities (Power, 1997).

Since the 1980's when technical and operational problems of large scale housing estates were manifested, there have been efforts toward overcoming them. The efforts focus on different scales, from neighbourhood regeneration and ownership status change to improvements on the housing design, size and quality. Despite the successful examples, such as Florijn Noord in the Bijlmermeer in the Netherlands (RICCARDO, 2008), or the Priory Green in Finsbury and the Barbican in the UK (Allan, 2007), many of the estates experience still problems in the recent years (Wassenberg, 2012).

Concerns on energy efficiency have come to be added to the already problematic post-war housing stock. Energy efficiency is a major concern in the residential buildings of that period, particularly when considering social conditions such as "fuel poverty" for households of low incomes (BPIE, 2013b) . It has become a problem since the 1970s, when the strong increase in the price of crude oil and natural gas since 1973 resulted in considerable rise in heating costs per dwelling (Priemus, 1986). The last decade, due to public and market awareness on energy and environmental issues, along with regulatory obligation (DIRECTIVE, 2002/91/EU) intensifies the need for energy saving measures.

After having an overview of residential building stock, in terms of type, age and ownership and highlighting the characteristics of post-war stock in particular, the analysis focuses on residential building envelope construction. Understanding the existing structure is important in order to decide the measures to upgrade the building envelope and, thus, it is an essential part of the present research. The following section identifies the most common construction types and organises then into categories, so that they can be used further in the research, to define the energy saving potential.

§ 2.3 Residential buildings construction

The building stock is very diverse, not only in terms of building type, size, function, ownership etc., but also in terms of construction, which is the most relevant aspect to this research as it determines the physical and energy performance that refurbishment needs to address. This section aims at giving an overview of construction methods encountered in European residential buildings. The construction methods described below do not exclude other constructions and materials, but they are the most common types, based on literature review (Balaras et al., 2000; C16, 2011; TABULA, 2010) and individual observation. Other types and variations can be related with the ones described, in terms of principle, material and performance.

The construction types are associated with distinct building methods and construction techniques into coherent time sections. Construction history is interrelated with technology and cultural history (Moe & Smith, 2012). The introduction of new materials and new construction techniques, to shift the costs of natural resources and labour, connected with architectural improvements or innovations, alterations of aesthetic tradition and wealth, reaction on structural damages, health care and energy saving have leaded to chances in the building stock during time. The driving forces have often been economic aspects (minimising of costs, competitiveness) but also administrative or juristic reasons (requirements by building code etc.) (TABULA, 2010).

Therefore, even though the time span of periods described below is not strict, they are indicatively defined with reference to technological changes in building and construction sector, new regulations or historical breaks. Table 2.1 presents an overview of time periods classification, together with the respective benchmarks and general characteristics, which is important for further categorisation of construction types.

Time period	Benchmarks	Characteristics
The pre-industrial years before 1870	Historical buildings (1600) Vernacular architecture	Built on experiences Hardly any legal requirements Use of locally available materials Masonry load-bearing internal and external walls Buildings with tall, big rooms
The pre-modernism years 1870-1920	Industrial development (1870) Modern Movement	Rapid expansion of cities Growing industrialisation Standardisation of construction Technological achievements (steel construction, reinforced concrete)
The interwar years 1920-1949	End of World War I, the Political renewal, social and artistic reformations along with technological progress Modern Movement prevailed	Large, homogenous residential developments Community urban planning, open public areas, amenities, parks Apartments with good daylight and ventilation, strictly functional layout
The post-war years 1950-1975	The years after the World War II Reconstruction Urban planning based on modernism ideas	Non-traditional building systems High housing production Cheap and quick construction Functional, sunny airy houses Middle-rise (up to 4 floors) and high-rise residential buildings with generous distance from each other
The prosperous years 1975-1990	Economic growth Energy crisis in 1973	Higher quality of construction First awareness of more "energy efficient" buildings First building refurbishments in older, historical buildings
Resent constructions 1991-Today Note: Buildings of that period wouldn't normally be considered for refurbishment	Ecological and energy awareness (Kyoto Protocol) followed by national and international legislation Technological achievements in advanced material Renewable energy sources	Minimum thermal performance imposed by regulations (EPBD) Building performance certificated Incorporation of RES into buildings Passivhaus and zero-energy buildings

Table 2.1
Architectural Periods

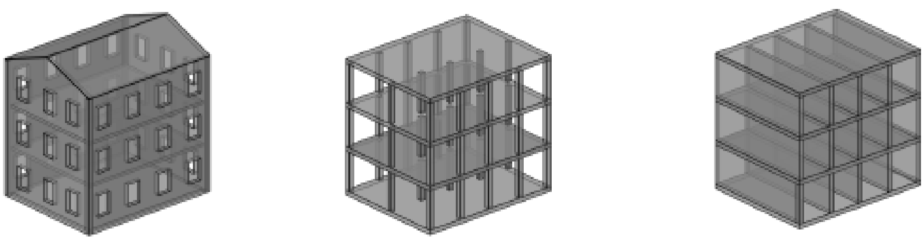
Structure

Even though building structure is not the focus on the thesis, it is a decisive parameter to understand the building. The structure design is also important for the type of intervention in building envelope refurbishment. The type of structures can be in general categorised in loadbearing external walls, skeletal frame and box-frame structure. Meijs and Knaack (2009) define the three types of construction as solid, skeleton and slab construction, according to the vertical elements function and the way the roof is supported.

Loadbearing external walls constitute both the structure and the space enclosing and climate-protection component. The façade bears the weight of the roof and internal floors. The walls are solid, constructed from monolithic or composite elements, perforated with opening for light and air. The method used initially to solve the problem of the weakening of the fabric of the solid wall by the openings creation was to use horizontal beams as lintels and arches (Knaack et al., 2007). The openings span is restricted to the structural limits of the lintels.

In skeletal frame structure, the horizontal elements are supported by linear elements, the columns. This structure method may consist of steel reinforced concrete, steel or timber beams and pillars. This form of structure allows the resolution of the wall into loadbearing structure and the infill, which is then the space-defining element (Knaack et al., 2007). . Skeleton structure offers the possibility for wide-span openings and fully glazed facades. Reinforced concrete frames in particular, used since 1890's, and well established by 1920 (Macdonald, 2003), was extensively used in the post war years, due to high prices or shortage of steel (Giebeler, 2009)

Loadbearing internal traverse walls, also known as box-frame or cross-wall, became popular in the post war years. Driven by the potential of simplified concrete construction, this method allowed to build as much and as quickly as possible and it was used in industrialised and high-rise estates developments (Macdonald, 2003). It is mostly prefabricated or in-situ reinforced concrete; however other constructions, such as internal brick masonry walls, are possible. The box-frame structural system permitted greater building depths and was therefore regarded as more economic (Giebeler, 2009). Moreover it offers the possibility of unrestricted façade design, with larger amount of glass area, lightweight walls and precast concrete elements.



a. Load-bearing external wall

b. Skeletal Frame

c. Box-frame

Figure 2.4
Schematic representation of structure types .

Building envelope

The building envelope elements are the roof, the exterior wall, the ground floor and the windows. The components construction can be in general categorised into heavy/ massive construction- such as masonry brick walls, concrete slabs, concrete walls- and lightweight construction. The variations of buildings envelope's construction across Europe are vast, depending on the region, the time period, the availability of materials, building traditions etc. The building function and design is also a decisive factor as to the construction type. The techniques follow the technological progress, but there are cases where construction principles adjust and persist. For example, even though reinforced concrete structures were widely used since the 1920's, there are still houses today constructed with wooden floors and roof. With regard to the walls, prefabricated panels were very popular in the post-war years and coexist with brick masonry (Andeweg et al., 2007). On the other hand, the window type is very much chronologically defined. Almost all window panes before the 1970's are single glazed and the frames are timber. Double glazing was introduced after the energy crisis and the raising concerns for energy losses (Giebeler, 2009) and more advanced and better performing technologies of glazing are being used as they appear, imposed also by legislation.

There are several ways to classify the residential stock construction. It can be traditional or non-traditional construction, prefabricated or in-situ, loadbearing or not, according to material, time-period, geographical area etc. The present study organisation focuses on the building envelope construction principle, with the façade construction as a starting point. The time period of the buildings' construction is definitely indicative of the construction technique and should be taken into account. However, due to the parallel use of different construction principles, the classification cannot be strictly chronological. Moreover, the organisation of construction types does not strictly depend on geographical area or country, as it is possible the same construction to be encountered in several areas. Nevertheless, some construction or variations are typical for certain areas, due to building tradition, material availability etc. For this reason, typical areas where each construction type was used are mentioned.

Table 2.2 presents the typical construction techniques found in European building stock. The starting point is the wall, because more variations on construction principles and materials are encountered. Each wall construction is associated with the window and roof construction, as well as the typical structure, without excluding the possibility of other variations to be found. An indicative time period and region where the construction was mostly used are indicated. Construction types for each component can be found in Appendix A. It needs to be clarified that the classification focuses on constructions that possibly will be considered for refurbishment in the near future. Constructions found in buildings in more recent years, particularly after the 1980's, with better thermal performance and energy characteristics is not the focus of the research, nor the classification. However, some of the construction principles indicated are still being used today, often with some modification.

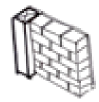
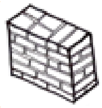
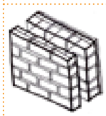
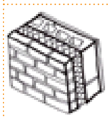
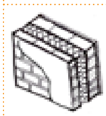
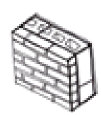
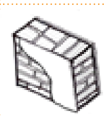
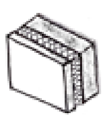
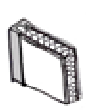
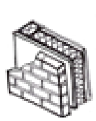
	Construction type		Description	Structure	Windows	Roof	Period	Area	U-values (W/m²K)
Traditional	Timber-frame		Timber-frame structure with brick or wattle-and-daub filling	Loadbearing external walls	Single glazing Timber frames	Timber structure Clay roof tiles	<1920	North-west, centre-east, south Europe	2.0
	Masonry walls		Masonry of solid brick or stone, 250-400mm				<1950		2.0-1.8
	Cavity walls		Two leaves of masonry with intervening air cavity				1920-1950		1.5
Non-traditional			Two leaves with air cavity and/or insulation. Lightweight masonry units, concrete walls, lime stone. Insulation thickness varies from 30-50mm to today's standards	Load-bearing external walls or traverse walls	Double glazing timber or aluminium frames	Reinforced concrete or timber structure	1950-today	North-west, centre-east, Europe. Usually facing bricks	1.1- 0.5
				In-situ reinforced concrete frame		Reinforced concrete slab with insulation	1975-today	South Europe. Usually perforated bricks	0.6
	Lightweight concrete/ perforated bricks		Lightweight masonry units (concrete or hollow bricks), often cladded	Load-bearing traverse walls, in-situ or pre-fab	Single or double glazing timber or aluminium frames	Reinforced concrete or timber structure	1950-1975	North-west, centre-east, e.g. Germany, Denmark, France	1.4
			Single or double layer perforated brick masonry, plastered	In-situ reinforced concrete frame			1950-today	South Europe	1.0-0.8
	Panel building		Prefabricated concrete panels, sometimes with insulation 50mm	In-situ reinforced concrete frame or pre-fab load-bearing walls			1950-1975	North-west, centre-east Europe, e.g. Germany, Poland, Denmark	1.1-0.9
	Lightweight façade		Sandwich panels consisting of asbestos cardboard/ plasterboard and insulation (40-70mm). Different cladding materials possible	Load-bearing traverse walls, in-situ or pre-fab				North-west, Europe, e.g. the Netherlands, Denmark	0.8
	Timber-frame, brick cladding		Timber-frame with insulation infill, boxed in plaster-board, Brick veneer. Different cladding materials possible	Load-bearing timber frame wall		Timber structure, clay roof tiles	1950-today	North-west, centre-east Europe	0.8-0.5

Table 2.2

Typical construction techniques encountered in the European housing stock, organised according to the building envelope

§ 2.3.1 Timber frame construction

Wood has been used for building construction since the first human shelters. External timber frame walls are used to carry the weight of the buildings. Several materials can be used for the infill, such as wattle-and-daub filling, brick or stone. Disadvantages of historic timber-frame construction method are primarily related to damages in the timber structure and to the energy efficiency. For example in the case of brick, the infill provides far from adequate thermal resistance, with a thermal transmittance coefficient U-value of around 2.5 W/m K (the minimum required by current standards is around 0.20 W/m K).

Timber framed constructions for housing were also used in non-traditional building systems (Diamant, 1965) and they still are used in recent years (Riley & Howard, 2002). The infill in this cases was made with plywood, insulation, plywood, water barrier membrane and then the cladding, Cladding can be in form of horizontal or vertical overlapping strips of wood, plywood, cement fiber board, vynil and metal, asphalt felt, or even external insulation finishing systems (EIFS) (Mehta et al., 2008).

The timber-frame loadbearing wall can also be the backing wall for the external brick layer. This brick layer, referred to as masonry veneer, is not loadbearing, single wythe of brick and is essentially an outside covering of the frame construction (Dietz, 1992). A cavity is needed between veneer and wall lining, against water penetration and to allow the ties to move. Good weatherproofing of the timber frame wall is essential, as the veneer is not expected to be entirely watertight. Brick veneers are the most common; however other materials, such as stone, are possible. The popularity of brick veneer lies in its aesthetic appeal and durability (Mehta et al., 2008).

a b c

Figure 2.5
Examples of timber frame construction with (a) wattle-and-daub filling, (b)brick filling, in Germany, and natural stone, in Greece .

§ 2.3.2 Masonry

Masonry consists of natural or man-made elements. Such units as fired clay bricks or natural stone. The choice largely depends on the availability of each material and the requested performance. Clay brick is predominant in central and northern Europe, particularly in areas where due to topography, clay, which is traditionally the raw material for bricks, was easily found in the proximity of building sites. It can be found in house construction throughout different time periods, from buildings dating back to antiquity until current constructions. The external wall of the storeys above ground level consist of clay brickwork for the 95% of buildings in Europe, built in the period from the industrial revolution to 1920's (Giebeler, 2009). Clay bricks were initially hand moulded from clay, loam or clay-like substances. Traditional bricks are solid and their dimensions may vary according to local format. Natural stones, such as limestone, sand stone, granite, are used on the base of the walls, to form the splashing water zone and often were used at critical connections, such the corners and window. However, masonry walls of natural stones are usual in Southern Europe traditional settlements and residential buildings, prior to 1920's

a b c

Figure 2.6

(a) Clay brick wall in Germany, (b) masonry natural stone wall in Greece, (c) wall with stone and brick mixed construction in Czech Republic.

Numerous examples of this construction method are available, as it was the most common technique until WW II. Buildings with masonry brick construction can be found both in cities and rural areas and in different housing types. The external masonry walls carry their own load, as well as the loads of the roof, the stories and their contents, by compression. A minimum thickness was specified for the top floor and increased by half a brick for every additional story. The steps serve as wall plates to bear the floor timber joists (Giebeler, 2009). The thickness of the wall depends on the number of stories. Timber joists form the roof and upper stories in most building prior to 1920's. The shape of the roof may vary from simple double-pitched roofs to more complicated shapes. They are usually covered with clay roof tiles. However, other materials, such as concrete roof tiles, fibre-cement sheets, or organic material (thatch, particularly in rural houses), are used. More advanced options, such as integration of photovoltaic panels are also possible in pitched roofs, in order to comply with the high requirements of energy efficiency. In later years, reinforced concrete floors and flat roof are also common.

a

b

Figure 2.7
(a) A masonry brick wall building in rural Germany.
(b) Historic buildings in Brussels, combining of clay brick and natural stone in the masonry.

§ 2.3.3 Cavity walls

Walls comprising two leaves of masonry with an intermediate air cavity are called cavity walls. This type of construction has been known since earlier years, developed in interwar years (Giebeler, 2009) and became standard in the post-WW II period. It presents certain advantages in comparison to the solid masonry wall. The air cavity improves the thermal insulation properties of the wall. Moreover, it provides better weather protection, as it prevents the façade becoming saturated from the interior. Additional advantages are material savings and shorter drying times. The disadvantage is the reduced stability of the double-leaf masonry. The connection between the two leaves is achieved by bonders or tiles of galvanized steel incorporated in the masonry.

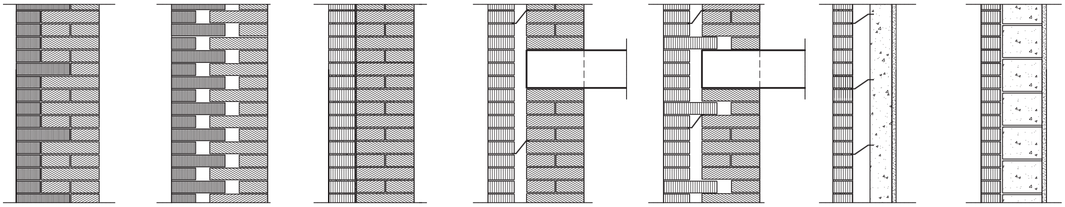


Figure 2.8
Various construction configurations of double-leaf masonry walls, with facing bricks in the outer leaf (adopted from Diamant, 1964; Giebeler, 2009, figure C3.12)

High strength facing bricks are used in the outer leaf of the wall for better weather protection. In many cases, the timber joist floors were replaced with reinforced concrete floors. Facing bricks are high-strength, frost and rain resistant bricks, suitable to be left exposed, instead of rendered, in the outer face of the wall. To gain their high strength they are fired above sintering point (1150-1300 °C). The reason not to build entire walls with high strength bricks was mainly higher costs. To comply with higher insulation standards, facing brick walls with cavity insulation are becoming common, in addition to lightweight clay or concrete walls. After the oil crisis in the 1970s, energy efficiency awareness was rising and according regulations made the use of thermal insulation compulsory. As a result, cavity insulation was used in double-leaf masonry walls. Nowadays, double-leaf walls with cavity insulation are constructed with various materials in different parts of Europe.

a b

Figure 2.9
Current construction of an external wall with facing bricks, lime stone (a) or concrete (b) backing wall and insulation in the cavity

§ 2.3.4 Lightweight masonry

After the 1920's, the use of solid clay bricks began to decrease and to be replaced by perforated clay bricks and lightweight masonry units. Apart from better insulation values, they allowed for larger formats at the same weight per unit, resulting in faster bricklaying and, thus, faster and cheaper construction, an important parameter particularly during the reconstruction years after the war. This construction offers savings in material and weight, shorter laying and drying times due to the larger format and better sound and thermal insulation. In the post war years, hollow bricks (vertically or horizontally perforated), as well as lightweight clay bricks were introduced. Their compressive strength is lower, thus, these constructions are combined with skeleton or traverse wall loadbearing structure. There are cases that lightweight masonry has been used to build loadbearing walls, in low-rise buildings. Examples also exist where the stacked hollow, lightweight units were filled with concrete, to improve their strength (Priemus & Elk, 1971).

There are considerable variations in the material, construction process and final result. The materials of the masonry units include clay in perforated or honeycomb bricks, concrete in hollow blocks, and aerated concrete (TABULA, 2010). The lightweight masonry wall can be used as backing wall to rendered or facing brickwork. Perforated bricks with plaster finishing are the predominant technology in south Europe (Andeweg et al., 2007). However, the construction techniques that fall into this category have a main common characteristic. They constitute an evolution to the traditional masonry, to provide easier and more economical construction, along with higher insulation values. The thermal transmittance achieved is approximately 1.1 W/m^{2}K, which is still very high for current standards.

a b

Figure 2.10

(a) Internal masonry leaf of concrete blocks in the Netherlands (Image source: courtesy of Hielkje Zijlstra).
(b) Wall with double perforated brick in Greece.

§ 2.3.5 Prefabricated concrete panels

Prefabricated concrete panels is the prevailing building technique for buildings of the post-war period in northern and east European countries, such as Germany, Poland, Hungary and Denmark. Pre-cast concrete walls are also encountered in the Netherlands, France and Belgium (Andeweg et al., 2007). The system comprises room-sized panels of pre-cast concrete fixed together with in-situ concrete or welded steel plates. The concrete panels can be loadbearing or not, depending on the system used and they are usually sandwich units, with an internal self-supporting wall panel, an external façade panel and thermal insulation in between. The U-value achieved is approximately 1.1 W/m^{2}K. Generally, no other cladding or colouring is added, so the final result is dark grey, sometimes with exposed aggregates or some decorative texture

Those system was developed because concrete was long lasting and flexible, as it can be poured on demand in different sizes. Prefabrication provided a solution to quick and economical mass production. However, disadvantages that manifest themselves in the early years after the construction. Due to standardisation and dimensions limits of the prefabricated concrete elements, the floor plans of the apartments are very uniform, narrow and difficult to adapt. Other problems emerged from the untried but widely replicated techniques, such as water damage due to lack of roof overhangs and guttering, cracking as reinforcements too close to the concrete surface corroded, improper fixing of the panels etc. (Power, 1997). Furthermore, the thermal performance of the panels is not satisfactory.

a b

Figure 2.11
Building with pre-cast concrete panels in Berlin, Germany. (Image source: courtesy Reinhard Hasselbach)

§ 2.3.6 Lightweight façade panel

In non-traditional buildings, prefabricated lightweight elements are commonly used to form the outer wall, particularly in the Netherlands and Denmark (Andeweg et al., 2007). The longitudinal façade between the traverse loadbearing walls consists of storey-high prefabricated timber or aluminium frame, incorporating the windows and opaque elements. Before the oil crisis, when the use of double glazing became more common, the transparent parts are single glazed. The opaque elements, usually as the parapet of the windows, are sandwich panels consisting of asbestos cardboard/plasterboard and insulation (40-70mm).

The performance, both thermal and acoustic, of this façade type is very poor, particularly considering the buildings with single glazing. Regarding the opaque element, even though insulation is applied, the U-value is way over current requirements. Additionally, being combined with travers loadbearing walls, it has similar problems to the panel buildings, with regard to narrow and non-flexible floor plans

a b

Figure 2.12
Examples of lightweight façade panel in buildings in the Netherlands

§ 2.4 Current condition of the stock

After the building is built, the physical aging process begins. Moreover, technological, functional, financial and social circumstances change can make the building outdated. Damage can be defined as the manifestation of lack of performance, referring to technical and aesthetical aspects, safety, health and usefulness. Performance requirements that were fulfilled in the past but are no longer satisfied can be perceived as damage (De Vent, 2011).

It is difficult to name all possible physical problems and performance failures that can be encountered in the housing stock. Each case is unique and has to be investigated individually. However, this section highlights some of the typical problems that constitute the current condition of the stock. The energy performance of the existing stock, which the research aims at improving, is part of this condition. Moreover, there are various physical problems, meaning that they are connected with damages of physical components.

§ 2.4.1 Energy Performance of existing residential buildings

The existing buildings stock in European countries accounts for about 40% of final energy consumption in the European Union (EU) member states. Residential use represents the two thirds of this consumption. Energy in households is consumed for heating, cooling, DHW, cooking and appliances. Space heating is the most intense end-use in European households, accounting up to 70%. This is typically less in the south European countries, with warmer climate. Even though the heating need is lower in these countries due to milder winters, the final energy use is relatively high. For example, buildings built in the period 1946-60 in Italy have an average energy consumption for heating 220 kWh/m^2 per year , which is very close with the average consumption of 246 kWh/m^2 per year in buildings of the same period in Germany (BPIE, 2011a). This suggests that the performance and the energy efficiency are not adequate.

The energy efficiency of buildings has improved over the last decade, but there is still a very long way to go. When considering glazing only, a recent study by the independent institute TNO shows that over 85% of glazed area in Europe's buildings are made of inefficient products whereas advanced double glazing and triple glazing six to eight times more energy-efficient exist (Glass for Europe, 2011). In 2006, over 70% of homes in the UK had an energy performance rating of band D or E according to the Energy Performance Certificate (EPC) bands. Less than 10% of homes achieve a rating of band C or higher, while 20% are in the most inefficient bands F and G (Ravetz, 2008). Similarly in the Netherlands, which is the European country with the biggest proportion of energy certified buildings (BPIE, 2011a), the vast majority of dwellings built before 1975 have label D or lower (Figure 2.13).

It is then evident that the older part of the building stock tends to consume more, contributing greatly to the high energy use of the building sector. This is because the techniques used at the time of construction had lower performance and efficiency standards. It is also indicative of the huge potential to improve the performance and reduce the energy demand by retrofitting.

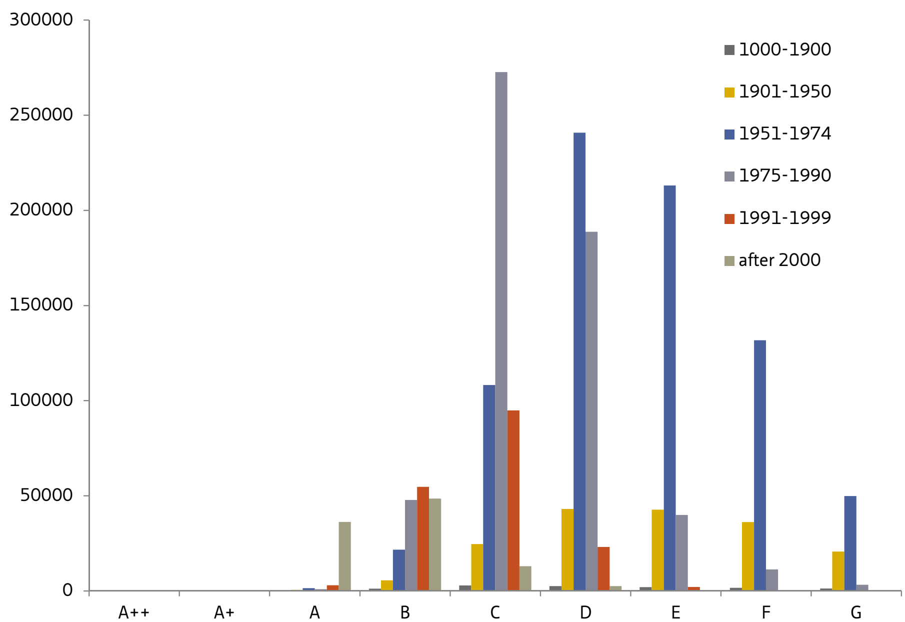


Figure 2.13
Energy labels for housing in the Netherlands in 2010 (source: AgentschapNL, 2011)

§ 2.4.2 Physical problems

Buildings suffer from a variety of physical problems, connected with the structure and the building envelope. Furthermore, the natural aging process is becoming visible in building components reaching the end of their life circle. The goal of refurbishment is, on the one hand, to extend the life of the components whenever possible and, on the other hand, to replace them if necessary. Typical physical problems of housing stock are related to building envelope components, such as masonry walls, prefabricated components, timber, roof and finishes. Building services components, such as pipework, wiring systems, sanitary fittings etc. are also physical problems. However, they are not further discussed, as the thesis focuses on the building envelope.

Damages to the external envelope can be caused by foundations movement. The building foundations move as a result of loads applied or activity, such as changes in ground water level and shrinkage or swelling of clay soils. Typical symptoms of foundation defects are cracks in external and internal walls, walls bulging or leaning out of vertical and floors inclining out of level (Noy & Douglas, 2005). Additionally, masonry and cavity wall suffer from structural damage due to cracking by shrinkage, temperature changes and structural movements. Structural damages manifest themselves in crack development, due to lack of strength, deformation, due to lack of stiffness, and tilt, due to lack of stability (De Vent, 2011). An additional problem of masonry and cavity walls is the decay of the joints connecting the timber floors to the walls.

Moisture is a major cause of damages. It causes a disintegration of masonry units, efflorescence (salt crystallization), and biological growth in the form of plants, mosses, algae and mould. Moisture is the biggest enemy for timber components, as well. This is particularly important to consider in humid and rainy climates. Timber is a hygroscopic material, which means that it absorbs moisture and then releases it. As such, it is mainly damaged by excessive absorption of moisture due to physical shortcomings and poor maintenance (Giebeler, 2009). This may not only cause cracks and deformations due to swelling and shrinkage, but also create a favourable environment for fungal infestation. Deformations of timber structural elements are possible due to inadequate sizing. This is particularly common in buildings built in the 1930's and directly after World War II, when there was a shortage of building materials.

a b

Figure 2.14

(a) Clay roof tiles with moss growth (b) typical damages in masonry brick wall: discoloration, moss growth, dissolving of binder.

Concrete elements are subject to a variety of damages, related to inherent material problems, environmental influences and poor design and workmanship (Macdonald, 2003). A common damage manifestation in concrete is cracking and spalling, but the cause is often difficult to determine (Noy & Douglas, 2005). Corrosion of steel reinforcement by carbonation and chlorides is a possible cause and it is affected by the material itself, as well as the quality of concrete design and construction. Inadequate design may also result in structural damages, together with ground settlement and overloading.

The finishing surfaces of the building envelope, such as the render on the wall or the roof tiles, are the first to show signs of damage as they are exposed to the weather. Cracking due to movement or loose rendering and mechanical damages on the roof by falling branches or wind are common. Moreover, organic growth, such as moss or algae, creates a degraded appearance.

In addition to physical problems, many existing buildings exhibit deficits regards protection against fire. Escape routes and fire compartments are not sufficient for current use requirements, while existing components have inadequate fire resistance (Giebeler, 2009). Moreover, sound insulation is generally poor in existing buildings, due to the properties of the materials used and lack of relevant considerations. Finally, the low energy efficiency of the stock, resulting in high energy consumption, as discussed in 2.4.1, is related with physical qualities of the building, so it may also be considered as physical problem.

Table 2.3 gives an overview of typical problems encountered in the stock's constructions. As the present thesis is not intended to be a refurbishment manual and its focus is on energy upgrade potential, the list is not exhaustive. Moreover, problems related to fire protection and acoustics are not included, as they are beyond the scope of the present research. Further analysis of problems and remedies can be found in literature, such as Chandler (1991); Douglas (2006); Giebeler (2009); Noy and Douglas (2005). Each building must be surveyed and its individual needs must be addressed by the refurbishment strategy. Measures to upgrade the energy performance of a building are complementary and coexist with measures to eliminate physical damages.

	Problems	Cause	Effect
Energy efficiency			
Poor thermal performance of the envelope (roof, walls and windows)		Different material/construction standards, absence of insulation, inadequate design/ technology	Energy loss, high energy demand
Poor air tightness of the openings		Inadequate design/ technology	Energy loss, high energy demand, user discomfort
Air leakage-High infiltration rates		Inadequate design, degradation of components (cracking, shrinkage)	Energy loss, high energy demand, user discomfort
Thermal bridges		Exposed components, absence of insulation, inadequate design	Energy loss, high energy demand, internal condensation
Out-dated installations		Different technology at the time of construction	High energy demand, risk of technical problems, user discomfort
Physical problems			
Foundations	Foundation differential movement	Ground compression	Cracks on walls, usually vertical or diagonal
	Inadequate and overloaded foundations	Inadequate design, internal use alterations, opening size augmentation	Movement cracks
	Unequal settlement	Clay soil shrinkage, due to weather or tree roots	Wall leaning, cracks
Masonry and cavity wall	Corrosion of ties and fixings	Moisture	Façade parts destruction, accident risk
	Cracking by shrinkage, structural movements	Inadequate design	Structural damage, accident risk , degraded appearance
	Disintegration of masonry units (moisture, salt crystallization, frost)	Various damage mechanisms	Degraded appearance, spalling
	Poor acoustic insulation	Different material/construction standards, absence of insulation, inadequate design/ technology	User discomfort
	Poor damp-proofing	Inadequate design	Water penetration, user discomfort
Timber components (structural and facade elements.)	External joints decay	Moisture	Structural damage, accident risk , degraded appearance
	Corrosion of ties and fixings	Moisture	Structural damage, degraded appearance
	Inadequate sizing, wrong choice of timber	Inadequate design	Deflection, deformation of structural timber elements
	Inadequate details of the junction with floor slabs and internal walls	Inadequate design	Degraded appearance
	Mould growth	Moisture	Health risk, degraded appearance
	Organic infestation (fungal, insects)	Moisture	Health risk, degraded appearance
	Rotten wooden parts of the window frame	Moisture	Health risk, degraded appearance, poor performance

>>>

	Problems	Cause	Effect
Roof structure and covering	Improper layering of roof tiles	Inadequate design/ technology	Accident risk, water penetration, poor performance
	Inadequate roof pitches	inadequate design/ technology	Water accumulation, poor performance
	Efflorescence (salt crystallization) and moss growth	Moisture, material composition, environmental conditions	Health risk, degraded appearance
	Mechanical damages	Inadequate design, random incidents	Accident risk, water penetration, user discomfort
Concrete components (structure, prefabricated elements etc.)	Structural failure	Insufficient design, structural movements (ground settlement), overloading or change of use	Cracks, spalling, accident risk , degraded appearance, further damage
	Reinforcement corrosion	Carbonation of concrete, insufficient design	Cracks, spalling, Façade parts destruction, accident risk
	Chemical reactions	Presence of chemical substances in the material, water, air	cracks, leaching
	Poor durability	Environmental influences (air, water, freeze-thaw damage)	Corrosion and concrete breakdown
Finishing surfaces (renders, tiles etc.)	Loose or falling render	Moisture penetration, material composition, environmental conditions	Degraded appearance
	Cracking (plaster, tiles)	Wall movement, inadequate design/ technology	Degraded appearance
	Mould growth	Moisture penetration, material composition, environmental conditions	Degraded appearance, health risk

Table 2.3

Overview of typical problems

§ 2.5 Refurbishment of the building stock

The next phase in the building life, after its construction and present performance, is the improvement and elimination of shortcomings for the future. The way to achieve this is refurbishment, which is also the subject of this research. Before proceeding in the following chapters with elaborating on energy efficiency in refurbishment practice and develop the research approach to support the design of refurbishment strategies, we need to give some definitions and discuss motivations and barriers.

§ 2.5.1 Definitions of refurbishment

In practice, the term refurbishment covers a wide range of measures. For the purpose of this thesis, it is necessary to define refurbishment is and what degrees of refurbishment exist. According to Giebeler et al. (2009), there are different terms for measures/intervention on an existing building. They range from simple repairs and maintenance to demolition and reconstruction. Figure 2.15 summarises the different level of intervention, from smaller to bigger intervention.

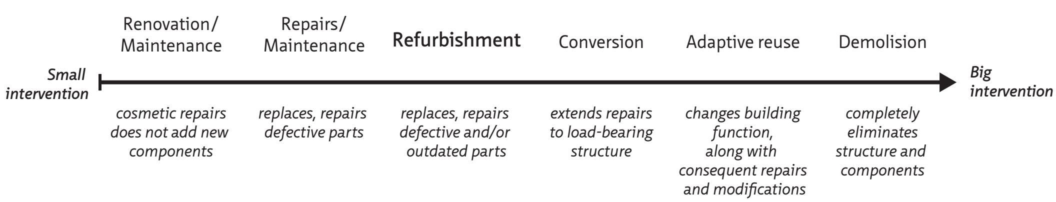


Figure 2.15
Intervention levels for buildings

The term applicable to the scope this thesis is refurbishment, which is in between repairs and maintenance and conversion. Maintenance is limited to replacement or repair of defective building components. Conversion also affects the structure of the building, such as load-bearing members and interior layout. Refurbishment does not include major changes in the load-bearing structure. In refurbishment not only the defective building components are repaired or replaced, but also the out-dated components or surfaces (Giebeler et al., 2009). Upgrade of fire protection, acoustics and thermal performance can be, thus, achieved through refurbishment. As the extend of refurbishment can vary significantly, Giebeler (2009) specifies three degrees of refurbishment, depending on the area of the building or the amount of components affects. Partial refurbishment includes only one component or part of the building, while the building is still in use. Normal refurbishment covers an entire building or a clearly separate, autonomous part of the building. In total refurbishment the building is stripped to its load-bearing frame.

The EPBD is using the terminology of “major renovation” (DIRECTIVE, 2010/31/EU). Minimum requirements to the energy performance suggested by the directive are applied in existing buildings, building units and building elements that undergo major renovation. Member states can define as major the renovation of a building where the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building, or more than 25 % of the surface of the building envelope undergoes renovation.

Another interpretation of major renovation is with the term deep renovation. The BPIE (2011a) states that, even though the EPBD stipulates the implementation of energy saving measures only in case of deep renovation of the building, it doesn’t specify the depth of renovation measures. It is clear that more targeted measures are required for fostering the deep renovation of the existing building stock. The report relates the refurbishment depth with the level of energy or greenhouse gas emission savings that are achieved when refurbishing a building, specifying as “deep” the renovation that achieves energy savings 60-90%, which typically adopts a holistic approach, viewing the renovation as a package of measures working together (BPIE, 2011a). The European insulation Manufacturers Association (Eurima) has issued a report on the economics of deep renovation (Hermelink & Müller, 2011). The models studied included measures such as insulation of wall, roof and cellar ceiling, upgrade of the windows, elimination of thermal bridges, installation of thermal collectors and ventilation system. Superficial renovations, as opposing to deep renovation, significantly increase the risk to miss the climate targets and huge absolute savings to remain untapped.

Based on the above definitions, the research approach uses the term “integrated refurbishment”. The renovation strategy should integrate different building components; thus, it is referred to as integrated refurbishment strategy. The key components to achieve an integrated refurbishment that tackle physical problems and improves the energy efficiency are the components that are subject to physical damage and where heat losses are happening. This is the building envelope, together with ventilation and heating sources. More detail on components and solutions of integrated refurbishment is part of answering the research question and can be found in Chapter 4.

§ 2.5.2 Motivation for refurbishment

Looking at the bigger picture, refurbishing the poor performing residential building stock to reduce the energy consumption and tackle GHG emissions is an important motivation and there is a lot of discussion, research and legislation to support it. Despite its sustainability value, the energy saving alone is rarely the main motivation for refurbishment. Decision-making, usually coming from the owner or manager of the property, is often initiated by the need of technical or functional upgrade, along with financial and social motivation. Usually the motives are interconnected. Whatever the motivation, the challenge is to incorporate energy efficient measures into the refurbishment strategy, which is the objective of this research.

Buildings suffer from various technical problems. Regular small-scale maintenance is always necessary, but sometimes damages require repair and out-dated components upgrade. Moreover, refurbishment can be decided on grounds of comfort improvement, such as reduction of noise or draught. Retrofitting of building services, replacement of windows and restoration of damaged components are some measures to improve the technical quality.

The motive can also be functional shortcomings, such as small apartment size, inadequate layout and lack of accessibility for the physically challenged. Over the years, the space consumption per person has more than doubled and the standards for facilities are considerably higher. Moreover the average persons per dwelling has decreased from 5-6 in the early post-war years to 2.43 persons per dwellings in 2002 (Andeweg et al., 2007). It is then evident that updates in the layout and number of houses are necessary. Accessibility is also important, particularly with the shift in the age-profile of European population (BPIE, 2011a). Buildings until the 1960's are not equipped with elevators, even in three or five storey buildings. These functional improvements can be incorporated in a refurbishment strategy.

Financial motives are very important. Investing in energy efficiency renovation has a direct benefit on reduced energy bills and easily accountable payback time. Furthermore, repairing the technical damage and upgrading the performance increase the property value. Even though the aging, neglected houses appear to have few social attractions and limited economic value, they have considerable potential value if they are upgraded (Power, 2008). Appearance, function and performance can change, increasing the attractiveness of the building. The improvements can then be part of an overall scheme to increase the value and the rent prices.

Together with financial, refurbishment has social motivations. It is used as a way to regenerate socially problematic areas, along with restructuring the socio-economic group of renters. It helps promoting a green and renewed image of the property and provides better housing. On a larger scale, apart from the reduction of GHG emissions, social benefits include employment opportunities through the refurbishment market development. In the residential sector, employment gains are typically higher than in other sectors (Waide et al., 2006).

§ 2.5.3 Refurbishment or demolition

To resolve the technical, operational and financial problems, a common discussion in housing management is refurbishment or replacement. Replacement is achieved with demolition and new construction, in order to maintain the same supply of dwellings. Demolition is the destruction of the built environment that occurs when buildings are torn down. Even though removing the problematic buildings may seem an easy way to reduce energy use and get rid of damages, it is not always the preferred solution.

Demolition is an integral part of urban accumulation processes and it has social and financial aspects. It is used to clear the urban landscape of outmoded elements and promote economic growth. Demolition is also used as a method of social control. Urban ghettos, where minorities are confined via discrimination, are viewed as potential threats to social order and are also frequently demolished to make way for highways, gentrified housing, etc. (Crump, 2012). Moreover, demolition and new construction is often promoted by the building industry, which prefers to maintain a conservative business-as-usual course, and other profit related demolition motives of involved parties, such as housing associations or the municipality (Thomsen, 2010). However, demolition is slow, costly and unpopular. It provokes community opposition among the very people who are supposed to benefit (Power, 2008) as in many instances, those living in locations targeted by demolition have little say in the disposition of their neighbourhood and often face difficulty in finding replacement housing (Crump, 2012).

From the sustainable and environmental point of view, there is an ongoing debate regarding life extension of existing or new construction (Thomsen & van der Flier, 2008). On one hand, transformation of the existing housing stock is a more environmentally efficient way to achieve the same result than demolition and rebuilding. This is because the building process and the materials used are both energy intensive while most of the building mass and structural elements in an existing property are already there and only rarely need replacing. As a result, new homes use four to eight times more resources than an equivalent refurbishment (Itard & Klunder, 2007). With regard to wider environmental impact, the exhaustion of available landfill sites also has serious implications for the scale of building and demolition. Demolition and building are the biggest source of landfill by volume, around 30% of the total (Power, 2008).

On the other hand the energy performance of new construction seems to be superior: better insulation and more comprehensive installations result in a better performance. Nevertheless, considering the requirement for new materials, however good the long-run energy efficiency in the use phase, new buildings have major energy, carbon and wider environmental impacts (Power, 2008) and the energy saving if we compare replacement to refurbishment is not substantial (Verbeeck & Cornelis, 2011). From a financial point of view, demolition and new construction is only worth if minor renovation with little energy saving is possible and the house is in such bad state that extensive, cost-intensive non-energy related measures are needed. Furthermore, the energy performance of renovation could be technically equal and arguments that the life span expectation and market position of renovation is expected to be insufficient to justify the investment and that the market demand for renovation is uncertain, while new construction enables better anticipation on housing demand in the future are not convincing (Thomsen & van der Flier, 2008).

In any case, demolition is necessary, but should be considered as the last resort. Buildings that suffer non-repairable structural problems or are located in areas where supply exceeds demand are not successful candidates for renovation to improve their condition and they are likely to be removed. It is estimated that by 2050 demolition will decrease the building stock by 8% (BPIE, 2011a). There is still a big proportion of the stock that can be refurbished to transform into functional and efficient buildings.

§ 2.5.4 Barriers and challenges

Even though there are various motivations to reconsider the existing residential building, prevailing renovation rates, average in EU, is as low as 1% and renovation depths are mostly minor (BPIE, 2011a). Both rate and depth of refurbishment must at least double and even triple, compared to the currently observed situation (Ad-Hoc, 2012). In the current situation, a significant proportion of the energy efficiency improvement potential is not realized (IEA, 2007). Experience over decades has identified several barriers that prevent or delay the uptake of renovation measures. These barriers are classified by the BPIE (2011) in the report "Europe's Buildings under the microscope" as financial, institutional/ administrative, related to awareness, advice and skills and the separation of expenditure and benefit.

Any renovation requires an investment and, therefore, financial barriers are a top priority. The lack of funds is the most cited argument that prevents investment on energy efficiency. Although the measures will be cost effective in the long term, the initial cost can be an obstacle for the decision. Moreover, energy cost often represent a small share of household expenditure (3-4%) and, thus, it is not a major concern for the majority of consumers to decide to take measures to reduce consumption, particularly if the payback period may exceed the period they plan to stay in the house. To tackle this problem, upfront funding and other financial incentives are necessary. The role of available financial programmes and innovative mechanisms becomes increasingly important. These cover a wide range of financial instruments such as grants, preferential loans, VAT reduction, penalties if minimum requirements are not met, energy service companies financing etc. Additionally, it needs to be clear that energy efficiency is a safe investment –particularly important in times of economic crisis- that also protects the consumers against increase in energy prices.

In addition to financial barriers, there is a wide range of administrative issues. The degree of housing privatisation can be an important barrier to refurbishment. In the case of privately owned stock, especially privately let stock, greater economic incentives are necessary. It may also prove hard to achieve resident consensus. Generally, public ownership would allow for a greater degree of control, making it easier to coordinate and carry out decisions on refurbishment, in particular with respect to the incorporation of energy efficiency measures (Waide et al., 2006).

Another concern regarding the speed and depth of renovation is lack of adequate advice and technical expertise. Compared to large scale new construction, working in existing dwellings requires completely different skills regarding technical, social and managerial craftsmanship, as well as the type, size and organization of the company. This also applies to designers, developers commissioners and governments, who's knowledge about how and when to successfully maintain, manage, adapt, transform and redesign older stock has still to improve (Thomsen, 2010). With regard to the energy saving potential, even though energy saving are generally appreciated, there remains a lack of understanding of the energy, cost and carbon savings from different measures. Moreover, focus on energy efficiency among building professionals is limited (BPIE, 2011a).

Finally, probably the most complex barrier regarding existing residential building refurbishment is the separation of expenditure and benefit, also referred to as the "split incentives barrier". Split incentives occur when participants in an economic exchange have different goals or incentives (IEA, 2007). Such a case is when one party owns the building and is requested to invest on energy efficiency, while another -the tenant- benefits from the resulting saving in energy. There are many examples where the party investing in a building may not be the party reaping the financial returns. Examples include landlords investing in a property where tenants pay the energy bill, landlords' inability to raise rents after a building renovation, due to legislative restrictions or other reasons, and developers constructing a new building or renovating an existing one, where market prices do not reflect the energy performance of the building (BPIE, 2011a). The solution is not simple. Barriers can be overcome by a combination of measures and policies, regulatory instruments for energy efficiency standards in appliances and buildings, and availability of adequate information about energy efficiency performance (IEA, 2007). Both technological options that provide the same service levels with less energy and behavioural options that reduce energy either by reducing or changing the service level, or by switching to those with lower energy intensity. These options have complex interactions, but may be combined into integrated policies that reduce energy related emissions (Barrett et al., 2008).

§ 2.6 Conclusions

Given the necessity to refurbish the housing stock, identifying and understanding the stock itself is an essential process. Not only does it serve to point out the problems that have to be addressed by refurbishment strategy, but also knowledge of the existing construction method also leads to successful refurbishment solutions. The chapter gave an overview of the residential building stock, in terms of general characteristics, such as ownership and age. Most importantly typical construction types of the building envelope were specified. The analysis of the residential building stock was based on three levels: past, present, future. The past refers to building construction, present is the existing condition and its problems, and future is the refurbishment strategy. The construction types encountered in every case largely depend on the building tradition and available material at the time they were constructed. Even though, the time-spam of each technique cannot be strict, the age of the building is a good indication for the state and the quality of the construction.

An interesting turn in the construction techniques happened in the post-war period. Due to the shortage in housing and the need for quick and cheap constructions, the techniques shifted away from the tradition and turned to industrialised building methods, which had a high degree of prefabrication, shorter construction times and less-skilled workers requirements. A second crucial historic coincident that determined the quality of constructions was the energy crisis in the 1970's and the consequential consciousness of energy use reduction. As a result, thermal insulation of buildings became a bigger concern and implemented in regulations afterwards. This lead to conclusion that buildings built after the war and before the energy crisis are performing inadequately and they are in need to upgrade their energy efficiency.

An overview of construction principles in Table 2.2 showed the main, typical construction techniques encountered in the European housing stock. They are categorised according to wall construction, because more variations can be found. The time period of the buildings' construction is definitely indicative of the construction technique. However, due to the parallel use of different construction principles, the classification cannot be strictly chronological. The categories identified were the following and each one presents a wide range or variations, as they developed through time, but they still share a common principle:

- Timber frame construction: External timber frame walls load bearing walls, with various material, such as wattle-and-daub or brick, used as infill. In more recent timber-frame construction the infill is realised with insulation, enclosed in plywood. There are several possibilities for cladding, such as wood stripes, metal or brick veneer.

- Masonry walls: Loadbearing external walls, consisting of natural or man-made elements. Clay brick is the most common material, but stone is also often used, mainly in the base of the walls. The thickness of the wall depends of the number of storeys and the loads.

- Cavity walls: Walls comprising two leaves of masonry with an intermediate air cavity provides improved thermal insulation and shorter drying times compared to solid masonry wall. Cavity wall construction is used to date, with possible variation in the material of the two leaves and the use of insulation in the cavity.

- Lightweight masonry: Non-loadbearing masonry walls, consisting of lightweight units such as perforated or honeycomb bricks, concrete in hollow blocks, or aerated concrete. They are used as infill of skeletal or box-frame structure. Compared to traditional masonry walls, this construction, mostly used after the WWII, offers savings in material and weight, shorter laying and drying times and better sound and thermal insulation

- Prefabricated concrete panels: Non-traditional construction consisting of prefabricated concrete panels, usually sandwich units, with an internal self-supporting wall panel, an external façade panel and thermal insulation in between. The external walls can be loadbearing or not, depending on the system.

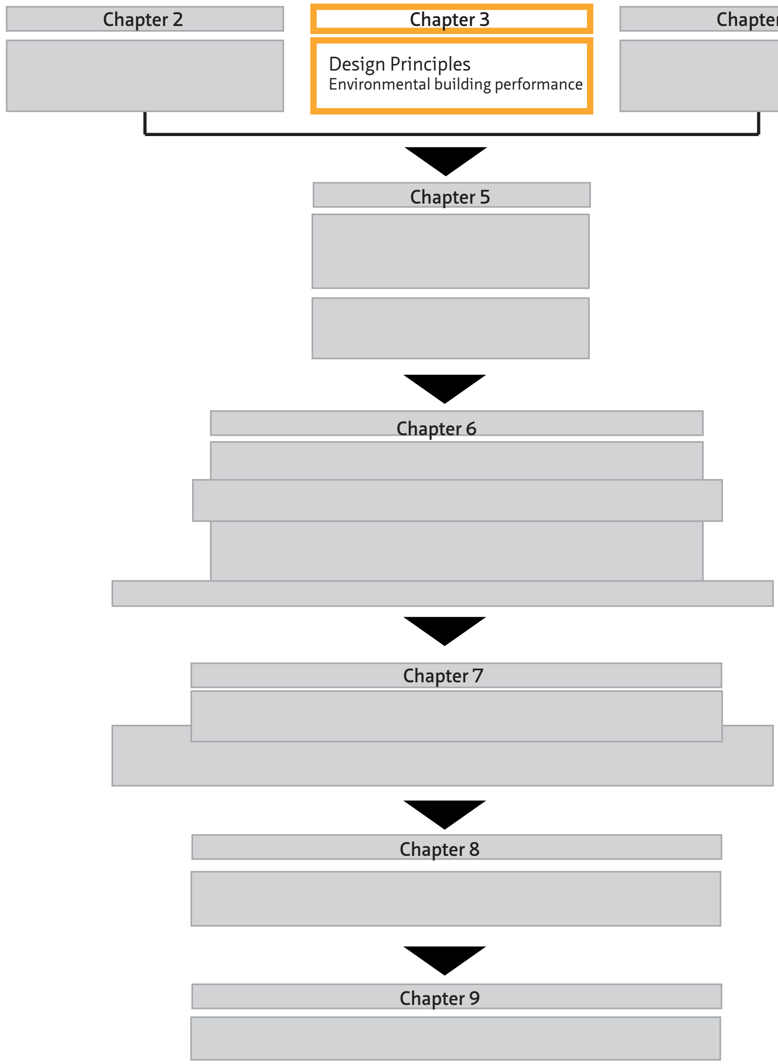
- Lightweight façade panels: Storey-high prefabricated timber or aluminium frame, incorporating the windows and opaque elements form the outer wall, by being placed between the columns of the travers loadbearing walls.

The building stock in its present condition faces several damages and failures that refurbishment has the potential to eliminate. Physical problems manifest themselves, as the components approach the end of their service life and they are subject to damages. With regard to energy efficiency, which is the focus on this thesis, a large part of the stock performs far beyond today's standards. Measures to solve physical failures and upgrade energy efficiency can and should coexist, as it is also more efficient from the financial point of view.

Finally, refurbishment is discussed as the way to achieve a well-performing building stock in the future. Based on various definitions along with research on required renovation depths, the thesis proposes integrated refurbishment as the proposed solution. Integrated refurbishment includes retrofitting measures for all building envelope components that are subject to heat losses, comprising the thermal envelope, as it is also explained in the next chapters (see also Figure 4.1). Next to the potential energy savings, there are several motivations for refurbishment, along with barriers that keep refurbishment rate at a low level. Efforts for policies and regulations, as well as information and awareness of the building industry and society in general, are necessary to overcome the barriers and promote refurbishment.

The residential building stock overview intended to get the reader acquainted with the range of constructions that might be a subject of refurbishment. It is not possible to cover every possible case and each building need to be individually investigated. The understanding of the construction and identification of problems is the first and one of the most important steps in the refurbishment design process. It determines the needed interventions and the possibilities of the refurbishment strategy. Furthermore, the existing performance defines the possible improvements; the poorer the performance is, the greater the room for improvement. The potential improvement is a key in order to answer the research question of integrating the environmental performance into the design of refurbishment strategies, as it will be developed by the research approach in the following chapters.

After evaluating the existing condition of the building and discussing refurbishment motivation and barriers, the next steps is to think of the possible principle solution to improve it and how these strategies can be implemented. For this reason, the following chapters 3 and 4 give an overview of environmental design principles and state-of-the-art refurbishment practice.


Chapter 2
Chapter 3
Design Principles
Environmental building performance
Chapter 4
Chapter 5
Chapter 6
Chapter 7
Chapter 8
Chapter 9

3 Energy efficiency in refurbishment strategies

The previous chapter presented the context of refurbishment, which includes aging buildings and the problems they suffer from. Since the object of refurbishment has been identified, the next question is what kind of strategies and measures can transform the aging buildings into energy efficient buildings. This chapter gives an overview of design principles that help the building to adapt to weather conditions and achieve occupants' comfort with minimum support from auxiliary energy sources.

Firstly, the connection between refurbishment and sustainability is introduced. Subsequently, in section 3.2, the environmental performance of buildings is defined. In this way, the required result of refurbishment are set. Section 3.3 presents the principles of environmental strategies that can be applied. These principles refer to both new and refurbished buildings. Their adequacy depends on a number of parameters. In the case of refurbishment, though, there are further limitations, as some of the most important parameters already exist. These limitations will be explained in the past part of the chapter, section 3.5.

§ 3.1 Introduction: Refurbishment is sustainable

Within the scope of the thesis, refurbishment is discussed as a mean to reduce building sectors energy demand. Reducing energy consumption in general and particularly in the building sector is a topic of high priority. In the recent years there has been a lot of discussion, policies, technologies and research on making building using less energy, while providing high comfort standards for the occupants. This awareness is related with society's efforts towards a sustainable development. This chapter sets off to explain why refurbishment has the potential to support these efforts. First, the relation between sustainability and the need to reduce energy demand of the building sector needs to be established. This relation has led to legislation and targets by international parties, which are also discussed in this section.

The term 'sustainable development' was popularised by the World Commission on Environment and Development (WCED) in its 1987 report entitled Our Common Future.

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (WCED, 1987)

Our Common Future reported on many global realities and recommended urgent action on eight key issues to ensure that development was sustainable. One of those key issues addressed by the WCED is energy (UNESCO, 2003). The importance of energy use is largely connected with the depletion of fossil fuels and climate change. Fossil fuels energy, meaning the energy produced by oil, gas or coal, is dominating the energy supply world-wide and is expected to retain its importance within the coming 20 years (Ibrahim, 1999). As the economies power ahead on fossil fuels, the spectre of diminishing reserves heightens anxieties. Most importantly, the demand in fossil fuels is generated above the underlying growth in the rate of supply (Smith, 2005). Nevertheless, problems with fossil based energy supply and use are related with environmental issues such as air pollution, acid precipitation, ozone depletion and climate change.

'Climate change' encapsulates the wide variety of accompanying impacts on temperature, weather patterns and other natural systems (Grubb et al., 1999). The list of evidence that the climate is changing is long, from increase in average surface temperature, sea level rise, melting of glacier ice etc. (Smith, 2005). The issue of climate change has been addressed since the 80s. After scientific consensus, governments established the Intergovernmental Panel on Climate Change (IPCC) to help them understanding and building some international awareness on the nature of the problem (Grubb et al., 1999). The fourth assessment report from the IPCCC confirmed that climate change exists and is projected to continue (Eurostat, 2009). Even though substantial and growing public doubt remains about the anthropogenic cause in climate change, 97–98% of the climate researchers most actively publishing in the field surveyed here support the tenets of anthropogenic climate change (ACC) outlined by the IPCC (Anderegg et al., 2010). There is a cause-effect relationship between the observed emissions of global warming and greenhouse gases, the two most important of which are water vapour and CO_2.

The IPCCC defined the context and principles upon which governments subsequently negotiated the 1997 Kyoto Protocol, which set the underpinning elements of global efforts toward tackling climate change (Grubb et al., 1999), imposing a 5% global cut in CO_2 emissions based on 1990 levels, come into action for 2008/2012. In addition to the Kyoto protocol, European Commission has endorsed ambitious target to reduce greenhouse gasses by 20% compared to 1990 levels, by 2020 (European Commission2007), along with a long term commitment to the decarbonisation path with a target for the EU and other industrialised countries of 80 to 95% cuts in emissions by 2050 (European Commission, 2010).

Energy use is the main responsible factor for GHG and hence climate change (Eurostat, 2010). The energy use produces 59.8% of GHG, followed by transport (19.5%), agriculture (9.2%), industrial processes (8.5%) and waste (2.8%), showed in Figure 1.1.a. Consequently a reduction in the use of energy can contribute considerably to the alleviation of the climate change and compliance with decarbonisation targets. Increasing the share of renewable energy to 20% and making a 20% improvement in energy efficiency European targets for 2020 (Eurostat, 2009).

Being the bigger energy user (40% of final energy consumption in the EU, as indicated in Figure 1.1.a, there is an urgent need to reduce the energy demand of the building sector. The importance of the building sector has been recognised and addresses by legislative parties and institutions. The International Energy Agency (IEA) has identified the building sector as one of the most cost-effective sectors for reducing energy consumption, with estimated possible energy savings of 1 509 million tonnes of oil equivalent (Mtoe) by 2050. Moreover, by reducing overall energy demand, improving energy efficiency in buildings can significantly reduce carbon dioxide (CO_2) emissions from the building sector, translating to possible mitigation of 12.6 gigatonnes (Gt) of CO_2 emissions by 2050 (IEA, 2010). The building stock has been on the focus of the European Union policies for energy savings. The Energy Performance of Buildings Directive (EPBD) (Directive 2002/91/EC) is the main EU policy instrument to improve the energy performance of buildings. The directive requires that an energy performance certificate is made available when a building is constructed, sold or rented.

In the European Commission roadmap to 2050 target, the building sector (residential and services) is explicitly mentioned as a key sector. The expected reduction reaches up to 53% by 2030 and 88 - 91% by 2050 (European Commission, 2011). This reduction is larger than in other sectors such as transport, agriculture and industry, indicating the importance of the building sector and the urgency of the measures to be taken. In order to achieve this significant reduction, the recast of the EPBD in 2010 suggests that new buildings should be low- or zero-energy buildings (DIRECTIVE, 2010/31/EU). As a greater challenge, however, is stated the refurbishment of the existing building stock. The analysis projects that over the coming decade investments in energy-saving building components and equipment will need to be increased by up to € 200 billion (European Commission, 2011). The building stock has been on the focus of the European Union policies for energy savings. The Energy Performance of Buildings Directive (EPBD) (Directive 2002/91/EC) is the main EU policy instrument to improve the energy performance of buildings. Among other measures, it introduced a framework for energy performance certification, with a deadline for all Member States to bring into force the necessary laws, regulations and administrative provisions by 4 January 2006 (Mudgal et al., 2013).

In addition to EPBD, the Directive on energy efficiency (EED) 2012/27/EU contains a number of measures designed to deliver energy savings across all sectors. Regarding the building sector, the EED suggests that the rate of building renovation needs to be increased, as the existing building stock represents the single biggest potential sector for energy savings (DIRECTIVE, 2012/27/EU, paragraph 17). Member States should establish a long-term strategy beyond 2020 for mobilising investment in the renovation of residential and commercial buildings with a view to improving the energy performance of the building stock. That strategy should address cost-effective deep renovations, which lead to a refurbishment that reduces both the delivered and the final energy consumption of a building by a significant percentage compared to the pre-renovation levels leading to a very high energy performance (DIRECTIVE, 2012/27/EU, paragraph 16).

Based on the above discussion, it is understandable that the building stock is relevant to sustainability, in terms of the energy it consumes, which is the focus of this thesis.The interest that legislative parties have taken in the building sector confirms its importance. Together the Energy Efficiency Directive (DIRECTIVE, 2012/27/EU) and the EPBD provide a framework for Member States to drive the reduction of energy use in buildings, thereby delivering a range of economic, environmental, societal and energy security benefits (BPIE, 2013b). In this context, the importance of existing building has been highlighted, in terms of potential for energy savings, necessary investment and as part of political decisions. It is clear that far more energy conservation and other sustainable benefits can be reached in the existing building stock than in newly built buildings (Itard & Meijer, 2008). An increase in building energy performance can constitute an important instrument in the efforts toward alleviating the EU energy import dependency and reduce carbon dioxide emissions, in order to reach national and international targets. The BPIE (2011a) reports that in order to reach the ultimate objective of transforming the existing building sector into a sustainable one by 2050, renovation rates need to rise from the prevailing rate of around 1% of the total floor area renovated annually, to around 3% p.a. from 2020 onwards. The real challenge, therefore, is to properly refurbish existing buildings in a manner that they use the minimum non-renewable energy, produce minimum air pollution and construction waste, all with acceptable investment and operating costs, while improving the indoor environment for comfort, health and safety. A strategic design process to achieve this goal is the objective of the present thesis.

Sustainable aspects of Refurbishment

The issue of refurbishment is complex, encompassing a number of parameters such as the architectural design and construction, energy efficiency along with political support and incentives, socio-financial effects and users' behaviour. To understand why refurbishment is sustainable, social, ecological and economical aspects are important. These are the three major perspectives encompassed by the sustainable development triangle, a concept adopted by the 1992 Earth Summit in Rio de Janeiro (Mohan, 2004). All three aspects influence each other.

Ecological relevance

Since the connection between sustainability, energy use and the building sector has been established, it is understandable that an upgraded, energy-efficient building stock is important from the ecological point of view. Studies (Nemry et al., 2010; Waide et al., 2006) have identified the potentials of refurbishment to upgrade the energy efficiency of the building stock. As a result, energy consumption and the respective GHG can be reduced.

The potential of the existing stock is firstly due to the fact that existing building stock exceeds the number of newly built dwellings by far, as the renewal rate of the stock is very slow. It is estimated that every year only 1% is added to the existing stock, which means that in a period of 10 years only 10% of the stock will be at least at the level the current building regulations demand for newly built dwellings. On the other hand, the condition of the existing stock is problematic, as it was built under far lower energy and sustainability standards (and with the use of poorer materials) at the time of construction. However, regarding materials and waste, studies show that the environmental impact of life cycle extension of a building is definitely less than demolition and new construction (Thomsen & van der Flier, 2008). The energy consumed during the production and transport of materials, the so-called embodied energy (Dixit et al., 2010), is stored in the construction itself and demolition means throwing this energy away. Consequently, refurbishment is the answer to upgrade the condition and efficiency of the aging building stock and, hence, reduce the energy demand of the building sector, resulting in the relevant environmental benefits.

Economic relevance

Along with embodied energy, buildings are also stored capital; money is bound in raw materials. While façades and technical installations may reach the end of their technical life span at the age of 30 years, the load bearing structure can last for a century or more. Thus, demolition would be not only a waste of energy but also a waste of capital.

The operational cost of a building is strongly related to its energy consumption. The energy prices have risen by more than 40% in the past 10 years, which directly leads to higher operational costs. Recent data from the International Energy Agency demonstrate a continuous increase in the oil prices, which have now reached and surpassed the levels before the financial crisis in 2008, confirming the rising trend. As a result, the increase in the energy bills is an actual issue. Research has shown that tenants would accept higher rental rates, if the operational costs were lower. Real estate developers express the economic refurbishment target: The total rent including utilities has to remain at the same level, but the share of the base rent must be bigger (Ebbert, 2010). Therefore, refurbishment has a direct economic effect, by improving the energy efficiency and reducing the energy consumption of the building.

Moreover, efforts toward increasing the rate and depth of renovation will stimulate at the same time the market uptake of highly efficient and renewable technologies and construction techniques that can deliver the expected increase in the actual energy performance of buildings (BPIE, 2013a). The Building Performance Institute Europe (BPIE) estimated in the report "Europe's buildings under the microscope" that deep renovation of the building stock to reach the 2050 targets may result in € 380 billion savings for the consumers. Moreover, the benefit to the society overall will be up to €10 000 billion, while around 1 million jobs will be created annually throughout the period to 2050, resulting in CO_2 reductions in excess of 90 % (BPIE, 2011a).

Social relevance

When buildings today are in need for refurbishment, the task is to keep this history alive and preserve its value for society. In practice this means that each project has to be valued for its qualities and potentials. The refurbishment then fulfils two important tasks. On the one hand, it preserves the design qualities and socio-cultural values of a building, a street atmosphere, or a neighbourhood. On the other hand, after experience with architectural ideals and urban concepts, today's planners are able to revise older concepts and repair mistakes of previous generations (Ebbert, 2010). For example, poorly designed urban surroundings, vacancy, which often occurs when buildings do not fulfil the current demands, and misuse of properties lead to a lack of acceptance by neighbours, vandalism and social problems. Furthermore, technical decay in the estates is connected with social decay (Priemus, 1986). Groups of users with socio-economic strength leave the estate and weaker groups replace them. This mechanism often results in high turnover, vacancy, lack of control, and in general in "unfavourable" living conditions. Hence, refurbishment can reverse this problematic social environment, as the building meets today's demands and provide a functional and attractive contribution to society.

§ 3.2 The environmental performance of buildings

Since the objective of refurbishment is to improve building performance, understanding what performance means is essential. Performance can be defined as the manner in which of the efficiency with which something reacts or fulfils its intended purpose. The specific definition of the term "building performance" is complex, since different actors in the building sector have differing interests and requirements (Haapio & Viitaniemi, 2008). With regard to sustainability, the integrated building performance incorporates environmental, social and economic performance (EN15643-1, 2010). The definition of environmental performance, according to EN15643-2 (2011) is the following:

Environmental is the performance relevant to environmental impacts and environmental aspects.

where: environmental impact is any change to the environment, whether adverse or beneficial, wholly or partially resulting from environmental aspects

and environmental aspect is the aspect of construction works, part of works, processes or services related to their life cycle that can cause change to the environment

Those impacts are related to the building fabric, referring to construction products, processes and services during the building life cycle and building operation, particularly the energy and water used by building integrated technical systems to serve the occupants' needs. Thus, energy consumption is an integral part of the environmental performance. It is related to the function of the building and it is necessary for the well-being and comfort of the occupants.

This section discusses the aspects of building performance that are important for energy demand, with regard to the scope of the thesis. First of all, it is necessary to explain indoor comfort, as it is a basic occupants' need and an objective in the building function. Moreover, it defines to a large degree the building related energy use. Subsequently, operational energy consumption in buildings is analysed, together with definitions of energy efficiency and different types of energy, which are often used not only in the present thesis, but also the general sustainability discussion. To understand and tackle energy consumption, there has been a growing demand for ways to assess the energy performance, for regulatory or other purposes. Methodologies and certificates to this end are also discussed.

Apart from the operational energy, environmental performance includes the energy during the different stages of the building's life cycle, namely energy used in materials, processed, transfer, end of life etc. Even though not directly connected with the scope of the research, life cycle analysis is a relevant part of the building performance and, as such, it is included in the discussion in Section 3.2.3.

§ 3.2.1 Comfort

Buildings provide shelter for human activities and therefore people need to feel comfortable in them. Comfort is the well-being of a person based on their subjective perception of a number of external parameters and it is also related to health of the occupants. As such, it is a basic requirement that the building need to fulfil. Because of its subjectivity, this perception is influenced not only by physical conditions, but also physiological (e.g. age, gender) and intermediary conditions (e.g. clothing). Comfort, therefore, is very difficult to quantify in exact values that satisfy everyone (Hegger et al., 2008). Indoor comfort includes a number of parameters of the indoor environment, such as temperature humidity, air quality, lighting and noise levels. A lot of research and practice has focused on studying the single components and identify criteria and limit values. Moreover, in the last decay, there have been attempts to approach the indoor environment holistically (Bluyssen, 2009).

For the present thesis and the discussion on energy efficiency refurbishment, thermal comfort is the most relevant as most of the energy spent in households is meant to achieve comfort temperatures. Nevertheless, all aspects of comfort can be improved and should be considered by the refurbishment strategy. The measures include adequate ventilation for indoor air quality, enlarged windows or shading for visual comfort, reduce noise levels by retrofitting of components etc.

According to the ISO 7730 (2005) standard, thermal comfort is described as being "that condition of mind which expresses satisfaction with the thermal environment". This is a definition most people can agree on, but not easily converted into physical parameters, as the perception of comfort is very different for each person. To this end, there are several approaches to assess and, furthermore, use as design criteria thermal comfort. Factors of thermal environment according to ASHRAE (2010) are metabolic rate, depending of the activity, clothing insulation, air temperature, radiant temperature, air speed and humidity. The predicted mean vote (PMV) model uses heat balance principles to relate the six factors to the average response of people on a scale from -3 to +3, to quantify thermal sensation. When the PMV is defined, the predicted percentage of dissatisfied (PPD) can be calculated and benchmarks of indoor environment can be set. ISO7730 (2005) suggests that an average performing building should be designed to meet the criteria of less than10% PPD and $-0.5 < PMV < +0.5$. Additional consideration should be in local discomfort in parts of the body. The most common cause of local discomfort is draught. But local discomfort can also be caused by an abnormally high vertical temperature difference between the head and ankles, by too warm or too cool a floor, or by too high a radiant temperature asymmetry.

During the 1990s, several extensive field studies from 160 buildings all over the world showed that in buildings with HVAC systems, the PMV model seems to work well. However, the studies also showed that in free-running or naturally ventilated buildings, there is a clear dependence of indoor comfort temperatures on outdoor air temperatures (de Dear & Schiller Brager, 2001). People seem to adapt, behaviourally and psychologically, and can accept higher indoor temperatures than those predicted by the PMV model. These findings encouraged significant revisions of ASHRAE's comfort standard in terms of climatically relevant prescriptions and ASHRAE Standard 55, first based on the heat balance model of the human body, was revised to include the adaptive comfort algorithm (ASHRAE, 2004). In Europe, the EN15251 (2005) was also adapted (Bluyssen, 2009).

Difficult as it may be to quantify comfort, it is still necessary in order to define certain design criteria. A number of international standards have been developed to provide indicative values for considering comfort in the design and assessment of buildings performance. Nevertheless, even if those criteria are met, people are still likely to experience discomfort. For example, if they were in different conditions prior to enter the space, the effect of prior exposure of activity may affect their comfort perception for approximately one hour (ASHRAE, 2010). Table 3.1 summarises benchmark values for comfort requirements also to be used further in the research as inputs for thermal performance simulation of refurbishment options. The information are based on EN15251 (2007), illuminance levels are suggested by EN12464-1 (2011) for lounge and circulation areas and the daylight factor (DF) by CIBSE (1999).

Temperature		Temperature range for heating, °C	Temperature range for cooling, °C
	Residential buildings, living spaces (bedroom, living rooms etc.)	20.0-25.0	23.0 – 26.0
	Residential buildings, other spaces (kitchens, storages etc.)	16.0-25.0	
Humidity		Relative humidity, %	
	Upper limit for dehumidification	60	
	Lower limit for humidification	25	
Indoor Air Quality		l/s/person	l/s/ m^2 (external envelope)
	Air flow	7	0.7
	Min air flow during occupied periods		0.05 - 0.1
		ach	l/s,m^2 (floor area)
	Air change per hour (estimated for space height 2.5m)	0.6	0.42
Lighting			
	Illumination levels	100-200 lux	
	Daylight Factor (DF)	2-5 %	
Noise		Sound pressure level, dB(A)	
	Living room	25-40	
	Bedroom	20-35	

Table 3.1
Benchmark comfort requirements

§ 3.2.2 Energy consumption in buildings

In order for comfort temperatures to be achieved, extra energy is needed to balance the heat losses with the heat gains. A general expression of energy balance, that is true for summer and winter, is the following (McMullan, 2002):
Fabric Heat Losses + Ventilation heat losses =
Solar heat gains + Casual heat gains + Energy for Heating or cooling

Building fabric consists of all construction products that are fixed to the building in a permanent manner, so that the dismantling of the product changes the performance of the building and constitute construction operation (EN15643-2, 2011). Fabric heat losses refer to the energy that flows through the building envelope. They are directly dependent on the thermal transmittance of the materials and the temperature difference between the inside and outside, which are expressed by the thermal resistance coefficient U-values. On the other hand, ventilation heat losses depend on the permeability of the façade, the size and quality of the openings etc. The façade design and properties also define the solar heat gains.

Apart from heating, other forms of energy consumption are also important in dwellings, such as domestic hot water and electricity for lighting, appliances. More than half the final energy consumption of residential buildings in the EU is used for space heating, (Itard & Meijer, 2008), reaching up to 70% depending on climate variations (BPIE, 2011a). It is also the energy use more relevant to the thermal comfort discussion and the one that can be significantly reduced with refurbishment. In residential buildings, water heating also plays a major role (25%). Cooling is an important source of energy use in buildings. In non-residential buildings it accounts for 5% (Itard & Meijer, 2008). In residential building in north, west and central Europe, cooling is not very often necessary; however it is used more in south Europe (BPIE, 2011a). Final energy consumption in the household sector grows at a rate of 1.1 % per year (EEA, 2002). This raise in consumption is mainly due to the increased use of appliances and higher standards of living in the EU. Improvements in energy efficiency per square metre and per appliance appear to have been offset by larger average sizes of dwellings and an increase in the average number of household appliances.

Energy efficiency and energy types

Energy efficiency of a system is the ratio between the energy output and input. The efficiency is related to the amount of energy that is being lost during the processes. With regard to heating systems efficiency, for example, it depends on how much heat is lost through the fuel production and how much heat is lost in the distribution system (McMullan, 2002). The distribution efficiency, which is the ratio between the energy output of the distribution sub-system and the energy input to the distribution sub-system, is different than the generation efficiency (EN15316-1, 2007). When referring to energy efficient buildings, we suggest that the building as a system has high efficiency, meaning, on one hand, the efficiency of the building technical systems and, on the other hand, minimal losses in the use of energy.

There are different types of energy in the production, distribution and consumption chain. The efficiency of each of the sub-systems defines the amount of energy in each stage, from production to consumption. Below, the different types of energy are defined, based on different definitions found in literature (EN15603, 2008; Hall, 2008b; Hegger et al., 2008).

- Non-renewable energy: energy taken from a source which is depleted by extraction (e.g. fossil fuels)
- Renewable energy: energy from sources that are not depleted by extraction, such as solar energy (thermal and photovoltaic), wind, water power, renewed biomass
- Primary energy: energy that has not been subjected to any conversion or transformation process. It is the "raw" energy contained in the fuels, such as coal, oil and natural gas. Primary energy includes non-renewable energy and renewable energy. If both are taken into account it can be called total primary energy. For a building, it is the energy used to produce the energy delivered to the building. It is calculated from the delivered and exported amounts of energy carriers, using conversion factors.
- Secondary energy: energy obtained from primary energy through the transformation process. The percentage varies according to source and process type. In electricity production, for example, it is only 30 to 40% of the primary energy contained in the fuels
- Delivered energy or final energy: energy supplied to the consumers, to be converted into useful energy (e.g. electricity at the wall outlet). It is a proportion of secondary energy, after subtracting transportation losses.
- Exported energy: energy, expressed per energy carrier, delivered by the technical building systems through the system boundary and used outside the system boundary. It can be specified by generation types (e.g. CHP, photovoltaic, etc.) in order to apply different weighting factors.
- Energy need or Net energy: the quantity of energy actually used by the building services, the energy needed to perform a given task. Energy need for heating and cooling, for example, heat to be delivered to or extracted from a conditioned space to maintain the intended temperature conditions during a given period of time. The energy need is calculated and cannot easily be measured (EN15603, 2008). It is derived from the delivered energy, taken into account the system efficiency.

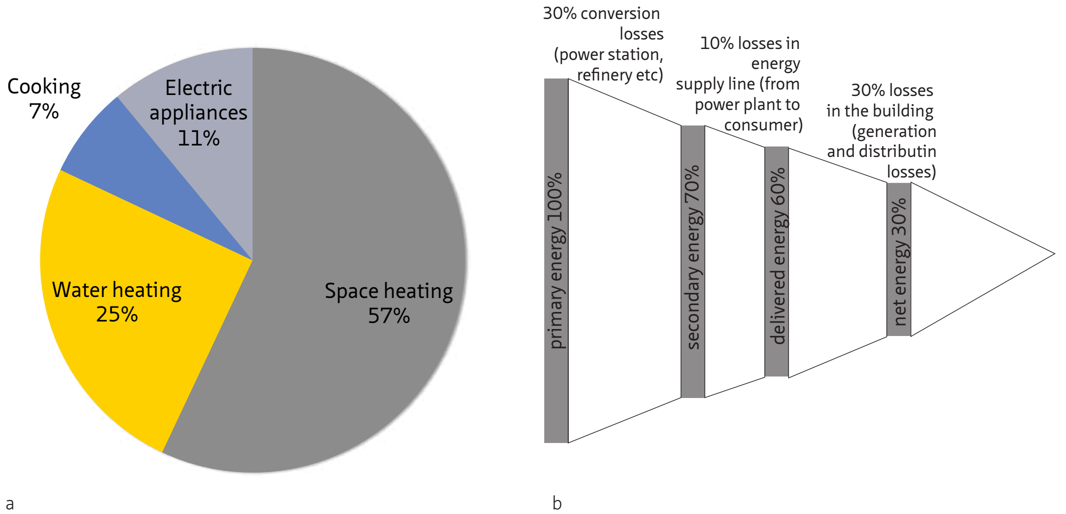


Figure 3.1

(a) Final energy consumption in residential buildings in EU countries: breakdown in end-use (source: Itard & Meijer, 2008, fig 2.8)
(b) Schematic energy supply chain. The energy losses percentages are indicative and not accurate, as they vary significantly in each country, depending on processes and energy mix..

In the efforts toward reducing energy consumption the primary energy is the most important, as it is the energy content of media occurring in nature (Hegger et al., 2008) and it can be used to quantify the impact on environment. To calculate primary energy, primary energy factor (PEF) is used. PEF, which is the non-renewable and renewable primary energy divided by delivered energy, depends on the different fuel types and it takes into account energy required for extraction, processing, storage, transport, generation, transformation, transmission, distribution and any other operations necessary for delivery to the building in which the delivered energy will be used. There are two conventions for defining primary energy factors; total primary energy factor, which represent all the energy overheads and it always exceeds unity, and non-renewable primary energy factor, which exclude the renewable energy component of primary energy and may lead to a primary energy conversion factor less than unity for renewable energy sources.

It is noted that the conversion factors have different values for each energy source and for each country. These factors cannot be compared because each country has a specific methodology for their determination (Santos et al., 2013), to representing local conditions for electricity generation and fuel supply. Table 3.2 presents example primary energy factors, obtained from EN15603 (2008).

A building generally uses more than one energy carrier, particularly throughout the whole life cycle. Therefore, a common expression to aggregate the used amounts, sometimes expressed in various units and always having various impacts is needed.

Standard EN15603 (2008) suggests to use Primary energy and Carbon dioxide emission rating. The primary energy approach makes possible the simple addition from different types of energies (e.g. thermal and electrical) because primary energy includes the losses of the whole energy chain, including those located outside the building system boundary. These losses (and possible gains) are included in a primary energy factor. In carbon dioxide emission rating, the emitted mass of CO_2 is calculated from the delivered and exported energy for each energy carrier. The transformation is based on CO_2 emission coefficient (EN15603, 2008). Both PEF and CO_2 emission coefficient are different to a national level.

	Primary energy factors f_p		CO_2 Production coefficient K
	Non-Renewable	Total	kg/ MWh
Fuel oil	1.35	1.35	330
Gas	1.36	1.36	277
Anthracite	1.19	1.19	394
Lignite	1.40	1.40	433
Coke	1.53	1.53	467
Wood shavings	0.06	1.06	4
Log	0.09	1.09	14
Beech log	0.07	1.07	13
Fir log	0.10	1.10	20
Electricity from hydraulic power plant	0.50	1.50	7
Electricity from nuclear power plant	2.80	2.80	16
Electricity from coal power plant	4,05	4,05	1340
Electricity Mix UCPTE	3.14	3.31	617

Table 3.2

Primary energy factors and CO_2 production coefficients (EN15603, 2008, Table E.1)

Energy performance assessments, certificates and standards

Since the EPBD (DIRECTIVE, 2002/91/EU) was adopted, there has been an increasing interest in understanding and quantifying energy consumption of new and existing buildings. In addition to the mandatory standards of performance dictated by regulations through the energy performance certificate, voluntary certificates and assessments has been adopted, driven by the growing market demand for environmentally sound products and services (Haapio & Viitaniemi, 2008). Next to international regulations and assessment tools, the mandatory or voluntary certificates vary according to different countries, types of buildings, environmental issues taken into account etc.

The introduction of the energy performance certificates has resulted in the development of various methodologies and tool to measure or predict the energy performance. To this end, the standard EN 15603 (EN15603, 2008) presents several assessment methodologies and classify them according to the information used to calculate or predict energy demand. There are two principal options for energy rating of buildings: calculated or measured energy rating. They differ in the type and detail of input data, calculation method and purpose they serve.

	Name	Input data			Utility or purpose
		Use	Climate	Building	
Calculated	Design	Standard	Standard	Design	Building permit, certificate under condition
	Standard	Standard	Standard	Actual	Energy performance certificate, regulations
	Tailored	Depending on purpose		Actual	Optimisation, validation, retrofit planning
Measured	Operational	Actual	Actual	Actual	Energy performance certificate, regulations

Table 3.3
Overview of energy rating types (source: EN15603, 2008, table 3)

The calculated energy rating includes energy use for heating, cooling, ventilation, hot water and when appropriate lighting. It can be specified as standard - or asset (Mumovic & Santamouris, 2009)- rating, based on conventional climate, use, surroundings and occupant-related input data, defined at national level and given in a national annex. This rating is called "design rating" when applied to a planned building. The calculated rating may also be tailored, which is calculated with climate, occupancy and surroundings data adapted to the actual building and the purpose of the calculation (EN15603, 2008).

The measured rating refers to the actual operational energy by all energy sources, which is delivered to the building and exported by the building. The time period should be an integer number of years. It should take the average over several most recent full years, as long as the building and its use pattern has been the same (EN15603, 2008). It is not possible to compare directly the energy performance indexes obtained from a calculated and a measured rating. However, the differences between these two ratings can be useful to evaluate the cumulative effects of the actual conditions of the building in comparison with the standard conditions (Mumovic & Santamouris, 2009).

When planning of retrofit measures for existing buildings, EN15603 (2008) The assessment of the energy saving obtained by retrofit measures is carried out using a building calculation model. This can be the same calculation model as for the tailored rating, using actual information for the specific building such as actual climatic data, air permeability of the envelope, ventilation rate, heating system efficiencies, actual internal conditions etc.

In addition to energy rating methodologies, life cycle assessment tools take into account the environmental performance holistically, including a wide range of information in different stages, including product, construction, use and end of life stage (EN15978, 2011). Energy use is only a fragment of the building performance, relevant in the building use stage.

There is a growing number of assessment methodologies and tools, varying in different countries, criteria, building types etc. Next to methodologies and tools developed on a national regulatory level (Maldonado, 2011), extensive record of research that presents and compares tools for simulations to predict energy performance (Crawley et al., 2008; Ma et al., 2012; Sdei et al., 2013) or environmental assessment methodologies can be found (Crawley & Aho, 1999; Eva Krídlová Burdová, 2012; Haapio & Viitaniemi, 2008) The international Energy Agency (IEA) in Annex 31 also gives an overview of tools in different countries (2001). Therefore this section does not aim at an inventory of assessment tools, but rather to provide insights on the type and uses of standards and certificates in a European and international level, including regulatory certificates dictated by the EPBD, performance standards as passive and active house and environmental performance assessment methodologies as BREEAM and LEED.

Energy Performance Certificate (EPC)

Within the scope of EPBD, an energy performance certificate (EPC) is required. The EPC expresses the energy performance of a building, determined on the basis of the calculated or actual annual energy that is consumed in order to meet the different needs associated with its typical use and shall reflect the heating energy needs and cooling energy needs to maintain the envisaged temperature conditions of the building and domestic hot water needs (DIRECTIVE, 2010/31/EU).

The different countries have set minimum requirements of performance for new buildings (BPIE, 2011a, table 2B7) and most of them for renovations. Moreover, each country has developed its own certification scheme. The rating system used is mostly calculated, some countries apply measured or a combination of rating (Maldonado, 2011). The certificate is expressed by a numeric indicator of primary energy use (DIRECTIVE, 2010/31/EU) and include recommendations for improvements. Many, but not all, Member States have gone for a format that closely resembles appliance labels (Mudgal et al., 2013), as label with distinct categories (e.g. A-G scale) are found to be more effective in communicating energy efficiency information than a continuous scale (Tigchelaar et al., 2011).

Although the certification schemes have been applied for few years, the proportion of dwellings not yet certified remain above 90% in most countries, with the exception of the Netherlands and UK (BPIE, 2011a). Tigchelaar et al. (2011) within the IDEAL EPBD project have identified some barriers in EPC use. In Central and Eastern European countries EPCs are often only obligatory for entire and new buildings. Therefore, many apartment owners lack an EPC. Across Europe, an EPC is often only obligatory at sales or change of tenant and there is no penalty or compliance enforcement for not issuing or showing an EPC. Therefore it can take decades before a dwelling is labelled. Finally, an EPC is often not available or not shown before buyers make an offer, in the purchase process, energy aspects are of minor importance compared to other property characteristics. Real estate agents play a crucial role in this trend.

On the other hand, expected utility costs are important for 60% of the survey respondents and type of heating system for 40%, while increasing energy efficiency and reducing energy bills are important for about 40% of the survey respondents. Additionally, there is a correlation between having an EPC with recommendations and energy efficiency improvements, i.e. people who have carried out energy efficiency improvements are more likely to be aware of and recall recommendations provided on the EPC.

In conclusion, the policy framework for transforming the building stock (through both renovation of existing buildings and construction of new buildings) should and can lead to the reduction of energy consumption in buildings. ZEBs, in particular have the promising potential to significantly reduce the energy use and as well to increase the overall share of renewable energy (Marszal et al., 2011) .EPCs (ratings and recommendations) can play an important role in encouraging property developers and the rest of the market in that direction (Mudgal et al., 2013).

nZEB Energy Buildings

The re-cast Energy Performance of Buildings Directive (EPBD) in 2010 requires that by the end of 2020 'all new buildings are nearly zero- energy buildings' (nZEB). A 'nearly zero-energy building' is defined as a building that requires nearly zero or very low amount of energy, which should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (DIRECTIVE, 2010/31/EU). With regard to existing building, the recast extended the scope of the initial EPBD to almost all existing and new buildings and removed the 1 000 m^2 threshold for major renovations (this threshold excluded 72% of the building stock) (BPIE, 2011a).

With regard to Zero Energy Building concept, increasing attention has been given, initiated by the EPBD. The European Member States 'shall draw up national plans for increasing the number of nZEBs. Concepts and examples for nearly Zero-Energy or climate neutral buildings already exist in various countries and from different sources. However the views on how such buildings should be defined and the means and techniques to achieve specific national targets show considerable differences across Europe. The definition of nZEB in the EPBD recast offers flexibility, but at the same time leaves uncertainties on the actual ambition level and the CO_2 emissions of such buildings (BPIE, 2011b). In order not to fall short of expectation, there is a need for commonly agreed ZEB definition framework and a robust 'zero' calculation methodology. This framework should allow for a variety of solution and not focus only on PV based solution, as this strategy is mainly addressing small and new buildings (Marszal et al., 2011).

Green buildings standards

Next to the mandatory level of energy performance required by regulations, it is always possible for each designer, owner or occupant to seek for a more efficient new or refurbished building, achieving greater savings in energy and better comfort. To this end, building standards have been introduced, intended to provide benchmarks and guidelines and eventually certify building performance. Passive house and Active house are concepts that have gained popularity the recent years.

"Passive House" is a building standard originally developed in Germany that suggest up to 90% less heating energy use compared to typical Central European building stock and over 75% compared to average new builds. The savings are possible through a highly insulated and airtight envelope with limited areas for opening and the optimum use of the sun, internal heat sources and heat recovery ventilation. During warmer months, passive cooling techniques such as strategic shading are applied (Passive House Institute, 2012). Moreover, specific requirement need to be met, for a building to be according to the standard, such as maximum annual heating demand of 15 kWh/(m^2a) U-values of opaque exterior components less than 0.15 W/(m^2K) and translucent components less than 0.8 W/(m^2K), with a g-value 0.5, limitations in the openings design.

The Active House principles propose a target framework for how to design and renovate buildings that contribute positively to health and comfort by focusing on the indoor and outdoor environment and the use of renewable energy. With regard to the specifications, the Active House building standard incorporates some of the same concepts of Passive House, such as insulation, air-tightness and optimal solar exposure and it sets limits to primary energy consumption. It also addresses and sets values according to the design ambition for daylight, indoor temperature and air quality, noise, percentages of energy demand covered by renewable sources, environmental loads and percentages of recycled building materials (Active House, 2013).

Both concepts of green buildings can be applied in refurbishment projects. The Passive House Institute, in particular, has therefore developed the "EnerPHit– certified refurbishment using Passive House components" certification procedure for such buildings. However, due to limitations such as the orientation and thermal bridges, it is not possible to achieve the standards in every case.

Uncertainties in energy performance assessments

Certificates of the energy and environmental performance are a positive step towards increased awareness and design of better performing new and refurbished buildings. Nevertheless, there is a lot of discussion and research whether the assessment methodologies and calculations can predict and reflect the actual performance of the building. Buildings usually do not perform as predicted, even when very sophisticated energy simulation methods are used. Some scientists call it a 'performance gap' or 'rebound effect'. One of the reasons of such discrepancy between models and real buildings is the influence of human behaviour and the preferences of occupants (Motuziene & Vilutiene, 2013).

Most standardized calculation tools typically predict energy consumption for heating in residential buildings assuming standard dwelling use: mean temperature fixed, infiltration plus dedicated ventilation rate imposed and internal gains standardized (Hens et al., 2010). These parameters depend on occupants' usage patterns that in reality are different than anticipated in the calculation, resulting in differences between calculated and actual energy consumption. Studies have shown that occupant behaviour might play a prominent role in the variation in energy consumption in different households but the extent of such influence is difficult to quantify (Guerra Santin et al., 2009).

Rebound effect is expressed as a percentage, valued by dividing the difference between calculated and actual energy consumption by that calculated consumption (Hens et al., 2010). Whether this percentage is positive or negative depends on whether the actual consumption is higher or lower than the calculated. A tendency identified by Majcen et al. (2013) is that very energy-efficient buildings actual consumption can exceed the predicted levels, while less energy-efficient dwellings are predicted to use more than they actually do. Particularly in refurbished buildings, it has been observed that the service demand is higher, when the efficiency improves, resulting in the rebound-effect due to building retrofit of about 15 to 30%. This leads to the conclusion that energy savings achieved in practice with energy conservation measures is lower than calculated. (Haas et al., 1998).

Overall, energy labels and energy calculation tools be seen as quantification of the thermal quality of the dwelling, but cannot predict the real energy consumption (Hens et al., 2010; Majcen et al., 2013). This being said, theoretical calculation of possible energy reduction can be useful in the early stages of the design, in order to understand what quality the building needs to fulfil. Moreover, it is relevant methodology for the purpose of the present research that aims at assisting decision-making.

However, in cases that precise figures are required, for example for investment payback period or demand side management systems (including the time-shifting of demand) more accurate calculation are necessary. To this end, detailed electricity and thermal demand profiles for domestic housing are an important prerequisite and there have been efforts toward generating realistic occupancy data, e.g. Richardson et al. (2008), or the harmonised European time use surveys, HETUS (2013), which provide a great variety of statistical images of people's use of time in European countries.

§ 3.2.3 Life cycle assessment (LCA)

Apart from energy consumption during its operation, a building requires energy to be constructed and disposed, as well as in the production and transportation of materials. To consider these energy streams in the building sector, analysis of the whole life of the building is necessary, known as life cycle assessment (LCA). Trusty (2010) defines LCA as an analytical method used to comprehensively quantify and interpret the energy and material flows to and from the environment over the entire life cycle of a product, process, or service. European standards, such as ISO14040 (2006), or EN15643-1 (2010), developed to provide a system for the assessment of environmental performance of buildings based on a life cycle approach.

The building life cycle starts with the acquisition of raw materials. It proceeds through the manufacture of products, construction work processes, and actual use of the building including maintenance, refurbishment and operation and finally, at the end of life, deconstruction or demolition, waste processing and recycling. Information from these activities is needed to assess the environmental impacts and aspects of the building (EN15643-2, 2011). The system boundary determines the processes that are taken into account for the object of assessment. For a new building, the system boundary shall include all the building life cycle stages, from material production to end of life. For an existing building (or part thereof), the system boundary shall include the stages representing the remaining service life, and the end of life stage of the building. As far as refurbishment is concerned, the boundary shall take into account production and transportation of the new building components, construction and waste management of the refurbishment process, and the end of life stage of replaced building components (EN15978, 2011).

The assessment of the environmental performance of buildings takes into account environmental information of construction products (EN15643-2, 2011). As such, the embodied energy of materials, which is the quantity of energy required to process and supply to the construction site, the material under consideration (G. P. Hammond & C. I. Jones, 2008), is interrelated with LCA. Ideally the boundaries would be set from the extraction of raw materials (including fuels) until the end of the products lifetime (including energy from manufacturing, transport, energy to manufacture capital equipment, heating and lighting of factory, maintenance, disposal etc.), known as 'Cradle-to-Grave'(greenspec, 2013a). With regard to the relation between embodied and operational energy, studies have shown that there is a linear relation between operating and total life-cycle energy (Sartori & Hestnes, 2007) and that operating energy represents by far the largest part of energy demand in a building during its life cycle. Hence, low-energy buildings result in being more energy efficient than conventional ones, even though their embodied energy is some higher. However, when nearly zero energy will be used to operate the buildings (DIRECTIVE, 2010/31/EU), the importance of the embodied energy will increase (Hildebrand, 2012).

Information related to embodied energy is provided by the products manufacturer. Efforts toward creating an inventory of materials' embodied energy have resulted in different databases, such as the University of Bath's inventory of carbon and energy database (G. Hammond & C. Jones, 2008), the Dutch Institute of building biology and Ecology (NIBE) environmental classification of building products (Haas, 2012), and the environmental product declarations database Ökobau.dat (BMVBS, 2013), used in the German sustainable building certification scheme, DGNB . In the building industry, embodied energy is most frequently expressed in mega joule (MJ) and global warming potential (GWP) in kilogram CO_2 equivalent (Hildebrand, 2012).

Despite the uncertainties in embodied energy values and LCA, they can be considered good benchmarks to determine the life-cycle performance of buildings. LCA has the potential to be integrated in the design process. As the requirements for sustainable buildings increase, considering energy and resources in all stages of building construction, use and disposal is necessary. Moreover, it is a valuable tool for design and construction in existing buildings stock. The associated long-term perspective included in LCA is important for sustainability certificates that support integrating into the design process and compliance with standards of products and services (König, 2010).

Environmental certification of buildings

Policy instruments such as labelling and certification schemes enable the objectives of sustainability to be implemented in society (König, 2010) The energy certification processes for buildings are a fundamental step towards improving buildings' energy efficiency. Nevertheless, energy certification refers mostly to operational energy and do not usually consider aspects related to the life cycle of the building. This can lead to the contradiction of obtaining a better energy classification, while producing a higher energy consumption or more CO_2 emissions in global terms (Zabalza Bribián et al., 2009). Therefore assessing holistically the environmental performance, including embodied and operational energy, is growing in popularity.

The objectives of assessments are to determine the impacts and aspects of the building and its site and to enable the client, user and designer to make decisions and choices that will help to address the need for sustainability of buildings (EN15643-2, 2011). Several environmental assessment tools developed for the building sector can be found. Overviews and comparison of tools can be found in the literature (Annex31, 2001; Haapio & Viitaniemi, 2008; König, 2010; Ortiz et al., 2009). Separate environmental indicators were developed for the needs of relevant interest groups. There are two well-known classification systems for the environmental assessment tools. One was developed by the ATHENA Institute and the other by IEA Annex 31 (2001). ATHENA classification has three levels: product focus, assembly focus, and whole building assessment (Trusty, 2009). The latter are most interesting in this thesis discussion.

The environmental assessment methodologies differ in aspects such as the number of criteria, type of weighting, LCA consideration, type of buildings etc. The results of the environmental assessment of a building can be presented in forms of graphs, tables, grades, certificates and reports. Different tools are developed and used in different countries, to address the country's specifics. Some of the most know certification schemes of level 3, whole building assessment, are BREEAM in the UK, LEED in USA, Green Star in Australia, HQE in France, and DGNB in Germany (König, 2010). However, their applicability is not limited to those countries. The criteria the assessment schemes look at include the use of land, water, energy, materials, health, transport and waste.

In the future, given the need for low-energy designs to dominate, the use of rating systems for the whole building environmental assessment will force, but also support, architects and engineers to increasingly aware of important aspect of sustainability, including land use, water recycling, renewable energy, sustainable materials and indoor environmental quality (Yudelson, 2009), as well as emphasis on the selection of green materials or products (Trusty, 2009).

§ 3.3 Environmental Design Strategies

Given the need to reduce the energy demand of building sector, upgrading the existing dwellings into passive, sustainable houses that use less non-renewable energy sources while providing improved conditions for the users is a focal point. To achieve that, we can apply simple methods and techniques, using an appropriate building design, material and systems selection, reflecting consideration of the local climate, make use of environmental elements, such as air and sun, and aim at providing thermal and visual comfort. These techniques are referred to as environmental or bioclimatic design.

The ideas of bioclimatic design have existed since man first sought for shelter. The term of bioclimatic design, however, was identified and developed in the 1960s (Olgyay & Olgyay, 1963), bringing together disciplines of human physiology, climatology and building physics. The Olgyay brothers referred to the bioclimatic approach as a set of criteria, specific to the project, such as location, surroundings, typology, orientation etc. and how they provide best protection from weather conditions, as well as the use of energy source, such as solar radiation, wind, water and vegetation. Currently, bioclimatic architecture is viewed as indispensable for environmental sustainability, together with viable economic and social reckoning (Minguet & Vázquez, 2009). It has been integrated in the building design and has been seen as a cornerstone to achieving more sustainable buildings (Hyde, 2008).

Bioclimatic issues, in the form of occupants' thermal comfort and passive, low-energy architecture have been used by design professionals as a starting point for designing new buildings. In refurbishment projects, re-applying these principles to improve comfort and energy efficiency poses some additional challenges. However, refurbishment or new-built, there are a lot of the same principles and considerations that need to be integrated in the building design and construction.

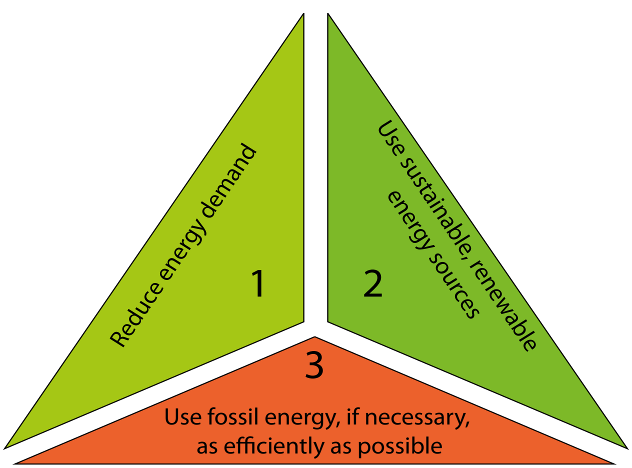


Figure 3.2
The "Trias Energetica" principles.

A concept in line with environmental design is the "Trias Energetica". It was introduced by Lysen in 1996 (AgentschapNL, 2013) and based on Duijvestein's (1993) three-step scheme, which ranked sustainable measures for the building industry with each step in order of sustainability preference. Most favourable measures were part of the first step and the least favourable ones formed the last step. The final form of the Trias Energetica, referred by many researchers is a hierarchical approach of sustainability. Firstly, prevent the use of energy (prevention); then, use sustainable energy sources as widely as possible (renewable); finally, when there still remains an energy demand, use fossil fuels as efficiently as possible (efficiency). Particularly for Zero energy buildings and homes, if use of finite (fossil) energy sources is inevitable, the third step suggests using them very efficiently and compensate with 100% renewable energy (AgentschapNL, 2013).

Within the Trias Energetica concept, there are two courses of measures to be taken during the retrofitting of dwellings: passive and active. Passive are the principles exploiting the design and properties of the building envelope to minimise or maximise the heat losses and heat gains respectively, reducing the energy demand (Step 1). In addition, systems for conditioning the building such as heating systems and solar power technologies (active measures) are used to produce (step 2) and distribute (step 3) the energy needed to achieve comfort of the occupants. Figure 3.3 presents an overview of the passive and active design principles, in relation to the Trias Energetica steps.

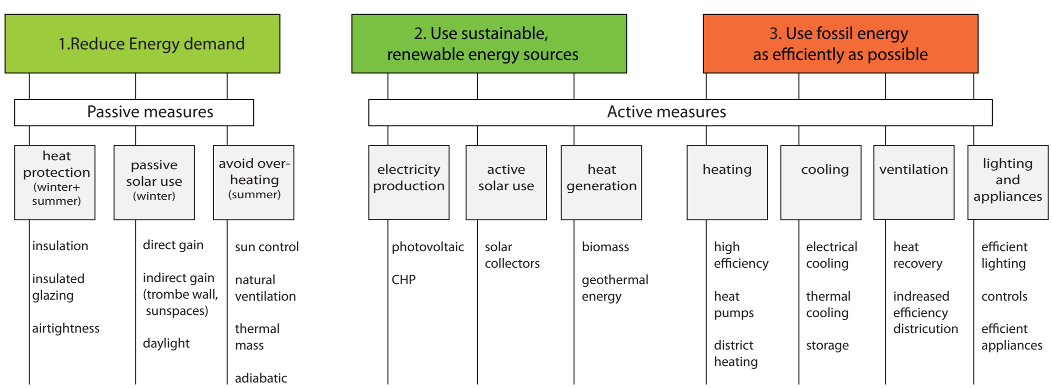


Figure 3.3

Overview of design principles of passive and active measures, in conjunction with Trias Energetica steps.

§ 3.3.1 Passive design

Passive design includes principles that are used to minimise the energy demand of the building. This is made possible with proper consideration of the local climate, building layout and material properties. Passive design principles can be broken down into the following basic functions.

Heat protection

Heat is a form of energy that flows from a high to a low temperature zone. To reduce the energy demand, the building envelope needs to be able to prevent, or at least minimise, the heat flow from the inside to outside in the winter and to the opposite direction in the summer. Reducing the heat transmittance is, thus, important in all season. It can be achieved by increasing the airtightness and thermal resistance of the building envelope, eliminating thermal bridges, with additional insulation on the wall, basement, roof and replacement of the windows.

Insulating materials improve the thermal and sound insulation of the building and they are mostly used in the opaque building components. They reduce transmission heat losses and produce higher surface temperature, which minimises ventilation heat losses in winter (Hausladen et al., 2008). For this reason, insulation is one of the first and most needed measures in refurbishment projects, where the thermal resistance of the building envelope is, more often than not, insufficient. In the transparent components of the envelope, multiple panes of glass with intervening air space must be used to improve the insulation value considerably. Additional improvements to the thermal performance of glazing units involve filling the space with a less conductive gas, such as argon, and application of low-emissivity coatings. Insulating materials and glazing technologies are discussed in detail in the following chapter.

Air tightness is important from a variety of perspectives, but most of them relate to the fact that air tightness is the fundamental building property that impacts infiltration. Infiltration, or air leakage, is the movement of air through leaks, cracks, or other adventitious openings in the building envelope (Sherman & Chan, 2004). From the energy perspective air leakage is a major cause of energy loss, as it allows heated air to escape. Even with today's levels of air-tightness, the envelope leakage can increase the heating needs by 5-20 $kWh/m^2/a$ in a moderate climate (BPIE, 2011a). Moreover it degrades the effectiveness of the insulation and allows potentially damaging moisture to enter the structural fabric. Air leakage occurs at joints of the building fabric, around doors and windows, cracks in masonry walls etc., as well as where pipes and cables pass through the building (Hall, 2008a).

Air-leakage is uncontrolled and needs to be minimised. However, in many cases, particularly old buildings, infiltration is the dominant source of outdoor air to preserve adequate indoor air quality (IAQ). Improving air tightness will provide insufficient air through infiltration and needs to be coupled with ventilation system. In buildings with such systems, especially those with heat recovery, air tightness may be a determining factor in the performance of that system (Sherman & Chan, 2004).

Ensuring airtightness is achieved through careful implementation of strategy throughout the design and construction phases. The application of insulation and window replacement improve significant the airtightness of the dwelling. Infiltration rates are defined in regulations at a national level. The values should be defined as: n(vol.h) or airflow / outer envelope or Airflow / floor area, for a pressure difference of 50 Pa or 10 Pa or 4 Pa. Air change per hour (ACH) is another unit to measure infiltration and ventilation and it refers to how many times the air within a defined space (normally a room or house) is replaced. A low leakage lever required in efficient buildings should be around 1.2 ACH at 50Pa (EN15242, 2007) and the passive house standard 0.6 ACH, while in the current stock it can be up to 16 ACH at 50Pa (Stephen, 2000), suggesting that there is big room for improvement in the building stock's airtightness.

Passive Solar use

Passive solar heating applies during heating season, when energy for heating is required to reach thermal comfort. It employs the structural elements of a building to collect, store and distribute solar energy without or with the minimum use of mechanical equipment (Hyde, 2008). The sunlight is directly collected through the glazed area of the façade, especially the south oriented surfaces.

Solar energy can also be utilised in the form of indirect gain. These methods involve usually a transparent outer layer and a heat-absorbing element between the incident solar radiation and the space to be heated, normally wall of high thermal capacity. Solar energy transmitted through the transparent layer is absorbed by the outer surface of the wall and conducted to the inner surface several hours later or is conveyed by the air flowing through the air between glazing and wall. In areas that receive inconsistent solar radiation, indirect solar gain can be of great benefit, especially when combined with air circulation measures (Smith, 2005). Popular technology of indirect solar heating is Trombe wall and attached sunspaces. Apart from the advantage on the energy efficiency, such constructions can have the benefit of enlarging the living space of the dwelling. During summer, when the heating effect is not needed, the glazed parts can be open or protected with adequate shading.

Shortcoming of passive heating is that it primarily occurs in the south part of the building. In a dwelling level, these is normally not a big problem, as the heat gains can be distributed in short distances and reduce the overall heating loads. If the building becomes larger, however, it is possible to require zoning in the energy use for the different orientation (Hall, 2008b). Moreover, since the windows are one of the mail sources of fabric heat losses, in case of direct passive solar heating the heat gains through the windows must be outweigh the heat losses.

Apart from the passive heating, the sun can be used for daylight, to reduce the need for electric lighting. Daylight is the preferred form of illumination in buildings. The human eye has evolved using it and its full spectrum output means it delivers better colour rendering properties of any light source (Hall, 2008b). Most importantly, with the energy use for lighting being 10% of total electricity consumption in residential buildings (Bertoldi et al., 2012), the use of daylight instead of electrical lighting can reduce energy demand.

The amount of sun radiation used both for passive solar heating and daylight, admitted in a space depends primarily on the amount of transparent and translucent areas of the façade. Additionally, the building orientation, shading and reflectance of the surrounding buildings, and weather condition are influential (Hausladen et al., 2008). The latter are parameters that cannot be altered by refurbishment. The design, however, of the refurbished building, whether it replaces the whole façade or changes slightly the openings' dimensions, may improve the use of sun in the building.

Overheating prevention

Avoiding overheating is important during summer season. There are several techniques to prevent overheating -or at least minimise the overheating effect- and maintain air quality, before resorting to mechanical means of cooling. Sun control and natural ventilation, particularly combined with high thermal mass, are such techniques. They are also very common in the residential context and have the potential of eliminate discomfort related to high temperatures in western European climate (Ligget & Milne, 2011), which is the scope of the research. Other measures, such as passive evaporative cooling are not very relevant to this climate.

Desirable as solar radiation might be during winter, it should be excluded during summer, to avoid overheating of the living spaces. The easiest way to block the unwelcome solar energy is shading devices. They come in many forms and shapes, varying from projecting eaves to venetian blinds and curtains. The choice depends on their performance, as well as functional and aesthetical reasons. External shading, for example, is more efficient than internal, even though high maintenance.

The orientation is also an important factor that determines the type of shading. Horizontal solar screening louvers can exclude direct sunlight on the south side with little visual interference. Permanent shading features, such as cantilevers, can be used as seasonal solar screening. They block the high-angles sun in the summer, while allowing low-sun penetration in the winter, enabling solar heating. East and west façades, where sun strikes at low altitudes, movable vertical louvers are preferred. By setting the angle of the louvers sunlight can be blocked, while retaining some of the view (Hausladen et al., 2008).

a　　　b

Figure 3.4
(a) Shading device in the renovation of Koningsvrouwen van Landlust – Eigen Haard (Image source: courtesy of DeGroot en Visser, photographer F. Huijin). (b) Internal blinds in winter garden of the Piazzaflat, Goringem (Image source: courtesy of SOLARLUX Nederland BV)

Airflow through buildings exchanges the heated internal air with cool outside air. Passively, this is possible with natural ventilation. Natural ventilation through the façade's openings is driven by the climatic forces of wind (wind effect) and temperature (stack effect). For this reason, natural ventilation is highly variable since, at any instant, both the pattern of airflow and the rate of ventilation will depend on the prevailing weather conditions (CISBE, 2006). Nevertheless, in moderate climates, we can have natural ventilation at most times of the year, particularly in the domestic environment (Hausladen et al., 2008). Moreover, natural ventilation through operable windows, give the occupant to adapt to the environment. Together with the cooling effect of air speed, it allows thermal comfort in a higher range of temperatures (ASHRAE, 2010).

To regulate high temperatures, natural ventilation can be combined with thermal mass, which is the heat capacity of the building components. If sufficient thermal mass is available, a part of the heat gains can be temporally stored and be later released (Hegger et al., 2008). The heat is normally released by means of purge ventilation during nighttime, when the temperature is lower. The technique works better for high (more than 10oC) diurnal temperature difference. Heavy weight construction, such as Concrete, terracotta and limestone (Jeanjean et al., 2013) can provide sufficient thermal mass. Important for thermal mass to be effective is the direct link to the interior. Suspended ceilings and internal linings prevent the heat flow between the air temperature and the building thermal mass, and, thus, should be considered during the design. The use of Phase Change Material (PCM) can be an alternative to take the place of thermal mass (Hausladen et al., 2008).

§ 3.3.2 Active measures

Passive measures alone are not able to eliminate energy demand, in all seasons, especially in the heating oriented climate of central Europe. Passive measures aim at minimising the heating demand. Parallel to these, active measures are necessary to produce and distribute the energy needed for heating, cooling, ventilation, DHW, lighting and appliances. In refurbishment project, updating the building services with more sustainable and efficient technologies, along with energy generation, should be an important consideration and should happen in parallel with building envelope upgrade.

In the case of residential buildings that the subject of the current work, there are some specific characteristics, comparing to other building types, that affect the systems design. Such characteristics are smaller internal gains than e.g. in commercial uses and varied use of space but conditioned in fewer, if not a single zone (ASHRAE, 2005). The inspection of existing and the detailed calculation and sizing of new technical installation are subject to each project and are carried out by specialised professionals. There are several guidelines in a national and international level (ASHRAE, 2005; CISBE, 2005, 2006; EN14788, 2006; EN15242, 2007; EN15316-1, 2007; EN15378, 2007) along with tools and software applications to support the design. Nevertheless, the decision process should be incorporated in the overall refurbishment scheme and should be in conjunction with other involved parties, such the architects and the users.

It needs to be highlighted that the present thesis focuses on design decisions for building envelope energy upgrade. Nevertheless, building services is an integral part of residential buildings' retrofitting and, in order to support further development of the research approach, this section gives an overview of building technical systems. The discussion is not exhaustive, as it does not include all possible technologies, but the ones most common in refurbishment practice. Moreover, it refers to the building's system boundary; for example, the energy that can be produced on the building site and not the renewable energy mix on a regional or national level, as these are decisions not affected by the retrofitting.

The active measures that can be incorporated in a refurbishment strategy are related with the use of renewable energy sources, particularly electricity generation with the use of PV cells or Combine Heat Power units, as well as heat generation from renewable sources. Systems to supply the remaining energy demand for heating, cooling, ventilation and lighting in an efficient manner are also important.

Renewable Energy Sources (RES)

Renewable is the energy that is obtained by tapping into natural processes (Hall, 2008b), such as sun radiation, wind, water movement etc. Since these processes are being repeated, the energy produced through them can be renewed. This is in contrast with energy produced from fossil fuel, such as oil or gas, whose earth reserves are not unlimited. Both electricity and heat can be generated by renewable energy sources.

Photovoltaic (PV) installations are technical systems that transform solar radiation directly into electricity. At the core of the installation there are solar cells, combined into modules that produce DC voltage (Schittich, 2006). Photovoltaic modules can help to reduce electricity demand from the power of in own use or be fed to the electricity network. The main drawback of PV technology is cost related. It is still expensive although it is potentially advantageous in reducing the environmental impacts caused by human activities. Nevertheless, a number of developments, such as silicon based systems, have led to in higher efficiencies and reduced costs of manufacturing processes. As a result, prices of photovoltaic modules dropped significantly in the last few years, making a purchase economically viable, especially with regard to rising electricity prices. Furthermore, more efficient storage options for individual use are possible, such as using electricity for the operation of an electric car.

The annual output of the PV system is also determined by the orientation and the angle of the module surface. For northern Europe, the highest annual radiation is for south-facing systems on an angle of 30o. The performance significantly reduces in vertical surfaces. However, the building façade area available, at rough calculations, is a considerable amount compared with the roof space. Thus, incorporating PVs in façade design results in reducing energy demands by producing electricity as well as enhance the performance of the façade. What is more, the payback period is improved as the PV panels replace the normal cladding of the building (Schittich, 2006). The task of integrating the PVs into the building skin is integral. The visual and constructional integration must guarantee that the installation does not conflict, but complements the requirements and characteristics of the building skin.

Heat can be generated from renewable sources, for example with active solar system or heating systems using renewable fuels. An active solar thermal system (e.g. from evacuated solar heating panels) combined with large hot water storage to supply domestic hot water (DHW) and heating, is an efficient solution particularly in the summer. Solar collectors convert direct solar radiation into other forms of energy, i.e. they preheat water using a closed circuit clarifier (Smith, 2005). There are different types of solar collectors, depending on the system construction. Evacuated solar heating panels are more efficient than conventional flat plate type collectors and will perform considerably better in cold, cloudy and windy conditions. The higher efficiency of evacuated solar heating tubes mean less area is covered on the roof by the solar heating panels- a desirable feature appreciated by most customers.

Moreover, heating systems can use renewable fuels, contributing to climate protection. Modern biomass heating systems are an alternative to fossil fuels and they are as efficient and easy to use as conventional systems. There can be various renewable sources used as fuel in modern heating systems, such as wood (in form of pellets or wood chips), vegetable oil or biogas. These heaters can serve various areas, so that they can be suitable for most of the buildings, according to the requirements.

Biomass is the organic substance. In the energy context, biomass is considered a renewable raw material that provide energy without producing additional amounts of CO_2 within its life-cycle, as the amount of CO_2 released has been taken up by the plants during growing. It is therefore considered a CO_2 neutral source and the primary energy factor of biomass is very low (Hegger et al., 2008). The term biomass describes a wide range of sources. The characteristics of the biomass fuel play an important role in how the system performs. Biomass heating systems use predominantly wood (Hall, 2008b), in form of logs, wood chips and wood pellet, made from wood and wood waste, straw, grain and other agricultural remains. Depending on the heating system, wood pellets come in different forms. As a further possibility include biodegradable wastes (such as dung, sewage etc.), vegetable oils, animals by-products that can be burnt as fuel.

Geothermal is the energy stored in the ground and it is another form of renewable energy. Geothermal heating is based on the principle that the temperature in the ground becomes more constant in deeper depth and beyond approximately 30m it corresponds to the average air temperature (Hegger et al., 2008). Water is pumped down a borehole in the ground and back to the surface, allowing the heat to be transferred by simple conduction from the ground to the water, which is then used to heat the building.

Figure 3.5

(a), (b) PV panels integrated in the façade and roof of the refurbished building Delfgaauwse Weije, in the Netherlands. (c) Solar collector panel and Photovoltaic cells as roof tiles in Germany.

(d) Biomass boiler, (e) wood pellets and, (f) wood chips (Image source: courtesy of 3N e.V.)

(g) Share of heating consumption in terms of final energy use in residential building with corresponding energy mix (adapted from: BPIE, 2011a, figure 1C5).

Efficient use of non-renewable energy

Even after using passive design principles and renewable energy sources, it is possible that additional energy by fossil fuels is required. This is provided by the technical building system' means technical equipment for the heating, cooling, ventilation, hot water, lighting or for a combination thereof (DIRECTIVE, 2010/31/EU). Even though the technical systems is not the subject of the present research that focuses on façade refurbishment strategies, this section discusses briefly possibilities for mechanical heating, cooling, ventilation (HVAC) and lighting, as they are important considerations in every refurbishment project to improve the energy performance of the existing building.

Heating

Heating refers to the system used to provide the heating energy demand to the space, in order for the inside temperature to reach the thermal comfort requirements. A variety of such systems exists; some are related to renewable energy sources, already discussed in the previous section. Hydronic systems that use hot water for transferring heat from the heat generator to the heat emitters are mostly encountered in residential context. The most usual type of heat generator for hydronic systems is a 'boiler'. Boilers are available in a large range of types and sizes and use different fuel, such as gas, oil, electricity or biomass. Figure 3.5.g. shows the mix of energy sources used for heating in different European countries.

The efficiency of any given boiler is a measure of how well it transfers the heat liberated during combustion into the heating system (Hall, 2008b). Boiler efficiency has improved markedly over the past two decades (CISBE, 2005), with achieved efficiencies up to 91% (SEDBUK, 2005). This is an important consideration, particularly in retrofitting, as it is most likely that old building have heating systems with much lower efficiency that current technology. EPBD suggests that boilers older than 15 years should be inspected and replaced (DIRECTIVE, 2002/91/EU) and the new boilers should be inspected every 2-4 years (DIRECTIVE, 2010/31/EU).

Hot water for hydronic systems may also be generated by heat pumps. They are assemblies designed as a unit to transfer heat. It includes a vapour compression refrigeration system or a refrigerant/sorbent pair to transfer heat from the source by means of electrical or thermal energy at a high temperature to the heat sink (EN15316-4-2, 2007). Heat pumps can exploit different sources of low-grade heat. There are different types, according to the heat source they use. Air source systems (ASHP) have advantages regarding space requirements and ease of installation, but they cannot offer the same year round efficiency as other source. Water source heat pumps (WSHP) offer the best coefficient of performance (CoP), but they are less common, as require a water source in proximity. Ground source heat pumps (GSHP) should not be confused with geothermal energy. GSHP pipes are only buried 1 meter below the surface, to use the solar energy stored in the ground. Geothermal energy, on the other hand, is heat within the earth in depths of around 30m (Hall, 2008a). The heat pumps are widely used for heating are reversible air-to-air units that can also be used for cooling (CISBE, 2005).

Hydronic systems are capable of working with a wide variety of heat emitters, such as radiators, convectors or under-floor heating. They offer a high degree of flexibility in location, appearance, and output characteristics and the choice depends on the specifics of each case. When heat pumps are used, a low temperature distribution system is advised. The efficiency of the heat emitters and circuit, together with the boiler's efficiency determine the heating system efficiency.

Heating can be provided by warm air, either by stand-alone heaters or distributed from central air-handling plant; in many cases the same plant is used for summertime cooling/ventilation. Almost all the heat output is provided in convective form. Warm air systems generally have a much faster response time than hydronic systems.

Combined Heat and Power (CHP) or cogeneration plants provide simultaneous generation in one process of thermal energy and electrical and/or mechanical energy (EN15316-4-4, 2007). Where there is no suitable existing supply of heat and installation of heat generation system is required in any case, the opportunity for using a stand-alone CHP unit should be evaluated. The decision depends on requirements both for heat and electricity, their diurnal and seasonal variability and the extent to which they occur simultaneously. It is important to have a reasonable match between the generated output and electricity demand, as the value of the electricity generated tends to dominate the economic analysis (CISBE, 2005). The energy efficiency for building-integrated cogeneration installations ranges, depending on the technology from 75% to 105%, which means that the energy output can be higher than the input (EN15316-4-4, 2007). CHP schemes may be useful for dense group of properties, such as high-rise flats, or even applied in a community level (Emmanuel & Baker, 2012).

District heating is an efficient way to provide heating, particularly when combined with CHP units. The heat is generated in a central source and delivered on demand as hot water to group of buildings (Hall, 2008b). Even though the very existence of this option is outside the building's boundaries, refurbishment should consider the necessary adjustments to be able to utilise the energy, such as efficient heat distribution system in the dwellings.

Cooling

Besides heat supply, limiting high temperatures in another important aspect of thermal comfort in buildings. This can be achieved with a number of techniques passive or active. In occasions that temperatures are too high, the use of mechanical systems is required. Cooling systems, referred also as 'air-conditioning system', is a combination of the components required to provide a form of indoor air treatment, by which temperature is controlled or can be lowered (DIRECTIVE, 2010/31/EU). A common system is a refrigeration plant, which uses electricity to cool air or chill water. The efficiency of a cooling system is normally called coefficient of performance (CoP). In cooling systems, energy consume is consumed, firstly, by the electric pump used to circulate the refrigerant and, secondly, by fans and pumps that move the water of the air (Hall, 2008b).

The cooled air is introduced in the occupied space by an air-supply system, usually from inlets on the ceiling or at floor level, depending on the system design. Care must be taken of the velocity and distribution, to avoid cold draughts. In the case of water cooling, water is circulated in pipes, similarly to hydronic heating systems that go through building components, such as in under floor heating system or suspended ceiling panels, also known as chilled ceilings. The surface temperature must be above the dew point of the interior air, to avoid condensation. For this reason, the cooling capacity is limited (Hegger et al., 2008).

Even though mechanical cooling isn't as relevant in residential context as it is in commercial and office buildings, especially in central and northern European countries, it is still important, particularly in south Europe (BPIE, 2011a). Therefore, it needs to be considered as part of retrofitting strategy, when passive measures are not enough to avoid overheating and ensure thermal comfort. Nevertheless, it is not a focal point of the current thesis, whose scope is residential building stock in countries of Central Europe, such as the UK, Germany and the Netherland.

Ventilation

Ventilation is the process of providing fresh air to occupants and removing pollutants from a space. Energy losses from ventilation and general air exchange can account for more than half of the primary energy used in a building. These losses comprise space heating and refrigerative cooling losses as well as the electrical load associated with driving mechanical services (CISBE, 2006). Mechanical ventilation system ventilation system where the air is supplied or extracted from the building or both by a fan and using exhaust air terminal devices, ducts and roof /wall outlets (EN15242, 2007).

The air extracted from building carries energy with it. Heat losses associated with building ventilation have significant importance in existing houses. (Nemry et al., 2010). A heat recovery ventilator (HRV) can help make mechanical ventilation more cost effective by reclaiming energy from exhaust airflows. HRVs use heat exchangers to heat or cool incoming fresh air, recapturing 60 to 80% of the conditioned temperatures that would be otherwise lost. Research has shown that, overall, heat recovery ventilation can be more profitable when compared with simple mechanical exhaust or natural ventilation, in terms of primary energy, carbon dioxide emissions and household consumer operating energy cost, particularly in Northern Europe (Laverge & Janssens, 2012). Models that exchange moisture between the two air streams are referred to as Energy Recovery Ventilators (ERVs). Furthermore, these systems are equipped with pollen filter, which is very helpful for people with allergies.

Lighting and appliances

With appliances accounting for 11% of the total energy used in residential buildings and lighting for 10% of electricity consumptions, considering this fragment of energy use during refurbishment can have benefits in the overall consumption. To reduce the energy use for lighting and appliances, the first step is to increase their efficiency. Information about the product efficiency is provided by the manufacturer. Directives on eco-design (DIRECTIVE, 2009/125/EC) and energy labelling of products (DIRECTIVE, 2010/30/EU) provide the regulatory framework. Energy renovation is an ideal opportunity to replace luminaires and other house hold appliances with more efficient ones. Apart from efficiency, the usage patterns determine the energy use, which can be improved by efficient controls and switches.

§ 3.4 Challenges to implement energy efficiency in refurbishment

In the refurbishment context, the above mentioned design principles are faced with additional limitations. Apart from the general limitations and barriers discussed in the previous chapter, the complexity of existing buildings is an important factor (Emmanuel & Baker, 2012). This is due to the fact the refurbishment deals with existing buildings and some of the parameters making the design principles effective are given and cannot be changed always possible to change and additional consideration is needed. In order to upgrade the building's efficiency, the key parameters of location, orientation and construction need to be taken into account (Konstantinou & Knaack, 2013). This section elaborates on those key parameters, with focus on environmental design possibilities, which are also essential in developing the approach to answer the research question of integrating the energy efficiency into the design of façade refurbishment strategies, as will be explained in the following chapters.

Climate

The term “climate” refers to the local state of the atmosphere that can be described by means of meteorological variables. To define climate, a time dimension of 30 to 40 years is employed, to distinguish from weather, which is momentary, or meteorological conditions, which is the weather in a period of week or season. Furthermore, climate can be divided into scales according to spatial dimensions into micro-, meso- and macro-climate (Hegger et al., 2008). On a building level, the focus of climate analysis lies on the mesothermal climate that describes the geographic situation and the microthermal climate which encompasses the topographic circumstances of a particular location as well as the urban influences of the environment (Bilow, 2012).

Based on characteristics such as solar radiation, air temperature and fluctuation, wind, precipitation etc., the Earth is divided into climate zones. The “eco-climatic classification”, dating from 1923 specifies 4 zones; polar, temperate, subtropical and tropical (Hegger et al., 2008). The Koppen-Geiger climate classification, based on the work of Wladimir Koppen and dating from 1900, continues to be the most widely used climate classification over a century later. The criteria for defining the climate types are based on annual temperatures, as well as the precipitation. There are five zones (tropical, arid, temperate, cold, polar) with additional classifications within each zone, such as dry summer or winter, hot or cold summer etc., resulting in 30 possible climate types worldwide (Peel et al., 2007). In Europe many different types are encountered, from polar in Scandinavia to arid in Spain. For the biggest part of Europe a rough division would be temperate to cold without dry season and with warm summer in the central, north and west part and temperate with dry and hot summer in the south part (Figure 3.6.b).

Both in designing new and transforming existing into high performing buildings, climate is always a limitation – or rather a starting point- for the decisions, as it determines the energy required to achieve a comfortable indoor environment. The different types of climates all over the world can also been classified, according to the degree days as heating or cooling dominated climates (Hunn, 1996). Degree days express the degrees the outside temperature drops below a base temperature, e.g. 15.5°C, and the number of days this drop occurs. These data, averaged over the years, can be used in the calculation of heat losses (McMullan, 2002). For example, in Finland the degree days are 5850, while 1282 in Portugal. Moreover, there is a correlation between degree days and fuel consumption (BPIE, 2011a). Thus, the first step in designing an environmentally conscious building is to analyse the local climate and make design decisions according prevailing environmental conditions.

For climate analysis, psychrometric charts can be used to illustrate the main climate elements The psychrometric chart is a set of graphs which are combined so that they plot the relationship between the different variables used to specify humidity, such as dry-bulb temperature, moisture content, vapour pressure (McMullan, 2002), but it is considered as the best representation of climatic variables (Attia, 2012). Hourly dry-bulb temperature and moisture content data can be plot on a psychrometric chart, creating point clouds that offer insight into the prevailing climate. (Bilow, 2012). Not only do they provide an understanding of the climate, but also an overview on appropriate design principles, as indicated in Givoni's Building Bioclimatic Chart (BBCC) (Givoni, 1992).

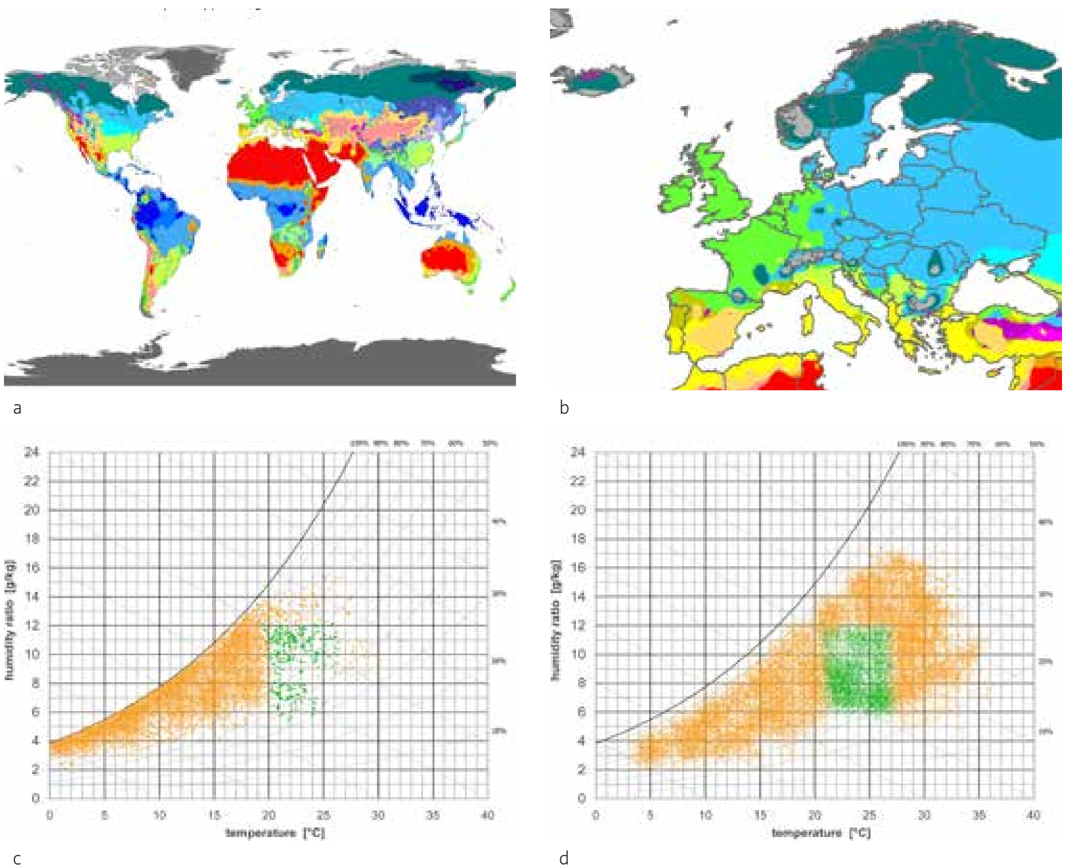


Figure 3.6
World (a) and Europe (b) climate classification according to Koppen-Geiger (source: adapted from Peel et al., 2007, fig. 8)
Plot on psychrometric chart of the climate of Copenhagen, Denmark (c) and Athens, Greece (d). The figures are adapted from Climate Consultant chart (Ligget & Milne, 2011), with weather data obtained from DOE (2013)

Orientation

The orientation of the building is significant for the behaviour of the building. It determines the azimuth and altitude angles of the sun to the façade and the intensity of solar irradiance. This is particularly important for design principles throughout the year, not only for passive solar use, but also to avoid overheating. Besides, depending on façade orientation the period that it receives direct sunlight changes (Hausladen et al., 2008).

In existing buildings, however, the orientation poses an additional challenge in implementing environmental design principles. The orientation is given and cannot be changed, as in the case of new construction. For example, green building standards like Passive and Active house that are based largely on passive solar heating, are not as easily implemented as in new houses. This fact acknowledged, it is still possible to design highly efficient refurbishment strategies, as long as the specific orientation is considered and adequate measures are taken. Supporting this kind of decisions is one of the objectives of the present thesis and is going to be further elaborated in chapters 5 and 6.

Construction of the building envelope

The building envelope is the most influential components with regard to energy consumption (3.2.2) and, as such, it should be the main target for energy saving measures. Besides, it is the component that mostly suffers from physical problems, as it is confronted with the external conditions and has a shorter life span than other components, the structure for example (Brand, 1994). Investigation of the building stock found 80% of the damages to be related with the building envelope (Andeweg et al., 2007).

The design, condition, and construction of the existing building define the potential improvement on energy demand. Characteristics such as the original thermal transmittance of building envelope components (wall, window, roof, basement), the openings proportion and the balcony location and size are influential on the energy reduction after refurbishment (Konstantinou & Knaack, 2013). Moreover existing envelope thermal performance is responsible for the current energy demand.

Openings' proportion to the opaque component also referred to as window-wall ratio (WWR) is an important attribute of the building envelope and it is determined by the original design and construction. Apart from the architectural and functional aspects, windows size influences the energy demand, as it determines the solar radiation that enters the space. Moreover, windows is the component with the poorest thermal performance, particularly in existing buildings; hence, the largest the area of windows the more heat losses. During refurbishment change this ratio to fulfil the new requirements and change the existing appearance can be part of the strategy, but it is not possible in all cases, depending of the structure or other parameters.

Apart from the energy saving potential, the existing construction of the building envelope, together with the load-bearing structure, is important for the feasibility of the measures. It extra weight is added, such as a new balcony suspended from the existing structure, the condition and size needs to able to bear it. Furthermore, if a component has to be replaced or windows to be enlarged, the components removed must not be loadbearing. Even in the case of insulation addition, the existing wall has to be checked for moisture. Solutions are available, but it is important to check the existing construction and, therefore, it is an additional challenge in the decision-making and design.

§ 3.5 Conclusions

There are several motives to reconsider the existing buildings. They can be technical, functional, economic and social reasons. However, when looking at the bigger picture, refurbishment of the aging residential building stock is connected with sustainability. Energy is an important aspect of sustainability, as it was defined by WCED (1987). Moreover, refurbishment is ecologically, economically and socially relevant.

To further discuss how refurbishment can improve the performance of the buildings and contribute to energy savings in the building sector, the environmental performance of buildings needs to be defined. Environmental performance is the environmental impact of the building fabric and building operation (EN15643-2, 2011). It is therefore related to the comfort and function of the occupants, as the building needs energy in order to meet the demands. Energy is also needed in the production and end of life stage of the building. Therefore, energy used throughout its lifetime is part of the environmental impact of a building.

Due to the growing concern of public, authorities and designers on environmental issues, several methodologies and certificates to predict and prove a buildings performance have been introduced. Energy performance certificates with benchmark requirements have been implemented in regulations for new and refurbished buildings. Voluntary certificates, such as performance standards of passive house or life cycle assessment of BREEAM and LEED, have also been developed. The performance evaluation methodologies aim at promoting and supporting the design and use of efficient buildings. Hence they are very relevant to this thesis, whose objective is also to support the design of energy efficiency upgrades.

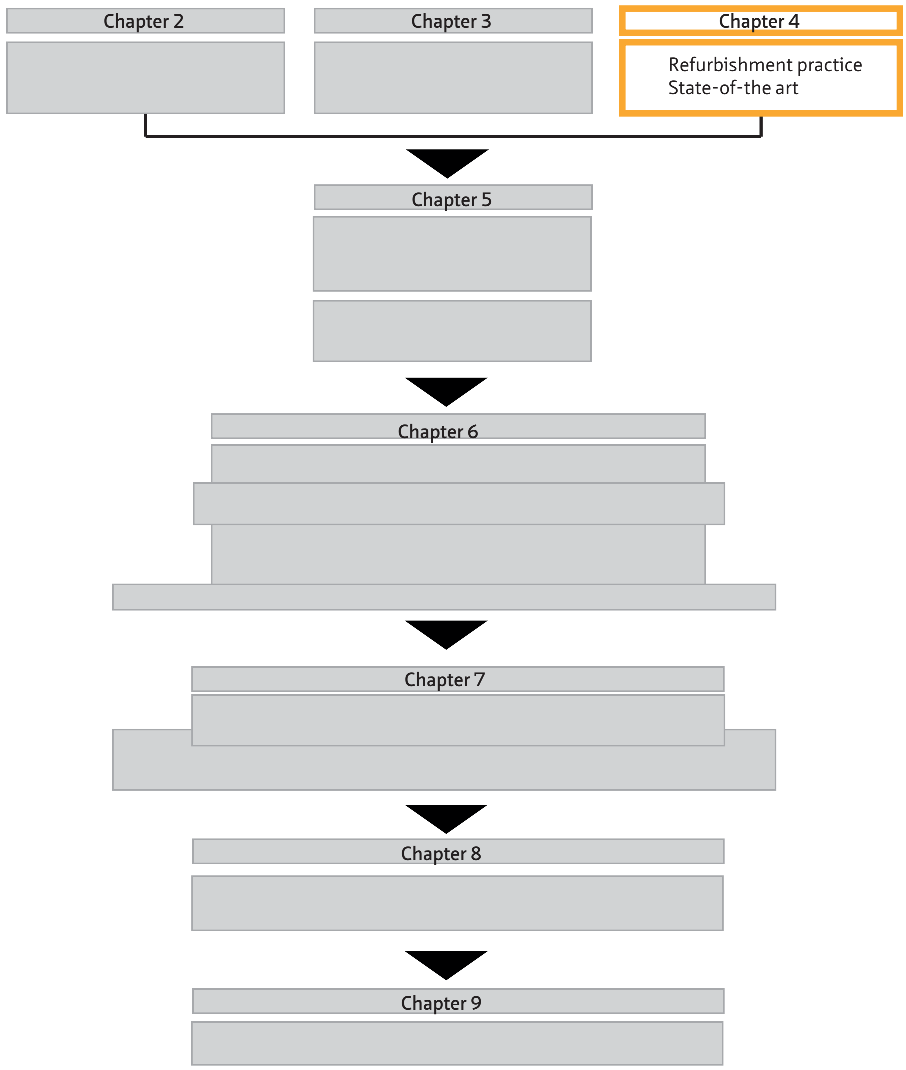
Discrepancies between predicted and actual energy consumption are unavoidable, mostly due to different usage patterns that the theoretical assessment anticipated. These methodologies can be seen more as an indication of building characteristics, rather than precise predictions. Nevertheless, they are an important step towards energy and environmental conscious design and have to be used and considered from designers and stakeholders to shape the refurbishment strategy.

To achieve the desired upgrades and create buildings that provide comfort with less energy, environmental design principles must be applied. According to Trias Energetica, there is a hierarchical approach of sustainability. Firstly, prevent the use of energy (prevention); then, use sustainable energy sources as widely as possible (renewable); finally, when there still remains an energy demand, use fossil fuels as efficiently as possible (efficiency). These principles can be applied both in new and refurbishment design. The climate is an important parameter defining the principles choice. Existing buildings pose some additional challenges as the parameters of orientation and construction is already given and need to be considered.

Within the Trias Energetica concept, passive and active measures can be taken during the retrofitting of dwellings. Passive are the principles exploiting the design and properties of the building envelope to minimise or maximise the heat losses and heat gains respectively, reducing the energy demand (step 1). In addition, systems for conditioning the building such as heating systems and solar power technologies (active measures) are used to produce (step 2) and distribute (step 3) the energy needed to achieve comfort of the occupants.

It must be highlighted that those steps are complementary to each other and they should all be considered in a refurbishment strategy. The present research focuses on the first step, which is reducing the energy demand in existing buildings. This can be primarily by applying the passive environmental design principles to building envelope upgrade. The active measures will then cover the remaining demand using as little non-renewable primary energy as possible, pre-requiring high efficiency and the use of renewable sources.

In the next stages of the research, an approach to incorporate those design principles and challenges into the refurbishment design process is developed. The first step to the approach development, which is the systematic organisation of possible refurbishment measures, will be elaborated in Chapter 4.


Chapter 2
Chapter 3
Chapter 4
Refurbishment practice
State-of-the art
Chapter 5
Chapter 6
Chapter 7
Chapter 8
Chapter 9

4 Building Envelope Refurbishment: Current Practice State of the art

Building industry is busy with refurbishment projects. The purpose of the current research is to support this process and enable effective choices, resulting in reduced energy consumption while maintaining high functional, architectural and comfort standards. To achieve that, it is necessary to combine existing practice of the building industry with specialised knowledge on upgrading the efficiency of the building stock. The previous chapters provided an overview of residential buildings' condition and problems, as well as principles that can be applied to achieve an improved the environmental performance of the buildings. This chapter discusses the state-of-the-art of refurbishment practice. In this way, the theoretical framework to the approach's development is set. The state of the art is presented in this chapter in terms of refurbishment strategies and how they can be grouped in strategies (4.2), materials that are used in refurbishment projects (4.3), and components' retrofitting measures (4.4) to refurbish the buildings envelope.

§ 4.1 Introduction

Refurbishment is an acknowledged issue in building construction practice. In the Netherlands for example, the total turnover of major repairs, renovation, adaptation and redevelopment accounts for beyond that of new construction (Thomsen, 2010). Already since late 90's (Genre, 1996), refurbishment activities represented 39% of construction sector revenue in EU and the figures were considered to represent the general tendency to come. In 2001, it represented around 50 % in large European countries (Flourentzou et al., 2001). This means that the building industry, including architects, constructors, material manufacturers etc., is already busy upgrading existing buildings. Given the task, the façade, and the building envelope in general, is the building component most widely addressed. Along with functional improvements and internal layout modifications, most refurbishment projects include retrofitting least parts of the building envelope.

The facade of a building is the main element of its architectural expression and the key feature of its existence, as it characterises the building and make it conceivable both from inside and outside. What is more, the façade plays a key role not only in the form and appearance of the building, but also in its performance, in terms of optimized energy use and indoor climate. Regarding the energy consumption of building stock, where the energy demand for heating is predominant, the facade constitutes undeniably an integral part of its environmental impact. The energy consumption for the heating of buildings is directly related to the heat losses through the building components and to losses through ventilation and air infiltration and inversely related to the heat gains in the buildings through sun radiation (McMullan, 2002), all parameters that depend on the quality and function of the external building envelope.

In spite of the importance of the façade for sustainable, comfortable and desirable living environment, the façades of the existing- and aging- building stock often fail to fulfil successfully their function. This can be due to technical deficiencies either created at the time of construction or, even more, emerging as building component approaching the end of their lifetime. Buildings suffer from a variety of physical problems (Chandler, 1991). A lot of these are connected with the external envelope. Taking into account that the expectation for the structural life of a building would be at least 60 years while the envelope and would show signs of obsolescence after only 20 or 30 years (Brand, 1994), it is understandable why building stock facades are in need for refurbishment.

To integrate the environmental performance into façade refurbishment strategy design, which is the objective of the thesis, it is necessary to provide information of the effect of possible solutions. In this way, the designer will be able to compare options and make informed decisions. The first step to enable the evaluation of the different measures is to systematically compile and organise them, according to the building envelope component they address.

Integrated refurbishment

Deep renovation with energy savings between 60% and 90% is necessary to reach the decarbonisation targets for 2050. Superficial renovations, on the other hand, significantly increase the risk to miss the climate targets and huge absolute savings to remain untapped (Hermelink & Müller, 2011). A deep renovation typically adopts a holistic approach, viewing the renovation as a package of measures working together, as oppose to moderate renovation, involving 3-5 improvements resulting in energy reductions the range 30-60% .

The building envelope becomes the most critical part when it comes to energy efficient building, both for new construction and refurbishment. Research (Míguez et al., 2006) have specify that the building envelope has to reach depth of refurbishment beyond 70%, in order to reach the European 2050 decarbonisation targets (Ad-Hoc, 2012). The significance of the building envelope is justified, as the energy consumption is directly related to it. Hermelink and Müller (2011) based on the pilot initiative "Low Energy Building Stock", included measures such as insulation of wall, roof and cellar ceiling, upgrade of the windows, elimination of thermal bridges, installation of thermal collectors and ventilation system.

Nemry et al. (2010) identified the contribution of the single construction elements to the environmental impacts of the use phase (total primary energy) according to climate zone and building types in Europe. The study analysed the impact of ventilation, windows, roof, exterior wall and basement. The results showed that, along with ventilation, heat losses through roofs and external walls important for a majority of single-family and multi-family houses. In high-rise buildings, the relative importance of heat losses from external walls is a significant. On the contrary, roofs are of lower importance in the case of high-rise buildings, as a result of lower share of roof to total building envelope surface and higher insulation level of the component. For single-family and multi-family houses, the heat losses through windows are lower, first, because the corresponding surfaces involved are lower than high-rise buildings.

The renovation strategy should integrate different building components; thus, it is referred to as integrated refurbishment strategy. The key components to achieve an integrated refurbishment that improved the energy efficiency are the components where heat losses that increase energy demand are happening. This is the external walls, windows, balcony, roof, and ground floor, comprising the thermal envelope. Thermal envelope is the enclosing components of the occupied and heated spaces. Defining the thermal envelope is important in order to understand where heat losses are occurring, since the components are adjacent to spaces with temperature difference. The thermal envelope does not always coincide with the building envelope, as it depends on the spaces design and function. For example, in the cases (a) and (b) of Figure 4.1, the thermal envelope is different, even though the building envelope is the same. This is because in building (a), the basement and the loft space are not heated. Thus the heat from the conditioned space is transferred through the first floor slab and the top floor ceiling and this is where measures to prevent this heat loss should be applied.

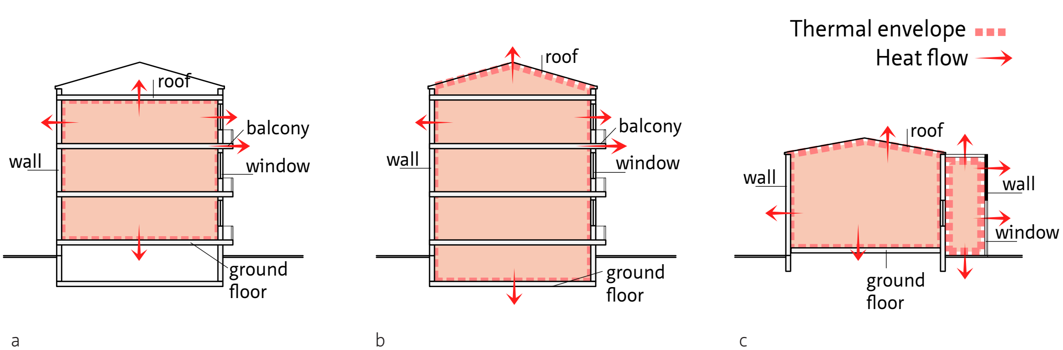


Figure 4.1
Examples of the thermal envelope, defining the building components where heat flow occurs.

Chapter outline

The thesis presents solutions to upgrade the building components that result in an integrated refurbishment strategy. The present chapter sets off to give an overview of current refurbishment practice and state-of-the-art solutions used in upgrading the building envelope of existing buildings. When designing a refurbishment strategy, the second step after investigating the current condition of the building is to look at possible options, in order to decide which measures are suitable for the existing problems and requirements. Hence, this overview of refurbishment measures is a necessary step in order to answer the research question, which is to provide decision support of the effect of refurbishment options.

There are three levels of decisions related to the choice of solution to upgrade each component: refurbishment strategies, material and component retrofitting measures. This overview presents and interconnects these levels. Firstly, the strategies are classified according to the type of intervention. Secondly, materials that are mostly relevant to refurbishment and subsequently the measures that the materials are applied are discussed. In the components' retrofitting measures section, the possible solutions are organised according to components of the building envelope, which are the external wall, windows, balconies, roof and basement. It needs to be clarified that, because the discussion covers a wide range of cases, the thermal envelope, as defined before, is further referred to as building envelope. Measures such as insulation of the first floor slab and the top floor ceiling are included in the retrofitting of roof and ground floor respectively. Similarly, measures that create extra space adjacent to the external wall and extend the thermal envelope, as the example (c) in Figure 4.1, are groups with wall retrofitting measures.

Regarding the material, while the overview is by no means exhaustive, it approaches materials from the perspective of passive design principles, discussed in section 3.3.1. The analysis of materials used in refurbishment precedes the retrofitting measures, as it is possible to use the same material in multiple measures. For example, insulation materials are used both for wall and for roof insulation, while glazing technologies are applied not only in windows but also balcony cladding or second façades construction. On the other hand, for the same measure, e.g. wall insulation, different materials are applicable and the choice varies in each specific case, based on the material properties, price, ease of application, or even environmental consideration, such as the embodied energy. For this reason, the chapter makes a separation between the measures to retrofit building envelope components and the material applied. In reality, those decisions are not necessarily separate and depend on the specific project. The relation between strategies, materials and measures for wall, window, balcony, roof, and ground floor is given in Table 4.6, Table 4.7, Table 4.9, Table 4.10, and Table 4.11 respectively.

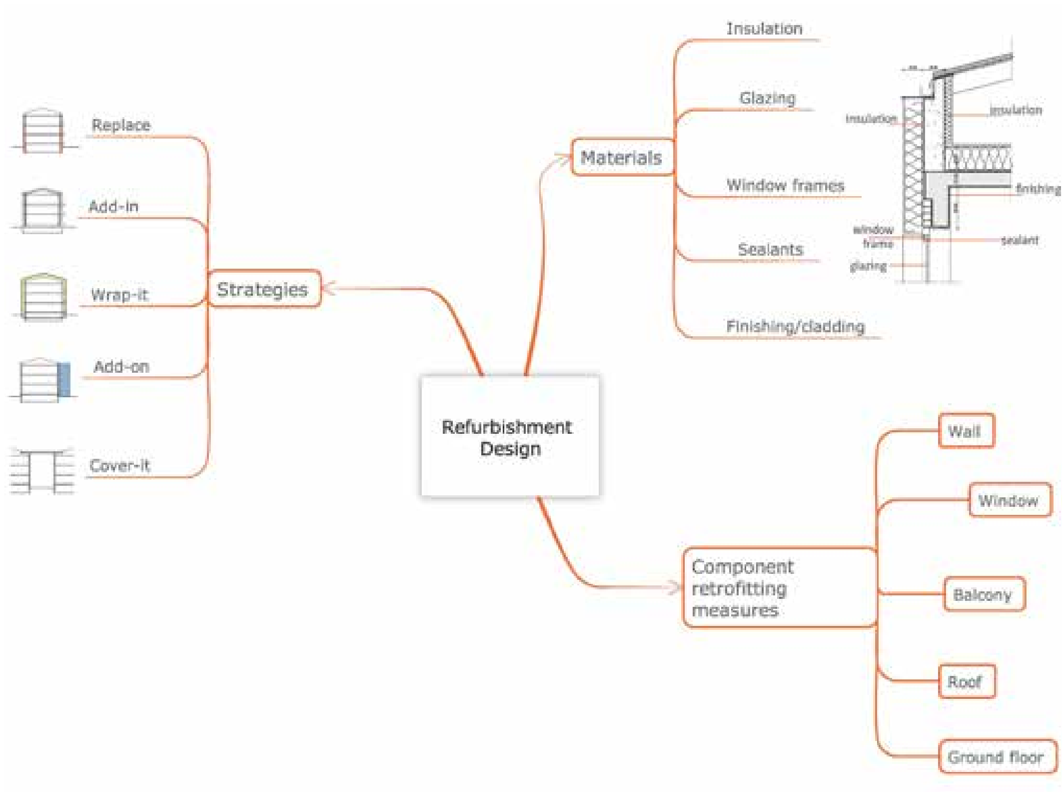


Figure 4.2
The schematic representation of the three decision levels composing the solution for each component, resulting in an integrated refurbishment design.

§ 4.2 Strategies – example projects

The building stock is confronted with various physical and functional problems and the building industry is busy trying to deal with these issues. There are a wide variety of refurbishment projects using strategies to address the shortcomings of each building and the specific requirements of each project. When considering common, state-of-the-art refurbishment strategies and examples, certain categories of intervention can be identified. Given the diversity of options, those categories represent a systematized approach to an overview of refurbishment strategies.

This section gives an overview of refurbishment strategies, as presented in Table 4.1. Refurbishment solutions can be grouped according to the way building components are replaces, upgrades or added and their result on the building envelope performance. The different strategies can be executed with different ways, but similar characteristics generally underlie the principal concept. It is also possible to encounter a combination of intervention categories. The list of strategies cannot be exhaustive, as design possibilities are limitless. The purpose of the overview is not to present all possibilities, but categorise them by identifying the basic principle and highlight benefits and limitations in each case, in order to help deciding on the type of intervention, which is a first important step to shape the refurbishment solution.

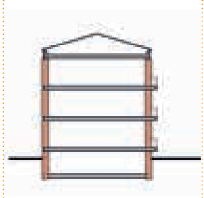
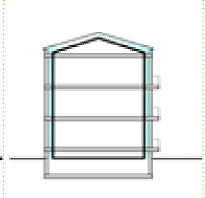
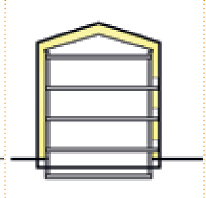
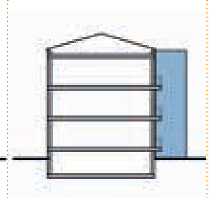
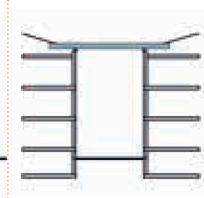
	Replace	Add-in	Wrap-it	Add-on	Cover-it
					
Description	Old façade elements removed and replaced with new ones	Upgrade from the inside	'Wrapping' the building in a second layer	New structure is "added on" to the existing building	Cover parts or entire internal and external courtyards and atria
Intervention-variation	Replace the entire façade Replace parts	Internal insulation Cavity insulation Box window	External insulation, Cladding of the balconies Second skin façade	Small intervention, such as adding new balconies New building as an extension Additional floor	Cover parts or entire Heated or unheated space
Benefits	New components with better performance Eliminate the physical problems	Adequate for monumental status Increase the thermal resistance	Solve thermal bridges Increase the thermal resistance Different cladding possibilities Little disturbance	Out-dated façade no longer exterior New façade with performance Increase space Functional benefits	Create thermal buffer Enhance natural ventilation with stack effect Out-dated façade no longer exterior Additional space
Limitations	Great impact on users Higher costs	Critical connection thermal bridging need attention Big disturbance for users	Not applicable to monumental buildings Possible space limitation	Needs to be combined with other strategies for facades non-adjacent to new structure Structural limitation	Not applicable to all cases Depending on layout and function of the building Overheating risk

Table 4.1

Refurbishment strategies according to type of intervention in residential building refurbishment

§ 4.2.1 Replace

Replacement of a façade is a common approach to upgrade a building. In this case, the old façade elements will be removed and replaced with new ones. The façade elements to be replaced can range from the entire façade or parts of it. The benefits of the strategy is that new, adequately performing components replace the old components, eliminating the physical problems of the aging components and providing better thermal and acoustic comfort.

If the entire original façade is removed, new products can be used for the new façade elements. All opportunities are open for a new building skin to comply with current building physical, technical and design requirements, like the examples of Figure 4.3. Also, the inner layout and the building services can be entirely renewed and redesigned to meet the new demands.

"Replace" strategy can be applied to several types of buildings, various types of perforated façades or façade panels to curtain walls. Curtain wall structures are particularly interesting for replacement, as new façade units can be prefabricated and installed relatively easily. The costs for the solution depend on the level of intervention and the materials used. Generally, the costs for a complete renewal are higher than for simply improving parts of the façade; but it constitutes but it can possibly have a longer life span. The condition of the existing components and the loadbearing structure are important consideration, concerning this strategy application.

Figure 4.3

"De Valk" apartment block, Apeldoorn, the Netherlands (Image source: courtesy of SOLARLUX Nederland BV). The architectural firm Groosman Partners designed the refurbishment for maximum contact with the exterior and the environment; light flooded living spaces, a new transparent look and low energy consumption were high on the list of demands. The existing façade was replaced with folding and sliding window frames for the living rooms as well as the bedrooms to allow maximum contact with the outside environment.

A shortcoming of the replace strategy is that, even though the performance of the component is improved, critical connections and thermal bridges may need extra attention. Moreover, the impact on the users will be significant, because the existing elements have to be removed and the new elements need to be attached to the structure. It is preferably applied when a building is already empty, either because of a long-term vacancy or during a change of tenant. Otherwise, the occupants might need to be relocated during the building period. Optimal logistics can help to minimize this problem as the construction and, thus, the disturbance can be reduced.

§ 4.2.2 Add-in

A common practice, especially in case that the building exterior impression should not be changed, is upgrading the façade elements from the inside. If a building is listed under monument protection, for instance, we need to consider improving the interior façade surface rather than the exterior. Insulation can be added to the internal side of the external walls, to improve the thermal performance of the façade and comply with current standards. The wall upgrade is often combined with replacement of windows, or secondary glazing, if windows cannot be replaced.

An important limitation of improving the envelope from the inside is that it doesn't solve thermal bridging. Critical connections at the edge of the slabs, balconies, window sills etc. need additional attention. Furthermore, since the construction works take place in the interior, there is big disturbance caused for the occupants, similarly to the "replace" strategy. Finally, the insulation is using up interior space, reducing the usable space.

In case of cavity walls, a variation of the "add-in" strategy is additional insulation in the air cavity between the wall leafs. The insulation is applied from the outside, eliminating the problem of the disturbance and the use-up of space. However, critical connections still need attention and the improvement of thermal performance is limited to the width of the cavity.


a


b

Figure 4.4

Renovation of Koningsvrouwen van Landlust in Amsterdam – Eigen Haard (Image source: courtesy of DeGroot en Visser, façade construction). The building was built in the 1930's and it is currently listed as a monument. The original steel framed windows had already been replaced with double-glazed windows in the 80's. However their performance was not sufficient, nor was the architectural quality, which was far from the original slim, steel profiles. For this reason a new system with a sightline of only 5 cm was developed to replace the windows. The system is highly insulated with an Uf=1.93 W/m^{2}K. The windows are structural glazed to be able to use a single sightline. There was a special coating applied with a steel look and twinkle. The window replacement was coupled with the application of internal insulation.

§ 4.2.3 Wrap-it

This strategy suggests 'wrapping' the building in a second layer. This second layer can consist of external insulation, cladding of the balconies or even a second façade. If there are no restrictions for the building design and the original façade provides sufficient structural integrity, the building envelope can be upgraded from the outside. This concept includes adding insulation and a new cladding and it is often coupled with replacing some components, e.g. the windows.

The main advantage compared to other strategies is that thermal bridging is solved along with increasing the thermal resistance of the envelope. Compared to complete replacement, the interventions from the outside are less intrusive and disturbing for the occupants, who don't need to vacate the building during the time of construction, like in the examples of Figures 4.5 and 4.6. Moreover, it is possible to gain extra living space, for example in the case of balcony cladding or a second skin façade. Different cladding materials can be used to renew the building's appearance. In the case of a second façade, the dimension can range from a few centimetres to several meters. It can cover the entire existing façade or a portion of it. The thermal barrier of the building will be shifted from the existing structure to the new façade. This will give the inside an entirely different climate and a buffer-zone will be created between the existing façade and the second façade.

a

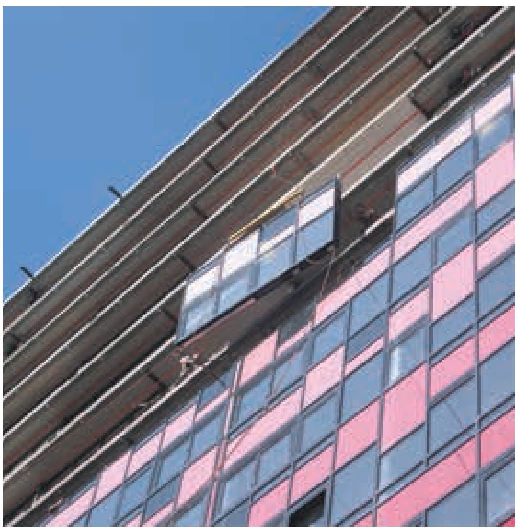
b

Figure 4.5

Renovated Urbanplannen apartment block, Copenhagen, Denmark (Image source: courtesy of JJW Arkitekter). The exterior wall was insulated from the outside with Rockwool insulation boards and cladded with cement fibre and glass panels.

a

b



c

d

Figure 4.6

(a) Existing, (d) renovated Torenflat and (b), (c) mounting phase, Zeist, the Netherlands (Image source: courtesy of Kremers Tilburg BV, Frowijn de Roos Architecten). The existing balconies were cladded with a new façade consisting of prefabricated, aluminium framed façade panels, combining transparent and opaque elements, with improved thermal performance. The new façade is hanged in front of the existing balconies, solving thermal bridging as well. To minimize the inconvenience of residents during assembly, the existing mounting holes of the removed balcony railings were used to anchor the façade. The number of newly drilled holes (noise pollution) was thus reduced to a minimum. The façade elements were prefabricated and finished at the factory and subsequently mounted horizontally and vertically during assembly on site.

§ 4.2.4 Add-on

When extra space or additional function is required, a new structure is "added on" to the existing building. The add-on concept can vary from small intervention, such as adding new balconies, to a whole new building as an extension to the existing one. Structurally, there are several options to realize this extension, for example by creating a secondary structure in front of the building or suspending the extension in front of the existing structure.

Extension of the building, apart from the additional floor area gained, may add other benefits to the building. With the extension constructed, the old façade is no longer part of the building envelope, while the new façade is built to comply with the requirements for improved environmental performance. The climate can be improved because of the new façade options and the possibility to include extra installations in the extension. The technical problems, such as thermal bridges, will be improved as well because of new and better connection solutions. This strategy should be combined with the previous concepts for those parts of the building envelope that are not connected with the new extension.

This intervention will have a great impact on the residents because parts of the old façade have to be removed and intelligent connections have to be created to connect the extension. This makes the execution of this concept quite difficult, but not impossible. One critical limitation can be the additional area of surrounding space needed.

An alternative approach to add-on strategy is the construction of an extra floor. In this way additional usable space is constructed, despite the luck of available space in the plot. The benefit in terms of energy performance is heat losses through the current top floor are eliminated, while the new top floor is constructed with adequate thermal resistance.

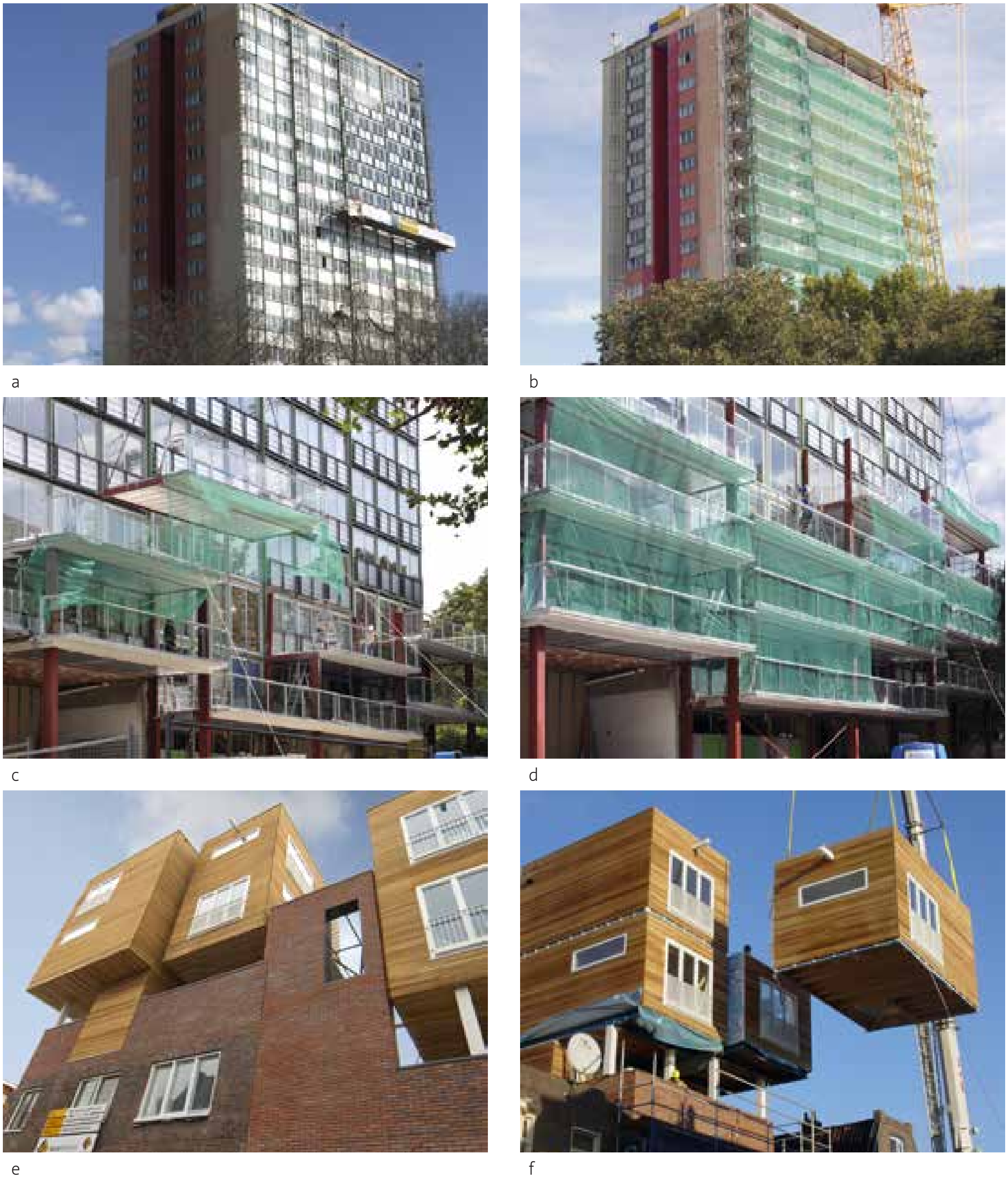


Figure 4.7
(a)-(d)The addition of new balconies in the Transformation of Tour Bois-le-Prêtre, Paris, France (source: courtesy of Druot, Lacaton & Vassal).
(e), (f) Lighthouse in Groningen, the Netherlands (source: courtesy of DAAD Architecten). Prefabricated wooden boxes were placed on top of the existing construction. In this way, new space is created, to address the issue of limited space in the city centre.

§ 4.2.5 Cover-it

A strategy to upgrade existing buildings is to cover parts or entire internal and external courtyards and atria. They are mostly covered with transparent elements to allow visual contact with the exterior and to increase heat gains. This strategy has great impact on the architectural appearance, the surrounding area and the building itself. It can also add functional space and it changes the relation between inside and outside. This solution is not generic because not every building is suitable for this intervention. The shape of the building is an important criterion for this strategy to work as a refurbishment possibility.

Potential insufficient thermal performance of the old façade and other problematic details do no longer pose a problem, because the heat transfer between occupied and new interior space, created where the courtyard was, is reduced. The new space may be heated or rely on solar heat gain. In both cases, adequate shading and ventilation are required to avoid overheating. This strategy should be combined with the previous concepts for those parts of the building envelope that are not adjacent to the covered space.

a

b

Figure 4.8
(a) Oosteserre construction in BK City, TU Delft, the Netherlands (Image source: courtesy of Photo Hans Schouten)
(b) Het Sieraad, Multifunctional centre, Amsterdam, Architect: O III (Image source: courtesy of BRS Building Systems BV)

§ 4.3 Materials

After looking at interventions to upgrade the building envelope and organising them into refurbishment strategies, the next question is how this strategy is possible to be realised and materialised. The choice of materials is not always easy, as they need to fulfil a range of criteria, connected with performance, processing, installation and ecological aspects. For this purpose the current section discusses the materials that are possible to be used in building components upgrades and gives an overview of their characteristics. Since the research scope is the building envelope energy upgrade and not refurbishment and conservation in general, the materials in this section and the retrofitting measures in the following section are presented from the perspective of the energy saving measures, as discussed in the previous chapter. Materials used to repair damages of the loadbearing structure- such as wood or steel components to reinforce old timber frame construction (Giebeler, 2009)- or deterioration of components, such as mortars for repointing of masonry walls, are not highlighted. The application however with measures that serve the structure and façade preservation is possible to be combined with the energy upgrade.

Material	Description	Design principle	Variations	
Insulation	Material with high thermal resistance that opposes the transfer of heat between areas at different temperature	Heat protection	Insulation from organic material Insulation from mineral material Insulation from oil Other high performance thermal insulation materials and solutions	
Glazing	Transparent material provides visual connection daylight	Heat protection Passive solar heating Sun protection	Insulated glazing Low-E coatings Chromogenic glazing	
Window frames	Components for fitting and operation of glazing	Heat protection Ventilation	Timber Timber/aluminium Aluminium Steel Plastic (uPVC)	
Sealants	Materials used to seal the building's fabric and prevent uncontrolled air and water flow	Heat protection/air-tightness Weather proofing	Membranes Expanded foam Gun-applied Tapes Fillers	Silicone Polysulfide-based Polyurethane MS polymer
Finishing-Cladding	Material of the final rendering, give final impression	Protect the construction underneath Heat protection/air-tightness	Plaster and renders Plasterboards Finish topcoats Photocatalytic interior paints	Phase change material (PCM) Cladding panels

Table 4.2
Overview of material used in the building envelope energy upgrades

The materials discussed in the thesis are related with passive design principles, as presented in Table 4.2. Insulation materials and multi-pane glazing are the most essential constituents for the envelope to prevent heat transfer. Glazing is also important for solar gains, which influence the buildings energy demand. Moreover, the window-frames detailing, the use of sealants and the finishing materials are important for ventilation, airtightness and weatherproofing. Each refurbishment solution normally uses more that one of the aforementioned materials, along with others, e.g. fixing apparatuses, that are not described in detail in the thesis, as their role is rather complementary than serving the passive design principles.

§ 4.3.1 Insulation

An insulator is a material with high thermal resistance that opposes to heat transfer between areas at different temperature (McMullan, 2002). The insulating effect of a material is based on the low thermal conductivity of enclosed air. There is a potentially bewildering array of insulating materials to select from (AEA, 2010; Giebeler, 2009; greenspec, 2013b; Lyons, 2010; Papadopoulos, 2005). They range from the familiar polystyrene and mineral wool through to alternatives gradually establishing themselves in the market such as sheep-wool and hemp. Besides the thermal and moisture related properties, the choice of material is determined by fire resistance, sound insulation and compressive strength considerations, cost, suitability and ease of installation (Giebeler, 2009; Thorpe, 2010),. An additional consideration for thermal insulation selection is that materials chosen are environmentally friendly themselves and do not contain or release pollutants, either resulting from the production process or due to their chemical composition (Knaack, Hildebrand, et al., 2012).

Depending on their make-up they are subdivided into fibre foamed and granulate or loose fill insulation (Hausladen et al., 2008). Different forms of insulation are adequate for different applications. Loose material, for example, is well suited to be inserted between wooden posts and beams (e.g. in ceilings) – or, more generally, in any structural hollow space. There is no loss of material and all cavities can be filled. Insulating panels or matting are cut to size and can then be accurately installed. Rigid foam insulation boards are appropriate for external applications, due to higher impact strength.

Insulation materials can also be grouped according to provenance (greenspec, 2013c). They are classified into inorganic/mineral or organic types according to their raw materials. Moreover, insulation technologies can be artificially manufactured, such as the vacuum insulation panels. Table 4.3 presents typical insulation materials organised according to their origin. Additional information about specifications, form and applications are also given.

Insulation from organic material

Insulation materials made of organic, renewable resources have been produced for several decades. Primarily, they consist of vegetable and animal fibre as well as granulate from vegetable components (rye, cork). Due to their technical and building physical properties, different insulation materials are suited for different applications. Depending in the application, the insulation material comes in different forms of delivery, including loose, matting and panels. The insulation materials made of renewable resources currently on the market have building inspectorate approval, i.e. they have proven their usability and applicability as defined by national building codes, just like the conventional products. The fibres most often used to produce insulating materials made of renewable resources are: Flax, hemp, wood, wood shavings, cellulose, sheep's wool as well as grass, seaweed and reed. In addition, granulates from rye or cork are used (fill and blow-in insulation) (Knaack, Hildebrand, et al., 2012).

Insulation from mineral material

Mineral insulation is a highly versatile product. The main advantage in comparison of other insulation types lies in high recyclability and fire resistance. The insulation materials come in forms such as mineral wool, foam, and loose-fill, with a wide range of application in building constructions. Mineral wool insulation is made from molten glass, stone or slag (industrial waste) that is spun into a fibre-like structure and which creates a combination of properties that no other insulation material can match. The most common types of mineral wool product are glass and stone wool insulation. Stone wool is made from volcanic rock, typically basalt or dolomite, an increasing proportion of which is recycled material in the form of briquettes. Mineral wool made from blast furnace slag (waste) is sometimes known as slag wool. Glass wool is made from sand or recycled glass, limestone and soda ash; the same ingredients as for familiar glass objects such as window panes or glass bottles (EURIMA, 2011).

Apart from mineral wool, foamy mineral insulators exist. Mineral foam, in the form of boards or cast in-situ, is a cost-effective material of mineral substances to upgrade the thermal resistance of the building envelope. Cellular or foamed glass is formed from a reaction between glass and carbon at high temperatures and has a cellular structure, which is impermeable. This makes it ideal as a barrier against soil humidity (AEA, 2010). Perlite is another mineral originated insulator, which comes in form of loose fill. It derives from siliceous volcanic rock, expanded by 4–20 times of the original volume, when heated above 870 °C (Sengul et al., 2011). This physical transformation makes expanded perlite an extremely efficient, low-density insulator (Perlite Institute). The resulting granular product is lightweight with countless tiny, sealed air cells, which account for its excellent thermal performance.

Finally, one of these new promising high performance thermal insulation materials for possible building applications (Baetens et al., 2011) are aerogels. They have extremely low densities (up to 95% of their volume is air), large open pores and a high inner surface area. This results in interesting physical properties, for example extremely low thermal conductivity and low sound velocity combined with high optical transparency (Hüsing & Schubert, 1998). Silica aerogels, which are the most common type, are an innovative alternative to traditional insulation due to their high thermal performance, although the costs of the material remain high for cost-sensitive industries such as the building industry. Research is continuing to improve the insulation performance and lowering the production costs of aerogels (Baetens et al., 2011).

Insulation from oil

The insulation materials derived from petrochemicals mostly have foamy texture and come in form of prefabricated boards. Their main advantage is high compressive strength and water resistance. On the other hand, their raw material is petrol, causing resource depletion and pollution risks from oil and plastics production. The embodied energy in those materials is also high. The main oil-derived insulation materials used in buildings applications are polyurethane foam, expanded polystyrene, and extruded polystyrene.

Polyurethane foam is a closed cell thermoset polymer. It can be applied as rigid foam, blown with CFC-free gas (generally HFCs, CO_2 or pentane), or as prefabricated products that have been moulded into discrete shapes. This product can be used as cavity wall insulation or as roof insulation, floor insulation, pipe insulation and industrial applications. Expanded polystyrene (EPS) is a rigid cellular form of polystyrene, with an open cell structure. It is a thermoplastic polymer, so can be reprocessed and recycled more easily than thermoset polymers. Building and construction applications account for around two-thirds of demand for EPS: loose beads are used for closed cavity walls, roofs and floor insulation and boards can be produced by fusing beads together. Pentane is used as a blowing agent. Extruded polystyrene (XPS) is also a thermoplastic polymer, however it has a closed cell structure and is often stronger, with a higher mechanical performance and is, in principle, often more expensive than EPS.

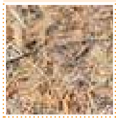
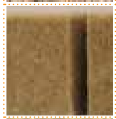
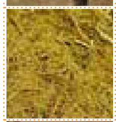
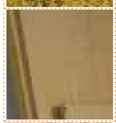
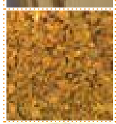
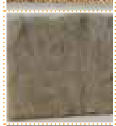
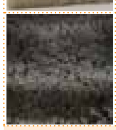
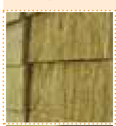
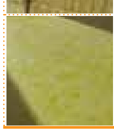
Other high performance thermal insulation materials and solutions

Vacuum insulation panels (VIPs) are regarded as one of the most promising high performance thermal insulation solutions on the market today (Baetens et al., 2010). The evacuation of air increases the insulating effect of the material because heat transport by convection and conduction is almost completely suppressed. Vacuum insulation panels (VIPs) have a thermal resistance about a factor of 10 higher than that of equally thick conventional polystyrene boards. In principle, a VIP is composed of a core of microporous material and an envelope. The core material is a load-bearing material that is inserted between the evacuated walls of flat panels in order to prevent them from collapsing (Fricke et al., 2008).

Vacuum insulation panels (VIP) are very thin. A centre U-value of 0.2 Wm^2K can be achieved for a VIP thickness of only 2 cm (Fricke et al., 2008). They are particularly advantageous in refurbishment projects, due to their minimal space requirements. From an economic point of view, even though they combine very good insulation values with modest layer thickness, they are expensive (Hausladen et al., 2008). “Vacuum insulation panels (VIPs) are currently quite expensive-in the order of 320 euro/m^2 for panels with a U-value of 0.15 W/m^2K compared to 32 euro/m^2 for fibre or solid-foam insulation. However the VIP is 8cm thick, compared with 30cm for the alternative” (Harvey, 2006). Thus, the additional cost needs to be balanced against a considerable gain in space.

Transparent insulation materials (TIM) are a class of products that make use of particular materials to enhance the solar heat gain, whilst reducing the heat loss by conduction and radiation (Smith, 2005, p. 77). A U-value below 1 W/m^2K and an energy transmittance greater than 50% characterize combine the advantages of opaque insulation and solar collection. TI materials’ physical properties increase the efficiency of thermal conversion of solar radiation, particularly in winter, when low elevation solar irradiance on vertical surfaces can be used effectively (Braun et al., 1992, p.431).

Research and development of transparent insulation systems (TI-systems) has been ongoing for 20 years. Different types of materials, such as, plastics, glass and aerogels, have been used to produce TIMs. The type and performance depends on the geometrical layout of the materials, often comprising parallel slat arrays, honeycombs or capillaries. Application in to building facades has shown that the material can provide approximately 100–200 kWh/m^2 year of solar energy gains, resulting in a financial return to building occupants when applied, without compromising thermal comfort within buildings (Wong et al., 2007).

	Insu-lation material	Density ρ (kg/m³)	Thermal conduc-tivity λ (W/mK)	Water vapour diffusion resistance index μ	Fire resistance class Euroclass	Forms available	Applications	Insulation thickness for U-value 0.2 W/m²K	Embo-died Energy MJ/kg
Organic									
	Flax	20-50	0.038-0.045	1-2	E	Batts, blown material, loose fill	exterior wall, cavity, ETICS, floor, loft, roof	18-20 cm	11-30
	Hemp	20-50	0.038-0.045	1-2	E	Batts, blown material, loose fill	exterior wall, cavity, ETICS, floor, loft, roof	18-36 cm	10.5-33
	Wood fibres	150-250	0.040-0.081	2-5	E	Boards, blown material	exterior wall, cavity, ETICS, floor, loft, roof	18-36 cm	17
	Wood-wool boards	60-600	0.080-0.100	2-5	E	Boards	exterior wall, cavity, ETICS, floor, loft, roof	40-45cm	10.8
	Cork	100-120	0.038-0.050	10-18	E	Granula-te, board	exterior wall, cavity, ETICS, floor, loft, roof	18-25	26
	Reeds	155	0.040-0.065	2	E	Batts	exterior wall, floor, loft, roof	20-29	
	Sheep-wool	20-50	0.040-0.044	1-2	E	Batts, blown material	exterior wall, cavity, ETICS, floor, loft, roof	18-20	20.9 (6 net thermaf-leece)
	Cellulose	25-66	0.040-0.045	1-2	E	Loose fill, blown material	exterior wall, cavity, ETICS, floor, loft, roof	18-20	7,6
Mineral									
	Rockl wool	20-40	0.031-0.040	1-2	A1	Batts, blown material, boards	exterior wall, cavity, ETICS, floor, loft, roof	16-22	16,8
	Glass wool	16-25	0.031-0.040	1-2	A1	Batts, blown material, boards	exterior wall, cavity, ETICS, floor, loft, roof	16-22	49,6

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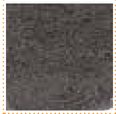
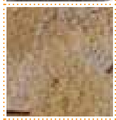
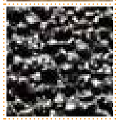
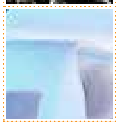
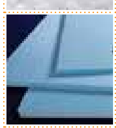
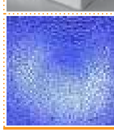
	Insulation material	Density ρ (kg/m^3)	Thermal conductivity λ (W/mK)	Water vapour diffusion resistance index μ	Fire resistance class Euroclass	Forms available	Applications	Insulation thickness for U-value 0.2 W/m^{2}K	Embodied Energy MJ/kg
	Mineral foam	70	0.035-0.051	3-5	A1	board	exterior wall, ETICS,floor, loft, roof	16-20	
	Perlite	60-160	0.040-0.060	5-25	A1	loose fill	exterior wall, cavity, floor, loft	25	
	Cellular or foam glass	10-120	0.040-0.055	∞	A1	loose fill, board	exterior wall, cavity, ETICS, floor, loft, roof	18-25	26
	Aerogel	180	0,013	∞	A	Batts, granulate, monolithic	exterior wall, loft, roof	6,5	53
Oil-derived									
	expanded polystyrene (EPS)	15-30	0.035-0.040	20-100	D to F	Board	exterior wall, ETICS, loft, roof	16-18	108
	extruded polystyrene (XPS)	20-50	0.030-0.040	5-23	E	Board	exterior wall, ETICS, floor, roof	13-18	95
	Polyurethene	30-40	0.025-0.040	30-100	C (B for Metal faced sandwich panels)	Board (PUR/PIR), in situ foam	exterior wall, cavity, ETICS, floor, loft, roof	11-18	101
Other									
	Vacuum insulation panels (VIP)	150-180	0.07–0.10 W/(m K)	∞	A (for VIP core)	Panels	exterior wall, floor, loft	3-4	81.9
	Transparent insulation			5-26		Board	exterior wall		

Table 4.3
Typical insulation materials

§ 4.3.2 Glazing

Glass is a key element in the architectural expression of buildings. It provides visual connection with outdoors and daylight indoors, enhancing the quality of the interior work environment (Selkowitz, 2005). It is one of the oldest materials used in building construction and it has become increasingly important since the 19th century (Borch, 2004), connected with developments in glass manufacture, as well as the architecture and engineering practice (steel-glass construction, Modernism etc.).

Currently, technology in the field of glass tries to solve the inherent problems of poor thermal performance and fragility that glass as a material has. A lot of effort has been put into the development of coatings, laminates and various specialized types of glass, to solve the inherent problems of poor thermal performance and fragility that glass as a material brings. Even though these technologies give wider possibilities in new buildings, they are also relevant to refurbishment, as the retrofitted glazing can upgrade the existing envelope performance.

Multi-pane and Low- E coating glazing

One of the shortcomings of glass is the relatively poor insulating quality. Multiple panes of glass with air space between improve the insulation value considerably (Carmody et al., 2004). Additional improvement to the thermal performance of glazing units involve reducing the conductance of the air space between layers by filling the space with a less conductive, more viscous or slow-moving gas. Manufacturers generally use argon or krypton gas fills (Carmody et al., 2004).

Low-emissivity coatings, called Low-E for short, reduce the surface emissivity of glass. Such coating materials are mainly transparent over the visible wavelengths of light, but reduce the amount of long-wave infrared thermal radiation both absorbed and emitted by the glass pane. This way, heat loss is greatly reduced with almost all re-emission taking place towards the interior of the building in cold climates, if the coating is on the outside face, or back out into the environment in a hot climate where the coating should be on the inside face.

A typical way of measuring the windowpane performance is the thermal transmittance coefficient U-value. The final thermal conductivity depends in the number of panes, the depth of the cavity, the gas infill and the coating. Table 4.4 compares glazing types with different characteristics. The values are indicative, obtained from ISO10077-1 (2006) and may vary in the specific products. Nevertheless, they show how the performance changes according to the glazing specifications.

Glazing	Number of panes	Normal emissivity	Dimensions (mm)	Gas infill	U Value (W/ m^2 K)
Single glazing	1	0.89	4	n/a	5.6
Double glazing	2	0.89	4-6-4	Air	3.3
Double glazing	2	0.89	4-12-4	Air	2.8
Triple glazing	3	0.89	4-6-4-6-4	Air	2.3
Triple glazing	3	0.89	4-12-4-12-4	Air	1.9
Double with Low E	2	<0.05	4-6-4	Air	2.5
Double with Low E	2	<0.05	4-12-4	Air	1.7
Triple with 2 Low E	3	<0.05	4-6-4-6-4	Air	1.6
Triple with 2 Low E	3	<0.05	4-12-4-12-4	Air	1.0
Double with Low E and Argon	2	<0.05	4-6-4	Argon	2.1
Double with Low E and Argon	2	<0.05	4-12-4	Argon	1.3
Triple with 2 Low E and 2 Argon	3	<0.05	4-6-4-6-4	Argon	1.2
Triple with 2 Low E and 2 Argon	3	<0.05	4-12-4-12-4	Argon	0.8

Table 4.4

Comparison of typical heat transfer through different glazing options (source: ISO10077-1, 2006, table C.2)

Other glazing technologies

Chromogenic glasses

The term refers to glazing in which transmission properties are variables. This means the glass is able to undergo a reversible change form darker or lighter or transparent to translucent on demand. Such technologies are photochromic glass that contains a coating of silver halide, which changes form clear to dark due to sunlight, and thermochromic has a coating of vanadium oxides, which exhibit a reversible semiconductor-to-metallic phase transition when temperature rises (Soltani et al., 2008). Thermochromic glass turns to opaque at around 30°C, reducing insolation by about 70%. It is more suitable for external solar shading, as if it is used for window it could react to internal temperature (Smith, 2005).

Another technology of switchable glazing, which is more controllable, is electrochromic glazing (Smith, 2005). Electrochromic glass has a coating of tungsten trioxide, which changes from clear to dark when current is applied. Their construction consists of a thin metallic coating sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up, which then moves various coloration ions, most commonly lithium or hydrogen. The effect is that the glazing switches between a clear and transparent blue-tinted state with no degradation in view (Carmody et al., 2004). Typical EC windows have an upper visible transmittance range of 0.50-0.70 and a lower range of 0.02-0.25.

Vacuum glazing

Vacuum glazing has excellent energy conservation and sound insulation properties. By evacuating the glazing cavity, heat transfer rates two to five times lower than those of gas-filled conventional glazing units are predicted (Koebel et al., 2010). Due to the thinness of vacuum glazing and its excellent thermal performance, it is highly suited to retrofit in existing buildings having the potential to significantly reduce heating and when combined with solar control glazing, cooling energy loads (Eames, 2008).

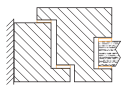
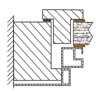
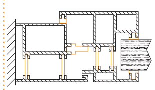
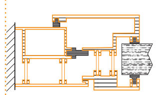
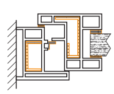
Limitations of this technology is related with the tensile stress of the glass, which required then an array of support pillars to take up the atmospheric load on the glass panes. The presently used spacers are made of mini-rings or mini-pillars arrays of metals, which have high thermal conduction and high production cost. Finally, due to their opacity, the metal pillars or rings can decrease the transmittance of visual light and alter the appearance of the vacuum glazing product (Zhao et al., 2013). Important to the service life of vacuum glazing is also the edge-sealing problem (Koebel et al., 2010).

§ 4.3.3 Window frames

Replacement of window frame is one of the most common retrofitting measures, coupled with the upgrade of the windowpane. Window frames, used both in new constructions and refurbishment, are available in different materials, as presented in Table 4.5 (Brock, 2005; Giebeler, 2009; Knaack et al., 2007). Typically window frames consist of timber, aluminium, steel, or plastic. The choice of the frame type depends on the properties and cost of the material, as well as the desired architectural expression.

As glazing and wall thermal performance improved, the window frame creates thermal bridging problems. The requirements for higher efficiency have led to the development of window frames with thermal breaks, which is an insulating material applied in the frame profile. ABS (acrylonitrile butadiene styrene), polyamide (nylon), polyethylene HD, polypropylene, PVC-U (polyvinylchloride), and polyurethane are some of the materials used (ISO10077-2, 2006). To define the thermal transmittance of the frame section, Uf, the thickness of the material, the thermal break material, the glazing and sealant used need to be considered.

When the glazing is replaced with more efficient, double or triple glazing panes, bigger frames profiles are required, to deal with the increase in the pane weight. Special window frames design in refurbishment may include considerations to preserve the aesthetical impression of the original building. An example is the refurbishment of the listed complex of Koningvrouwen in Amsterdam (Knaack, Konstantinou, et al., 2012), where a special aluminium profile to resemble the original steel frame was applied.

Material	Schematic section *	Properties	Limitations	Thermal conductivity, λ W/(mK)*	Embodied energy **
Timber		Psychological/aesthetical effect as a “warm” material Low embodied energy Good thermal behaviour	Need regular maintenance Special considerations against water penetration, mould and insect infestation	0.13	55
Timber/aluminium		Aluminium cladding covering the entire exterior of the frame Weather protection Psychological/aesthetical effect as a “warm” material in the interior	Need regular maintenance Special considerations against water penetration, mould and insect infestation	See thermal conductivity for timber and aluminium	See embodied energy for timber and aluminium
Aluminium		Extruded profiles Structural integrity Precise and airtight construction Easy maintenance	High thermal conductivity. Thermal break needed. High initial cost High embodied energy	160	196 (256 with thermal break)
Steel		Profiles made by folding sheet metal High bending and torsion strength Good fire protection properties	Thermal break required High cost Corrosion protection needed	50	n/a
Plastic (uPVC)		Extruded profiles Impact and scratch resistance Low cost Easy installation and maintenance Resistant against water and corrosion	Prone to heat deformation Not fire resistant Limited structural strength	0.17	186

* adapted from ISO10077-2 (2006)
** (non-renewable PE in MJ/kg) source Okobau.dat (BMVBS, 2013)

Table 4.5
Window frame types

§ 4.3.4 Sealants

Air leakage is a major problem in existing buildings and it is necessary to be controlled in refurbishment projects. Good air barrier materials and systems are necessary to reduce air leakage (Haehnel, 2005). Sealants are material used to seal the building’s fabric and prevent uncontrolled air and water flow. The materials and the application depend on the type of leakage. Sealants come in a range of different forms, such as membranes, expanded foam sealants, gun-applied sealants, tapes, fillers (EST, 2005). In terms of composition, sealants can in general be categorised into silicone sealants, polysulfide-based sealants, polyurethane sealants and MS polymer sealants (greenspec, 2013c). Polyethylene air barrier is the most commonly used. For air barrier connection silicone base sealant and adhesive tape are the most durable. Spun bonded olefin and acrylic sealant can exhibit problems at high temperatures. (Sherman & Chan, 2004).

With regard to windows, air leakage occurs around the frame, in the connections with the wall, as well as between the operable parts of the frame. Leakage at the wall-frame connection may account for 14% of the total leakage of a single-family detached dwelling. This source of air leakage can be reduced greatly by using alternative sealing method, such as casing tape, poly-return, poly-wrap and foamed-in-place urethane (Sherman & Chan, 2004). Some materials used for weather stripping and sealing the edge of the windows are indicated in ISO10077-2 (2006).

§ 4.3.5 Finishing and cladding

The material of the final rendering of the façade is the one confronted directly with the environmental conditions, both external and internal, and, thus, the first to show first the signs of decay. Therefore, it is an essential part of any refurbishment work. There is a wide range of finishing and cladding material, depending on the type of project, the budget and the final result required. They vary from the most simple and traditional materials, such as plaster, brick cladding, wood or granite, to more advanced materials, e.g. glass fibre reinforced concrete panels, High Pressure Laminate plates, metal or plastic.

Plaster and renders

Renderers are finishes applied to the wall surface, in one or more coats. Their basic composition consists of a binding agent such as cement, lime, gypsum, a structural filler, most commonly sand, that makes up for most of a plaster's volume and is the strongest component, and, finally, water. When water is added to a plaster/render mix, binding agents cause the filler particles to adhere to each another, creating a pliable, cohesive material that spreads smoothly and bonds onto walls. As the water evaporates, plasters set, or cure and the binding agents create a hard, protective finish. Fibres and other additives can also be used for reinforcement and elastic performance, as well as to improve plasticity, durability etc. (greenspec, 2013c).

Plaster, also referred to as stucco. is one of the most common finishing materials. It has been used since antiquity, from stone and brick to wattle and daub (Brock, 2005). It provided the waterproof layer of external walls (Meijs & Knaack, 2009), as well as a smooth surface for painting and decorative patterns. Once limited to Trowel-applied finishing of lime, gypsum, or cement, the definition of plaster has developed to include acrylics and polymer-modified base coats (Brock, 2005). There are different types of plaster according to their binder (Giebeler, 2009), which is responsible for a plaster's strength, moisture resistance and permeability.

Based on those properties, plasters are divided up into plasters and renders for outdoors and plasters for indoors. Cement-based and lime-based plasters, as well as synthetic resin and silicate dispersion plasters are suitable for outdoor use, where the requirements are to be water replant, withstand moisture, temperature changes and mechanical damages. Plasters for indoor use should, above all, be breathable, abrasion-resistant and suitable for decorating or covering with coatings, wallpaper and tiles. Interior plasters are usually based on gypsum or gypsum- lime or lime-cement or gypsum cement skim, but recently, clay-based plasters have been making a modest impact on the market owing to their excellent environmental credentials (Giebeler, 2009; greenspec, 2013c).

Plasterboards

Plasterboard is a versatile material in building construction, used in application such as internal walls and partitions, suspended ceilings, and lining of internal insulation. Standard plasterboard consists of a non-flammable core of gypsum sandwiched between two layers of cardboards liner (Borch, 2004). Several treatments or additives are used to improve the plasterboard qualities. These include silicone and wax to provide moisture resistance, vermiculite added to specifically designated fire resistant boarding, glass fibre to enhance fire protection (greenspec, 2013c) and give the possibility for three-dimensional shapes (Borch, 2004).

The qualities of plasterboards make it a good, easy and cheap solution for a wide range of application for internal finishing. Ceilings and walls can be lined in a continuous way. Its ability to absorb and release moisture helps to regulate indoor environment. Sound control is an additional benefit. Perforated plasterboard has a high sound absorption capacity and they are available in a variety of perforations, patterns and sized, offering many design possibilities (Borch, 2004). Regarding environmental considerations, it is a recycled and recyclable product. Lining paper is typically 90% recycled and the content of new plasterboard can be up to 25% recycled plasterboards. The main environmental impacts associated with plasterboard result from the production process, transportation and disposal (greenspec, 2013c).

Finish topcoats

Paint is the usual finishing coat, applied over plastered surfaces or material such as wood and metal. It has a dual role being both decorative and protective. Most paint types are made from three basic ingredients: the pigment that provides colour and opacity, the binder, which acts like a glue in holding the pigment to the surface, and the solvent, either water or organic, such as white spirit, which maintains the pigment and binder in liquid form. Various additives are also used to improve the ease of spreading, the drying time, resistance to bacterial and fungal growth etc. Paint works by its application to a surface followed by the evaporation of the solvent, thus leaving a film comprising of the pigment and binder.

Paint is subject to environmental and health concerns, as it has an impact on the environment during the manufacturing process and on health during its use phase, mostly connected with the presence of VOCs. Volatile Organic Compounds, VOCs, are organic compounds that have high enough vapour pressures to enable them to vaporise into the atmosphere. VOCs are taken as the major sources resulting in poor indoor air quality, which negatively affect people's comfort, health and productivity (Xiong et al., 2013). Though organic solvents are the main source, VOCs are also emitted from other components such as some pigments, fungicides and biocides, leading to a degree of variance amongst brands and colours of paint described as low-VOC (greenspec, 2013c).

To address these issues, a number of legislative regulations, as well as codes and standards have been introduced, aiming at reducing the impact of paints. They set limiting values for the VOCs content, together with other requirements, such as reduced hazardous waste of by-products during titanium dioxide production (greenspec, 2013c). Moreover, new photocatalytic paints have been launched on the market, which are claimed to have air-purifying effects. The goal of photocatalysis is to degrade or decompose organic pollutants such as formaldehyde, volatile organic compounds (VOCs), bacteria, and other chemical substances under sufficient UV light.

Phase change material (PCM)

In order for buildings to have the ability of absorbing solar energy and achieving the goal of "time-shifting", it is not only necessary to ensure the building envelope have a certain heat resistance, but also to have a big heat capacity, which enhances heat storage capacity and thermal inertia. Phase change materials are able to absorb heat and store it in the form of latent heat energy without an increase in surface temperature. This is in contrast to conventional heat storage materials. When the temperature rises a PCM changes from one physical state into another, by storing energy but not rising its own temperature until the phase change is complete. When temperature falls, PCM release the stored thermal energy (Hausladen et al., 2008). Salt hydrates or paraffins are normally used for PCMs, which are integrated into the materials used to construct internal features or facades components. PCM can be encapsulated into building material (Hausladen et al., 2008), p. 130) mostly plaster e.g. gypsum plaster mixed with PCM, or wall boards (BASF, 2013) and other facade elements (Hausladen et al., 2008).

Cladding materials

Cladding materials, often in the form of panels, can be used as the finishing layer of the façade, giving the possibility of wide range of material and appearance of the building. The construction consists of a substructure that normally creates a cavity between the insulation and the panel, creating a ventilated façade. Depending of the material, it is also possible to apply the panel as the finishing surface without the cavity, attached on the wall of insulation, as in the case of ceramic tiles, or be a self-supported layer, e.g. of masonry brick known as brick veneer.

Most construction materials used as cladding in new buildings can also be applied in refurbishment. They range from ceramic tiles and bricks to plastic, steel or textile. The possibilities and variations are extensive and it is not in the thesis scope to analyse. Information of each material properties and application are available in the literature, e.g. Borch (2004), as well as the manufacturer. The choice of the material depends mostly on the desired appearance and texture of the refurbished building. Additional considerations include cost, extra loads and environmental impact of the product.

a

b

c

d

Figure 4.9

Different cladding material a. Façade with translucent layered green composite plates with the plant motif, b. perforated steel façade, c. ceramic tiles, d. timber cladding.

§ 4.4 Components' retrofitting measures

Following the discussion on common materials in refurbishment projects, this section investigates the technologies and systems using those materials to upgrade the building envelope performance. The measures are organised according to the building envelope component they address, namely the external wall, window, balcony, roof and ground floor. The present section aims at analysing the different options and highlighting their function, application and limitations. The measures are also associated to the strategy they can be used in and the materials applied to realise the measure. The use of different material is necessary in each measure.

Discussing typical measures for each component retrofitting supports the systematic compilation of options, which the first step towards the approach development, which is going to be explained in Chapter 5. Benchmark thermal transmittance coefficient for each measure and the effect on heating demand consist the second step in the approach methodology, which is the measures' quantification, and will be presented in the following chapter.

§ 4.4.1 External wall

External wall can be perceived as the opaque element of the façade and it is one of the mainly source of heat losses is dwellings (Nemry et al., 2010). A large part of the building stock does not have sufficient thermal resistance of external walls, as there were different technologies and performance standards at the time of construction. Moreover, insulating material lose some of their insulating effect because of degradation processes, such as water penetration, organic infestation, diffusion of the infill gas etc. (Al-Homoud, 2005; Giebeler, 2009; Stazi et al.). The possible measures aim at preventing heat transfer through the construction elements along with reducing the air-leakage due to cracks and insufficient connection, related with the high infiltration rates found in the building stock. Table 4.6 gives an overview of external wall retrofitting measures, which are then discussed further in the section.

	Description	Strategy	Material	Function	Limitations	Variations
Cavity insulation	Loose or foam insulating material ejected in the existing cavity between inner and outer wall leaf	Add-in	Insulation	Heat protection: Increases thermal resistance. Performance depends on existing cavity depth	Not suitable in all cases. Not sufficient insulation thickness	Different insulation types and thicknesses
Internal insulation	Insulation on interior of wall sheathing with plaster or plasterboard	Add-in	Insulation Lining Water barrier Plaster Render	Heat protection: Increases thermal resistance and air-tightness to required level	Risk of interstitial condensation. Use up internal space Disturbance for users Abolishes the effect of thermal mass	Different insulation types and thicknesses
Exterior Insulation and Finishing Systems (EIFS)	Rigid insulation boards on exterior of wall sheathing with plaster	Wrap-it	Insulation Water barrier Coating	Heat protection: Increases thermal resistance and air-tightness to required level	Thermal bridging of the fixing Water leakage risks Low impact resistance	different insulation types and thicknesses
Ventilated façade	Rigid insulation boards on exterior of wall, with panel for finishing. Substructure for the panels needed. Air cavity	Wrap it Replace	Insulation Water barrier Sub-structure Cladding material	Heat protection: Increases thermal resistance and air-tightness to required level. Diverse external finishing	Thermal bridging of the fixing. Cost	Different insulation types and thicknesses, cladding
Timber-frame wall	Timber self-supporting structure with insulation infill and panelling,	Replace Add-on	Timber Insulation Plasterboards Cladding	Heat protection: Increases thermal resistance and air-tightness to required level	Applicable for non-loadbearing facades. Prefabrication requires detailed survey Disturbance for occupants	Different insulation types and thicknesses, cladding
Second Façade/ Single glazing	Cladding with single glazing, 0.50-2m away from the existing wall. Aluminium frame structure.	Wrap-it Add-on	Single glazing Opaque parts: Sandwich panel or insulation, cladding material Aluminium frame	Heat protection Passive solar heating Thermal buffer, unheated. Insulation on existing envelope is not necessary	Overheating risk. Extra structure may be required Cost. Extra space requirements	Different types and design of glazing, shading, opaque elements
Second Façade/ Double glazing	Cladding with double, insulated glazing, 0.50-2m away from the existing wall. Aluminium frame structure.	Wrap-it Add-on	Double glazing Opaque parts: Sandwich panel or insulation, cladding material Aluminium frame			
Additional space/ Second façade integrated	Additional construction adjacent to existing floor. Possible to be structurally independent	add-on	Double or triple glazing Opaque parts: Sandwich panel or insulation, cladding material Aluminium frame	Create extra usable, heated space. Prevent heat loss through adjacent facade		

Table 4.6

Overview of external wall retrofitting measures

Cavity insulation

Cavity walls have been built for many years, but became more common in the 1920s-30s and standard in the post war period. Cavity-walled houses are amongst the easiest to refurbish in an energy-efficient way, as the cavity can be filled with insulation (EST, 2006b). The installation is done by drilling injection holes through mortar joints, injecting the fill material into the wall cavity and covering the injection holes with colour matching mortar or render (EST, 2007).

The insulation material that can be applied as cavity insulation should be in loose fill, foam or granulated form such as blown mineral wool, Urea-formaldehyde foam, bonded polystyrene beads and perlite. Therefore, the installation process includes barriers to prevent the fill entering the cavities of adjacent properties and sealing air ventilators that cross the cavity.

Filling the wall cavity with insulation results in improving the thermal performance of the existing building in an easy and efficient way and it is applicable to a large portion of the stock. The installation usually takes less than half a day to complete and it is done entirely from the outside so it causes little disturbance to the occupants. Additionally it does not affect the external appearance of the wall, which makes it applicable to cases of monumental buildings.

However, cavity insulation is not suitable in all cases. Each wall needs to be assessed to be suitable for the cavity fill considered. Where defects are identified, these should be satisfactorily rectified before work begins. Any dampness problems should be investigated to determine the cause and then remedied (EST, 2007). The cavity should be continuous. Where bricks have been used as wall ties and to bridge the cavity, as in some older properties, the wall is likely to be unsuitable for filling. Moreover, the performance of the insulated wall is determined by the cavity depth. The depth varies of course in every building, but looking at the historic development, in the post-war buildings for example, the cavity width is approximately 50mm, while wider cavities, partially or fully-filled with insulation are found after the 1980's (EST, 2006b). The final wall thermal performance, depending on the insulation thickness, may not be sufficient, due to the limited depth of the cavity. Therefore, it is not advisable to apply cavity insulation is buildings with a cavity less than 50mm deep.

Internal insulation

Internal insulation is the preferred solution for monumental or other buildings that their appearance should not be changed. It may also apply to multi-storey buildings where access for applying external insulation is not easy. The insulation can be fixed internally with different methods. Adhesive can be applied directly to the board in strips. To prevent air movement behind the board, it is important to seal the perimeter and the surround of any openings with a continuous band of adhesive. Mechanical fixing should also be included as for adhesive applications. Where the background is uneven or has been previously damp, a frame, most commonly, of timber batters should be used. The timber battens, at least the thickness of the insulation are screwed or nailed to the wall. The rigid, semi-rigid or quilt insulation is cut to fit tightly between the battens. A vapour protection membrane is fitted across the face of the studwork and covered on the internal face by plasterboard or alternatively a service zone and plasterboard (greenspec, 2013b).

Problems with the application of internal insulation occur if the walls are unsuitable because of rain penetration of rising damp and cannot dry. Moisture control of the wall should be executed. If the wall is subject to rain penetration, the insulation can be placed away from the wall (min 30mm), to create a ventilated cavity. In this case, the battens are fixed between floor and ceiling (greenspec, 2013b).

Another problem is the risk of interstitial condensation. Attaching insulation to the interior leads to lower temperature of the existing wall. If the warm, moist interior air flows behind the internal insulation, condensation between the wall and the insulation will occur. (Giebeler, 2009) It is therefore important to separate the inside air from the insulation by applying a 'vapour barrier', also known as a 'vapour control layer', to the warm side of the insulation (EST, 2008).

Moreover internal insulation cannot tackle excessive thermal bridging and additional measures are required, such as insulating the floor, or part of it (1m along the wall). Finally, the effect of temperature regulation by thermal mass is unavailable. Additional limitations include the thickness of the internal lining, which could be difficult to accommodate if the room sizes are too small. The use of internal insulation is not suitable if ornate plasterwork and the interior appearance needs to be retained. The disruption to the occupants (and associated costs) is great and needs to be taken into account. It is better is it is part of a refurbishment that would involve disrupting the internal surfaces and fixtures, because the application of internal insulation would not lead to any additional disruption (EST, 2008).

Exterior Insulation and Finishing Systems (EIFS)

Exterior Insulation and Finish System (EIFS) is an exterior wall cladding that utilizes rigid insulation boards on the exterior of the wall sheathing with a plaster appearance exterior skin. It can also be found in the literature as insulated render (greenspec, 2013b), synthetic stucco (Brock, 2005) or External Thermal Insulation Composite Systems (ETICS) (EAE, 2013). EIFS in its current basic form was developed in West Germany in the 1960s and introduced in the United States in 1969 by Dryvit (Zwayer, 2010). The typical construction of an EIFS includes the following layers: insulation boards, attached to the existing wall using, mechanical fixings (and/or adhesive) through to the wall, reinforcing for the render base coat and the finish coat. Over the years, variations of this system have been developed (Zwayer, 2010), comprising different types of insulation materials, as opposed to the usual extruded polystyrene (XPS). Various insulations materials and their application have been discussed in the section 4.3.1. With regard to EIFS, the most common insulation material is mineral and foam insulation boards are the most common. For the application, the density of the insulation is important. The finishing of EIFS is called lamina and its main purpose is protection from water. It consists of a base coat with reinforcing mesh and the finish coat (Brock, 2005).

a b c

Figure 4.10
Examples of External Insulation Finishing Systems (EIFS) with different insulation material and different finishing surfaces..

EIFS is an economical and easy-to-apply solution, usually applies as part of an overall refurbishment strategy. Even since 1980s, 80% out of the 40% of all exterior cladding in Germany and Switzerland that were cladded with EIFS were used in retrofits. The system is applied over masonry and concrete walls, especially in Europe (Brock, 2005), but its application is also possible in light-weight constructions (Künzel & Zirkelbach, 2008). It is suitable for poorly insulated walls, as well as in cases of insufficient weatherproofing of the existing walls, causing damp, draughts and heat loss. The application of EIFS results in increased thermal resistance of the external wall and improved airtightness. The final U-value depends mostly on the insulation material and thickness and it is relatively easy to comply with the respective regulations for thermal performance, especially compared with internal or cavity insulation. Moreover, it solves thermal bridges cased in structure-wall connection, eliminating problems of damp, condensation and mould growth, coupled with adequate ventilation. Finally, the system provides minimum disturbance in the interior of the house, where the occupants may stay during the time of installation.

Problems observed with in-service EIFS installations are primarily related to moisture intrusion (EAE, 2013). Even though no moisture problem in cold and moderate climates when the detailing of joints and openings is well done, water leakage cannot be excluded completely (Künzel & Zirkelbach, 2008). The normal EIFS composed of vapour retarding EPS insulation boards cannot provide much drying towards the exterior and may therefore bear a moisture damage risk for the underlying substrate. Applying high density mineral wool insulation provides useful breathability in situations where trapped moisture can damage the structure.

Moreover, the required impact resistance needs to be taken into account in the choice of insulation material. To increase impact resistance particularly in the ground floor, impact resistant materials are advisable. If no different material should be used, due to design or budget reasons, a hard coat or polymer-modified EIFS or a heavier reinforced mesh should be selected (Brock, 2005).

Other issues regarding EIFS are related to the connection and properly sealing around windows, doors, pipes, conduits, terminations and other penetrations of the field of the EIFS. Finally, it needs to be considered that the external insulation and the respective finishing system will change the original exterior walls. This often a positive effect, as renewed appearance is one of the requirements retrofit. In many cases, though, changing the appearance is not allowed, for monumental of other reasons, making EIFS an inapplicable choice.

Figure 4.11
Application of insulation externally on the wall (Image source: courtesy of ROCKWOOL International A/S).

Ventilated façade

Ventilated façade, also referred to as rainscreen systems (greenspec, 2013b) or dry-cladding systems (Thorpe, 2010), comprises the outer skin, the air cavity, the insulation layer and the existing, backing wall that frequently includes an insulating layer. The outer skin or panel is called the 'rainscreen', as it forms the primary rain barrier. However it does not prevent the passage of air through open joints between the panelling components. An air gap is needed to prevent water crossing the gap and penetrating the insulation or the backing wall. The air gap provides ventilation and, depending on the design, may provide pressure equalisation across the outer skin. Any water penetrating the cavity is drained away.

To fix the cladding, a support system designed to carry both the mass of the rainscreen along with the projected wind loading is installed. Support structures vary in their format and complexity according to the nature of the cladding material, drainage and rainscreen system. Most support systems are proprietary and are often designed together with a cladding system from the same manufacturer. The support system will usually comprise of vertical or vertical and horizontal fixing rails fixed back to the structure using brackets. Additional brackets may be used to fix the cladding to the supporting rails.

The main advantage of the ventilated façade is the wide range of architectural expression that it offers, as there are various possibilities for the cladding material. In refurbishment projects in particular, the renewed appearance with the use of ventilated façade system is often a decision-making argument. The benefits of the ventilated façade system on the building envelope performance are very similar with those of the EIFS. It improves the thermal resistance of the external wall, reducing heat losses and infiltration rates. The choice of insulant and its fixing is similar to EIFS and mostly some type of rigid insulation boards is used. It needs to be noted that there is no allowance for the effect of the cladding itself because the space behind is fully ventilated. The thermal performance of the wall depends then on the insulation material and thickness and not the cladding material.

A limitation of the system is the added structural weight on the existing façade, particularly in case heavier cladding material, such as concrete panels or natural stone, is applied. Moreover, depending again on the cladding material and the fixing system, the construction cost can be significant higher that the EIFS. The benefits of the system have to be balanced against its feasibility and expense, according to each projects design and ambition.

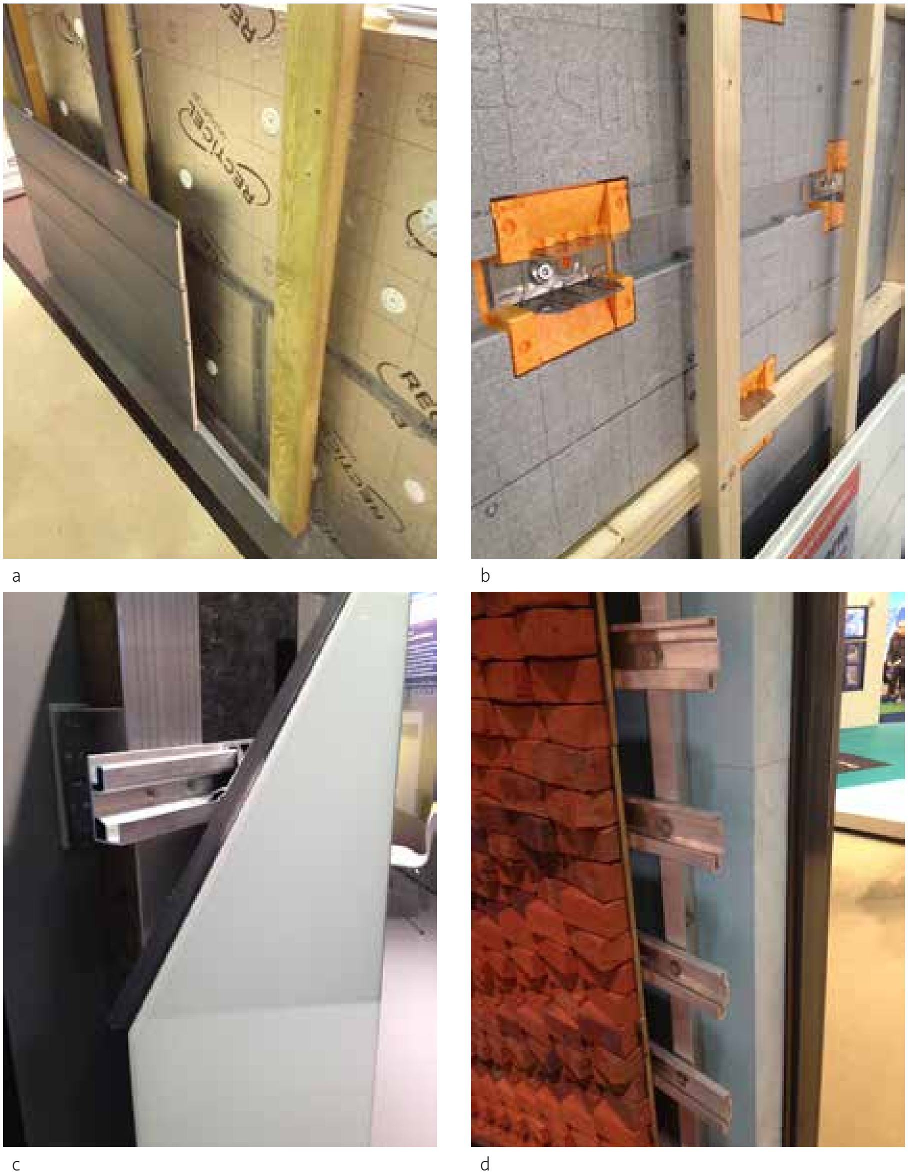


Figure 4.12

Examples of cladding material and support systems.

Timber frame wall elements

If a wall or façade panel component is to be completely or partly removed, it can be replaced with a lightweight construction. Timber frame construction is common. Infill is realised with insulation and finishing layer. The windows are incorporated in the construction. The new construction can achieve high thermal resistance and airtightness standards, as the required thickness of thermal insulation and is easily applied. An advantage is the low weight added to the existing structure. Moreover, since the original façade has been removed, it gives more design possibilities. Furthermore, the use of timber is favourable in terms of embodied energy.

An example application of timber frame wall elements for refurbishment was further developed by the research project TES EnergyFaçade. The name stands for Timber-based Element Systems for improving the energy efficiency of the building envelope and the method is based on prefabricated retrofit building elements is a systematic process of surveying and renovation planning, construction based on assembly of offsite fabricated customised timber façade panels, replacing either certain layers of, or the existing building envelope in its entirety. TES elements combine a self-supporting structure with insulation infill and panelling, which can be made of a wide range of cladding materials (e.g. timber boards, timber panels, glass, aluminium etc.). The system gives possibilities for spatial intervention or modular expansion and integration of HVAC and solar-active components (Heikkinen et al., 2009).

The timber frame wall elements are better suited for non-loadbearing facades, as loadbearing walls complete removal is complicated. Moreover, prefabrication requires a detailed survey of the existing building. Finally, given than the existing walls are removed and replaced, disturbance for occupants is significant. However with prefabrication, assembly in site time can be reduced.

a

b

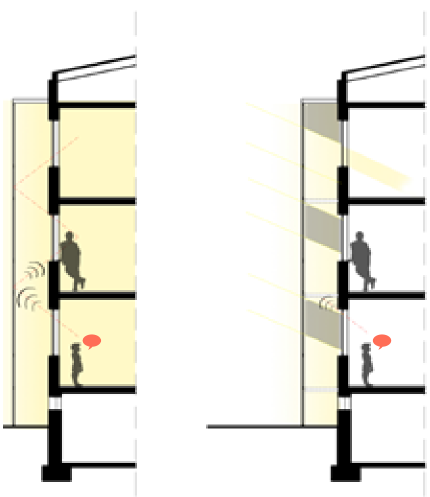
Figure 4.13

The TES Energy Façade system, mounting (a) and pre-fabrication (b)
(Image source: courtesy of lattkearchitekten, Augsburg)

Second Façade

Second façade refers to the construction of an exterior façade layer that is separated from the existing facades, forming the room enclosure, which then becomes interior. Depending on the specific design, the distance between interior and exterior façade layer can vary. In order to utilise the effect of a thermal buffer in the space between the two façades, ventilation openings are installed in either one of the exterior and interior façade or in both. The air in the gap between the façades heats up due to solar radiation and hence serves as a buffer toward the interior space. Due to the thermal difference, the warm air can be used as a generator of natural ventilation of the interior room or the space in between the façades (Knaack et al., 2007).

Depending on the method used to conduct air in the space between the two façades, double-skin façades can be grouped into four main categories (Knaack et al., 2007): box-window façade, when the air only circulates within one façade element, shaft-box façade, where the air rises in vertical shafts, corridor façade, where the air circulates within the gap between the façades horizontally across one storey, and second-skin façade the air circulates across the entire, unrestricted gap cavity.



1

2

Figure 4.14

(a) Scheme of a Second Façade (SF). (b) Second Façade in the renovated Leeuw van Vlaanden, Amsterdam, the Nertherlands (Image source: courtesy of heren 5 architecten bv bna, www.heren.nl, photographer Kees Hummel)

The exterior façade layer consists of either single or double glazing. The choice of glazing type depends not only on the required thermal performance, but also the function of the space. The percentage of transparent to opaque surfaces and the depth of the cavity may vary. If single glazing is used, the space created can be used as a winter garden or circulation area. The benefit for the thermal performance is that the temperature is higher than outside, due to solar gains and internal gains, and, thus, a thermal buffer is created, reducing heat losses from the interior to exterior space. If double glazing is used, the space can be used again as a buffer zone, but it may also be incorporated in the dwelling thermal envelope. It will be then a conditioned space and the solar gains will benefit directly the heat balance of the house. The integration also has the benefit of enlarging the living area.

Due to high solar gains, attention is needed to prevent overheating. Adequate ventilation and solar shading is necessary. Depending on the design and function of the space between existing and second facade, operable openings can be integrated. Although the second façade, even with operable windows can have a favourable effect on sound insulation to outdoor noise (Mahdavi et al., 2013), care should be taken in the acoustics design to prevent sound reflection between the different dwellings.

The main limitation of a second façade as a retrofitting measure is cost related. The construction of a second, curtain-wall façade can be cost and labour intensive, particularly if it cannot be suspended on the existing façade and new foundations need to be constructed. Moreover, extra space in the perimeter of the building is required for the measure feasibility. This is more often possible in the rear, courtyard facades of the estate rather than the street side. Cladding existing open galleries is a way to achieve the benefits of a second façade, overcoming those limitations.

§ 4.4.2 Windows

Window is a key component to energy efficient buildings. They typically account for about 30–50% of the transmission losses though the building envelope, even if their area fraction of the envelope is far less (Gustavsen et al., 2011). Given that over 85% of glazed area in Europe's buildings are made of inefficient products whereas six to eight times more energy-efficient exist (Glass for Europe, 2011), there is big room for improvement in the windows' performance of the housing stock.

<table>
<tr><th>Measure</th><th>Description</th><th>Strategy</th><th>Material</th><th>Function</th><th>Limitations</th><th>Variations</th></tr>
<tr><td>Upgrade windows</td><td>Double glazing applied on existing window frame</td><td>Add-in</td><td>Glazing</td><td>Heat protection
Solar gains
Increase thermal resistance of window pane</td><td>Additional weight and width of glazing
Air tightness not improved</td><td>Different types of glazing and frame fixing</td></tr>
<tr><td>Secondary single glazing</td><td>Secondary single glazing window pane, in the inside</td><td>Add-in</td><td rowspan="4">Glazing, Window frame, Sealant</td><td rowspan="2">Heat protection
Buffer zone. External appearance unchanged.
Acoustic performance improves</td><td rowspan="2">Adequate ventilation needed in the cavity
Secondary glazing draught-stripped, while the existing windows left without seals.</td><td rowspan="4">Different types of glazing and frame</td></tr>
<tr><td>Secondary double glazing</td><td>Secondary insulated window pane in the inside</td><td>Add-in</td></tr>
<tr><td>Replaced windows with double glazing</td><td>Replace the existing glazing and frame with SotA double-glazing windows</td><td>Replace</td><td rowspan="2">Heat protection
Solar gains
Increase thermal resistance and ait-tightness.
Solves thermal bridging in window frame</td><td rowspan="2">Thermal break in frame needed.
Correct site installation includes sealing round window and door frames.
Improves infiltration, ventilation considerations needed</td></tr>
<tr><td>Replaced windows triple glazing</td><td>Replace existing glazing and frame with triple glazed windows</td><td>Replace</td></tr>
<tr><td>Shading fixed</td><td>Shading devices placed outside the window pane, in form of overhang, fixed louvers etc.</td><td>Wrap-it</td><td rowspan="2">Shading devices, Aluminium, plastic, timber etc.</td><td rowspan="2">Solar protection</td><td rowspan="2">Consider orientation for the type of shading
Overheating of the shading device results in unwanted heat gains</td><td rowspan="2">Different types shading devices</td></tr>
<tr><td>Shading adjustable</td><td>Shading devices placed in or outside the window pane, in form of movable louvers, venetian blinds etc.</td><td>Wrap-it</td></tr>
<tr><td>Enlarged windows</td><td>Existing window and parapet removed and replaced with enlarged, improved window pane</td><td>Replace</td><td>Glazing
Window frame,
Sealant</td><td>Heat protection
Solar gains
Higher solar heat gains.
Larger transparent proportion.
Different relation inside-outside</td><td>similar to replace windows</td><td>Different types of glazing and frame</td></tr>
</table>

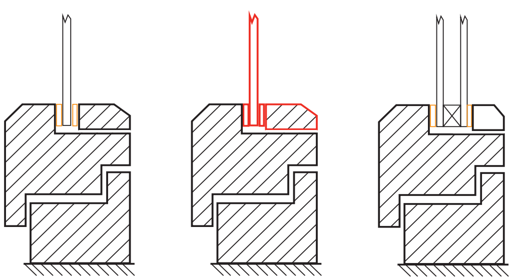
Table 4.7

Overview of window retrofitting measures

Upgrade window panes

In cases when minimum intervention is sought, it is possible to improve the window performance by replacing only the windowpane, most commonly the old single with double glazing. The old glass pane is removed and the new is fixed on the existing frame, usually timber. As the new glazing has different width than the old, it is supported usually by an additional part, nailed on the old frame. The advantage is that thermal and acoustic performance of the window is economically and quickly improved.

The window upgrade option is not applicable to all frame types and window sizes. The existing frame may not be able to accommodate the additional weight and width of the new glazing. Moreover, air tightness and thermal performance of the window frame are not improved. It is not easily combined with wall insulation, as the existing width of the profile is not enough for the connection. Overall, it is not a recommended long-term solution and other options should be consider.



a

b

Figure 4.15
Example of double glazing pane fixed on the existing timber frame

Secondary glazing

Secondary glazing, also known as box window (Knaack et al., 2007), refers to the application of a second, new window inside of the existing glazing. The secondary glazing is often an option in monumental buildings, where the external appearance should not be altered. The main advantage of this measure is the increase in airtightness, due to the interior airtight window, while the heat losses are reduced as the cavity between the windows creates a thermal buffer. Secondary glazing also achieves better sound insulation (Giebeler, 2009).

The secondary glazing should be operable to provide access to the existing window. The selected system should be one that can be opened easily for ventilation. It should be possible to leave the secondary glazing slightly open and so allow a trickle of ventilation into the room (EST, 2006a).

The existing sill should be extended to overlap any new insulated wall lining. The secondary glazing system should be well sealed, whereas the existing window should remain un-sealed to allow any water vapour in the cavity to be vented to the outside.

If window replacement is not an option, the second choice is secondary glazing. Though not as effective as window replacement, secondary glazing can non-the-less render a slight improvement to overall thermal performance through creating an insulating barrier of air.

The limitation of this measure is that the thermal transmittance does not reach performance standards. A minimum 20mm gap between existing and secondary single glazing is recommended. In a timber window this results in a U-value of approximately 2.9W/m^{2}K and in a metal window approximately 3.4W/m^{2}K (EST, 2006a). If the secondary glazing is double, the required performance can be achieved. Nevertheless, the extra cost and the detailed application have to be considered.

Windows replacement

If possible, for example when monumental status does not apply, it is advisable to replace the old with new, high performance windows. It includes replacing both the glazing and the frame. The new window needs to comply with legislative requirements, but higher performance standards, such Passivhaus, is possible to be achieved. Each European country has its own limiting U-values for windows, most of them requiring not higher than 2.2 W/m^{2}K. Hence, the use of double glazing with Low E coating is the minimum requirement (see also Table 4.4). Lower thermal transmittance may eliminate even further the heat losses. Glazing with U-value as low as 0.8 W/m^{2}K is possible with the available technology, namely with triple glazing, Low-E, argon filled units.

However the U-value is not the only consideration regarding glazing choice. Triple glazing windows gives better thermal insulation. Sound insulation is improved with triple glazing application, but not significantly (Tadeu & Mateus, 2001). The condensation that is possible to occur in double panes, depending on U-value and exterior temperature (Muneer & Abodahab, 1998), is less often in triple glazing.

On the other hand triple glazing is heavier than double glazing. This increases transportation and installation costs. Moreover, the solar gain factor g-value is lower in triple glazing, suggesting lower solar heat gains, which are related to the energy demand. Both embodied energy and cost are higher for triple glazing, which is understandable since more material is used. Table 4.8 compares the different properties of high performance double and triple glazing.

As far as the frame is concerned, the replacement gives the opportunity to choose between different materials, design and colours. Section 4.3.3 already discussed the different materials. The frames should be of high quality and designed for the chosen glazing units. They should meet the standards for airtightness and thermal performance.

Glazing type	U-value (W/ᵐ2K)	g-value	Thickness (mm)	Weight (kg/m²)	Embodied energy (MJ/m²)*	Cost (€/m²)**
Double glazing	1.3	0.75	24	20	469	25
Triple glazing	0.8	0.5	36	30	703	75

* source Okobau.dat (BMVBS, 2013). Value of triple glazing based on the value of double glazing, with the respective change of the weight per m^2

** indicative prices for the glazing alone (source: Brugge, 2014)

Table 4.8
Comparison between double and triple glazing. The figures refer only to glazing

Overall, replacing the window is the preferred solution, when possible, at it improves both the thermal resistance of the glazing and frame, as well as the airtightness. Replacement windows should incorporate 'trickle vents' in the top of the frame as well as draught seals. Correct site installation includes sealing round window and door frames. Filling the gaps between the frame and the surrounding wall with expanding foam will improve the window's thermal performance and reduce draughts. Where low-e glass is used, it must be installed the right way round, usually indicated by the manufacturer (EST, 2006a). In heating oriented climates, the coating is placed on the inner pane of the window, in order to reflect the long wave radiation in the form of heat back to the occupied space. Finally, limiting the extent of thermal bridging around wall openings should be a priority. The general strategy is to bring the window into line with the insulation layer (greenspec, 2013b).

Enlarged windows

During refurbishment, if the structure allows, the parapets of the existing windows can be removed and then the window area is enlarged. The existing frame and windowpane are removed and the replacement window corresponds to the enlarged opening. The considerations regarding choice and performance of the new window are similar to those discussed in window replacement. The larger grazed area allows for higher solar heat gains can possibly result in lower heating energy demand. Overheating might become an issue and, thus, the sun control and ventilation have to be acknowledged.

Other benefits include the refreshed appearance of the building and the relation between interior and exterior spaces. The enlarged windows can be used as balcony doors, to give access to a new added balcony, or even a French balcony can be created with the application of a railing outside of the window.

Shading

The role of shading devices in controlling solar gain to avoid overheating is a passive measure to reduce cooling loads. Shutter, blinds and curtains are commonly encountered in residential buildings. Overhanging balconies or other elements also provide solar protection. If already present, their use should be preserved as part of any refurbishment scheme. Apart from avoiding cooling energy demand, shading can be beneficial for heating demand as well. Heavy curtains can perform a useful task in reducing heat loss during nighttime. Where curtains are undesirable, insulated blinds should be considered (greenspec, 2013b).

Several aspects are to be considered as far as shading devices are concerned. EN13659+A1 (2008) specifies the requirements for shutters, with regard to impact resistance, safety, thermal resistance, durability, dimensional tolerances, and other. The choice is subject to the above parameters, as well as the desired design and performance.

§ 4.4.3 Balcony

Balcony is a common feature of the building envelope, offering the possibility to create private or semi-private exterior spaces for the dwellings. Although it covers a small percentage of the building envelope area and the heat losses are not significant, compared with the rest of the components (Ge et al., 2013; Goulouti et al., 2014), it is a major cause of thermal bridging, particularly when it is constructed as a continuous slab. To tackle this problem, there are a number of refurbishment possibilities. They can be in general grouped in two types of actions. The first is to prevent thermal losses through the slab itself, with the application of insulation on the slab or the creation of thermal break between balcony and internal floor. The second refers to close the balcony to turn it into a heated or unheated occupied space. Apart from the special benefit of enlarging the habitable space of the dwelling, it prevents heat losses through the fabric, since the temperature in the balcony is no longer as low as the exterior. Even in the case of an unheated space, such as a winter garden, the use of the incoming solar radiation creates a buffer zone and reduces heat flow. The edge of the balcony slab still needs to be insulated.

<table>
<thead>
<tr><th>Measures</th><th>Description</th><th>Strategy</th><th>Material</th><th>Function</th><th>Limitations</th><th>Variations</th></tr>
</thead>
<tbody>
<tr><td>Insulate balcony slab</td><td>Insulation applied on all balcony surfaces (top and below)</td><td>Wrap-it</td><td>Insulation</td><td>Solves thermal bridge</td><td>Labour intensive
Inefficient use of material
Change in balcony level- problems in detailing</td><td>Different insulation types, thicknesses and width</td></tr>
<tr><td>Cut off balcony</td><td>Cut off the existing balcony and insulate the floor edge</td><td>Wrap-it, replace</td><td>Insulation</td><td>Solves thermal bridge</td><td>Labour and cost intensive
Lack of exterior spaces (if the balcony is not replaced)</td><td>Replace or enlarge, with thermal break between new balcony and wall
Insulated balcony connectors systems</td></tr>
<tr><td>Balcony cladding single glazing</td><td>Cladding with single glazing. Aluminium frame structure.</td><td>Wrap-it</td><td>Single glazing
Opaque parts (if applicable): Sandwich panel or insulation, cladding material
Aluminium frame</td><td rowspan="2">Balcony space as buffer zone. Thermal comfort temp on balcony extended. Thermal bridging solved</td><td rowspan="3">Overheating risk.
Insulation at the edge of the slab required
Extra structural loads
Lack of exterior spaces (if the balcony is not replaced)</td><td rowspan="3">Different types of glazing and frame.
Cladding design</td></tr>
<tr><td>Balcony cladding insulated glazing</td><td>Cladding with double glazing. Aluminium frame structure.</td><td>Wrap-it</td><td>Double glazing
Opaque parts (if applicable): Sandwich panel or insulation, cladding material
Aluminium frame</td></tr>
<tr><td>Balcony space integrated</td><td>Cladding with double glazing. Aluminium frame structure.</td><td>Wrap-it</td><td>Double or triple glazing
Opaque parts (if applicable): Sandwich panel or insulation, cladding material
Aluminium frame</td><td>Balcony space integrated in thermal envelope. Thermal bridging solved
Extra space</td></tr>
<tr><td>New balcony</td><td>New, possibly bigger balcony suspended on existing wall, or on independent construction. Thermal break between new balcony and existing envelope</td><td>Add-on</td><td>Concrete of steel structure,
Various finishing material</td><td>Shading of window in floor below. No effect on thermal performance of envelope.</td><td>Structural limitations due to extra weight.
Cost
Space requirements</td><td>Different size, design and construction of balcony</td></tr>
</tbody>
</table>

Table 4.9
Overview of balcony retrofitting measures

Insulate balcony slab

Insulating the balcony slab at all sides is a solution to eliminate thermal bridges. This is achieved by minimising the heat flow through the continuous slab, which is partly in the internal and partly in the external space. The smaller the temperature difference, the less heat flows. Details b and c in Figure 4.16 show that the effect on the temperature difference in the slab between interior and exterior is the same when the whole width is insulated as the half width.

However, this solution is not material efficient, as it requires insulation to be applied on all balcony surfaces. Moreover it results in unsatisfactory details such as thick edge and steps at the balcony entrance (Giebeler, 2009). As a result this is not the preferred solution, unless other possibilities are not acceptable, for example in case the structural calculations do not allow for any extra loads or cutting.

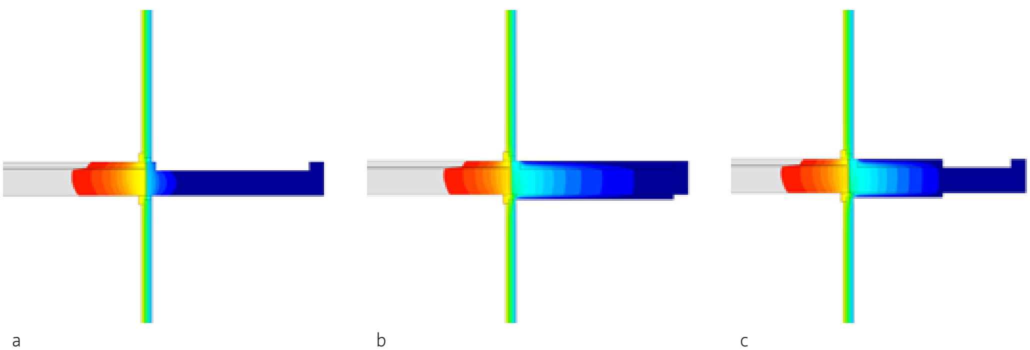


Figure 4.16
Thermal simulation model of the balcony with TRISCO software, showing the temperature transaction within the balcony slab in the original situation without insulation (a) and after the insulation application (b, c).

Cut off and replace balcony

To eliminate the heat flow through the balcony slab, a solution is to remove the slab and insulate the edge, creating a thermal break. When removing the balcony, the obvious disadvantage is the resulting lack of external spaces for the dwelling. For this reason, the balcony is often replaced, or even enlarged, if possible.

A solution to that can be used to this end is the application of insulated balcony connectors systems, such as the system from Ancon (2014), and Schöck (2002). Schock solution, for example, provides a way of breaking the thermal bridges by separating the balcony slab from the floor slab with a small insulation layer. Reinforcement goes through this element and it provides structural continuation. This solution solves the thermal bridging and keeps the original appearance of the building, if this is desired. Nevertheless, the limitation of this measure are related with the possibly insufficient strength of the existing wall, which may prevent the new balcony to be suspended (Giebeler, 2009). In that case, the construction of new foundations is required. The drawback is then the additional construction costs and the requirement of space, surrounding the building.

Balcony cladding

Both measures of insulating the balcony slab or creating a thermal break after the balcony is removed can solve thermal bridging, but have technical difficulties. An alternative, which is also combined with spatial benefits for the dwellings, is cladding the balcony. A façade element, fully glazed or incorporating opaque parts, is placed in front of the balcony slab. The balcony space is no longer external and heat losses are reduced not only through the balcony slab, but also through the wall and window.

Similarly to the second façade measure (SF), the balcony space can be heated or unheated. The difference to a SF is that the balcony may not occupy the whole façade and, hence, only the rooms adjacent to the balcony are mostly influenced. If the space is unheated, it acts as a thermal buffer. The temperature in the balcony space is higher than the outside temperature, mainly due to solar gains and, thus, the heat flow between the heated, occupied space and balcony is reduced. The balcony can be used as a winter-garden, as comfortable temperatures can be achieved.

If the balcony space becomes a heated space, it is integrated into the thermal envelope and it is part of the dwelling occupied space. The in-between walls can be removed, to enlarge the adjacent rooms and giving various possibilities for the internal layout re-arrangement. In this case, there is no external space for the dwelling, but new balconies can be constructed to compensate.

Different types of glazing are possible to be used. The decision depends on the space function. If the balcony space is integrated in the thermal envelope, the cladding construction has to comply with the thermal performance for transparent and opaque components. This suggests that the glazing should be insulating, achieving a U-value of approximately 2.00 W/m^{2}K, while the opaque elements, possibly some type of sandwich panel, the insulation need to have adequate thickness to reach a U-value of 0.2 W/m^{2}K. The exact numbers vary in different countries, as it will be discussed in Table 5.1. If the balcony space is not heated and, thus, not part of the thermal envelope, thermal performance compliance of the cladding is not necessary.

The cladding should have a high percentage of transparent areas, in order to ensure solar heat gains and achieve the thermal buffer effect. This may also increase overheating risk and, therefore, sun control and operable openings for ventilation need to be implemented. Depending on the façade specific design, it needs to be ensured that the balcony edge is insulated, to prevent thermal bridging. Additional considerations include the cladding cost and the extra structural loads to the balcony slab. As in all cases, the measure feasibility can be decided when balancing shortcoming to benefits for the space usage and energy savings.

a b c

Figure 4.17
Piazzaflat apartment block, Gorinchem, the Netherlands (Image source: courtesy of SOLARLUX Nederland BV). The new design transformed all balconies into winter garden that act as buffer zones and increase the usable living space of the individual apartments. To have a winter garden and a balcony, folding and sliding windows were applied. The glass elements also increase the acoustic insulation properties and offer improved living quality. For mounting of the façade elements, the existing balustrade connection holes in the balcony slab were used, minimising construction time and effort.

§ 4.4.4 Roof

Heat transfer through the roof is a major cause of energy losses. Top apartments have around 30% more energy demand to middle apartment. Upgrading the roof thermal performance should be an integral part in any refurbishment strategy. Table 4.10 presents an overview of retrofitting measures for the roof. The possible measures vary depending on the roof construction, the use of the attic space, the refurbishment design etc.

Measure	Description	Strategy	Material	Function	Limitations	Variations
Pitch roof insulation	Insulation between rafters, lining. Advised for unheated attic	Add-in Wrap-it	Insulation, Plasterboard, Water barrier, Roof covering	Increases thermal resistance to required level	Insulation thickness, due to rafters' depth. Height of the space. Timbers should be inspected for damp, rot or infestation. Appropriate ventilation must be provided. Air-tightness of lining	Insulation between and below or above rafters Different insulation types and thicknesses
Insulation of top floor slab	Insulation on attic floor. Advised for heated attic	Add-in	Insulation	Prevents heat loss through top floor slab to unheated attic space	Ventilators are needed to maintain cross ventilation of the roof space, preventing condensation	Different insulation types and thicknesses
Flat roof	Additional insulation on roof slab, waterproofing	Wrap-it	Insulation, Water barrier, Roof covering	Increases thermal resistance to required level	Careful detailing at the edge and parapet areas Insulation should be placed below the weatherproof membrane	Different insulation types and thicknesses. Roof accessible or not
Green roofs	Additional insulation on roof slab, waterproofing, soil and plants	Wrap-it Add-on	Insulation, Water barrier, Soil	Increases thermal resistance to required level, offers additional aesthetical and functional benefits	Additional load. Similar to flat roof	Different insulation types and thicknesses

Table 4.10
Overview of roof retrofitting measures

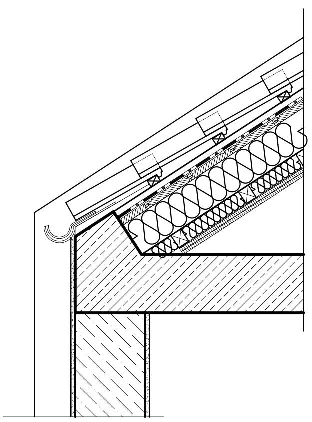
Pitch roof insulation

Pitched roofs in older building- typically wooden joist construction- have often inadequate performance and need to be upgraded. The choice of such measure depends on the function of the roof space. If the roof space is- or planned to be- occupied, hence, heated, the roof structure must be insulated, to prevent heat losses for the interior to exterior.

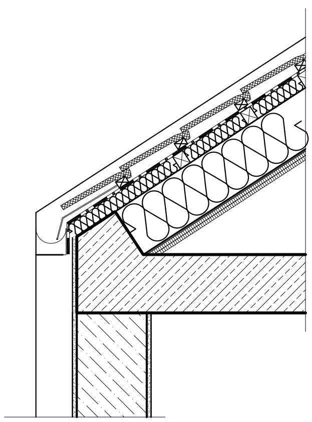
Two types of pitched roof insulation are possible; internal roof insulation, where the insulation is added between and/or under the rafters, and external roof insulation, where the insulation is placed above rafters (Thorpe, 2010). If only insulation only between the joist, the insulation will not be thick enough. In order to achieve a U-value of 0.20 W/m^{2}K, for example, more than 150mm of expanded polystyrene are required. Considering the usual rafters' sizing and the additional min 50mm for ventilation required (EST, 2006a), it is understandable that insulations needs to be installed not only between, but also below or above rafters.

To decide on the type and application method of roof insulation, the existing depth of the roof structure and the insulation thickness to achieve the required U-value need to be considered. Additionally, it is important to plan whether the roof tiles or lining is going to be replaces, depending on the degree of deterioration and the overall refurbishment design and budget. When roof tiles are renewed, insulation between and above rafters is recommended. However, large insulation depths that may raise the finished height of the new roof significantly, which careful consideration, for example in the case of a terraced house where the tiling is continuous across neighbouring properties.

Rigid insulation boards with interlocking edge joints should be specified where possible. Seal the joints between foil-faced boards with self-adhesive aluminium tape. Any service penetrations in the vapour control layer should also be sealed. Important consideration is regarding the vapour control and ventilation. Provide a vapour control layer, usually polyethylene, on the warm side of the insulation to prevent moist air passing through. This should be joined to any vapour control layer in the adjacent walls, to avoid the risk of interstitial condensation (Thorpe, 2010). Moreover, timbers should be inspected for damp, rot or infestation. Remedial works should be carried out prior to installing insulation (EST, 2006a). Appropriate ventilation must be provided when insulating the roof structure.



a



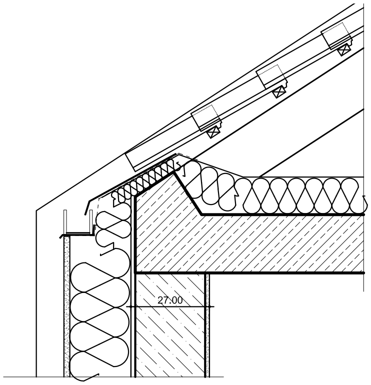
b

Figure 4.18
Typical detail of insulating between and under (a) and between and over (b) roof rafters.

Insulation of top floor slab

Insulating the top floor slab, referred also as ceiling level insulation (EST, 2006a) or loft insulation (greenspec, 2013b) in the literature, is a measure to preventing the heat transfer between the occupied floors and unheated spaces through the ceiling, either concrete of timber construction. This is in many cases the situation in unoccupied attic spaces below pitched roofs.

To minimise thermal bridging and improve airtightness, the insulation is normally applied on top of the slab, in the attic space. Moreover, the application is easier and the height of the occupied room below is not compromised. Quilted or loose-fill insulation materials are generally used, such as mineral wool or other loose fill form material, as discussed in Table 4.3. In timber floors, it is best practice to apply the insulation between – and across the top of – the ceiling joists. Cross ventilation has to be maintained in the attic space, preventing condensation (EST, 2006a).



a

b

Figure 4.19

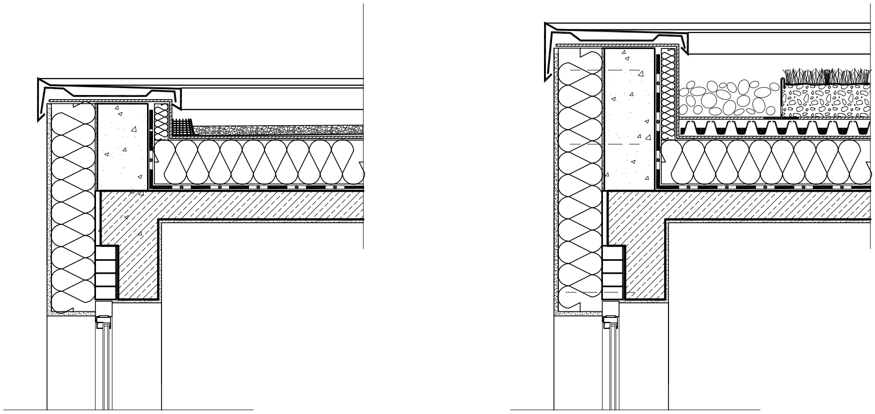
Typical detail of insulating the top concrete slab (a) and loose wool insulation blown between and above in ceiling joists (image courtesy of ROCKWOOL International A/S) (b)

Flat roof

This measure is applicable to existing flat roofs, timber or concrete, when the thermal performance is not adequate and/or damages and deteriorations require improvement of the roof. The components that may be preserved need to be specified for each specific building. Additionally, it applies in pitched concrete slab roofs, with possible considerations for the fixing to the components according to the slop. Finally, it is possible to remove the completely of partially a timber pitched roof and insulate the previously top floor ceiling, resulting in the creation of roof terraces, for example.

The preferred method is to locate the insulation above the roof deck. This method is referred to as warm roof (greenspec, 2013b) In the insulation is placed below the roof, apart from the height reduction, there is the risk of interstitial condensation. A ventilated void between deck and insulation is then required. In a warm roof construction, the insulation should be placed below the weatherproof membrane and above the vapour control layer. Careful detailing at the edge and parapet areas of flat roofs is important for high thermal performance and longevity.

Depending on the condition of the existing roof the flat roof insulation construction can vary. Where the existing deck is sound but the waterproof membrane is aged, a new membrane is placed over the existing complete with insulation and ballast, to stabilize the insulation (inverted warm) or the existing membrane is prepared as a vapour check and insulation is added complete with a waterproof membrane over (warm). If both existing deck and roofing system has failed, they are removed and replaced (greenspec, 2013b). In both cases, the detailing of the solution should provide enough insulation thickness to reach best practice thermal performance.



a b

Figure 4.20
Example detail of flat (a) and green (b) roof, constructed on an existing concrete roof.

Green roofs

Green roofs are vegetated layers that sit on top of the conventional waterproofed roof surface (GRC, 2013). The components used in green roofs are generally the same as those in roof gardens, differing only in depth and project-specific design application and include several layers (Wark, 2003). Depending on the depth of the growing medium, green roofs are characterised as intensive or extensive (Hall, 2008a). In the scope of retrofitting, extensive green roofs, with a thinner soil layer, are most likely to be considered.

The construction consists of a number of layers. Insulation and water proofing is applied on top of the existing structure. A root resistant material, the form of an independent membrane or a monolithic root-resistant version of a waterproofing membrane, protects possible root penetrations. Furthermore, the installation includes a protective layer, typically between 2-12 mm, which protects primarily from damage during installation and increases the water holding capacity of the green roof system, and a drainage layer, available in a variety of materials, including hard plastic, polystyrene, foam, and coarse gravel, which allows excess water to drain away and sometimes incorporates water storage. Finally the growing medium and vegetation are placed (GRO, 2011).

The applications of green roof are similar to those of flat roof, discussed above, as a measure to upgrade the existing roof. It needs to be noted that green roofs are not included in U-value calculations as they are considered to be continually saturated. The U-value will be taken to be the same as the roof without the extra green roof layer. The roof will however benefit from increased protection from heat in the summer and some protection from cold in the winter (GRO, 2011), as it regulated the roof surface temperature. Additional benefits are related to health, including the provision of clean air, psychological and functional associated with the use of green spaces, Moreover, they have environmental advantages, as green roofs can facilitate, amongst other, biodiversity in urban areas, storm water management, and reduction of urban heat island effect (Hall, 2008a).

A main consideration is the extra weight to the structure. Even though it is fairly easy to address the weight in a new building, existing building must be investigated for the structure capacity to bear the added load, which can be up to 170 kg/m^2 (Hall, 2008a). The structural calculations have to include in the roof dead load the saturated weight of the green roof, snow loads and any further imposed service loads, such as pedestrian access loads. Along with weight consideration, the extra cost for installation, compared to a normal flat roof, has to be accounted. The budgetary considerations need to include maintenance as part of the life cycle cost analysis for the building, allowing the most appropriate green roof specification to be realised (GRO, 2011).

§ 4.4.5 Ground floor

Ground floor refers to the floor construction of the lower occupied storey. The occupied space on the ground floor is subject to heat losses to the ground or the unoccupied space below, such as cellars and basements. Therefore, ground floor apartments have approximately 20% more energy demand than middle apartments (Table B.7). To tackle these heat losses, the ground floor slab needs to be insulated. The choice of material and insulation method depends on the existing construction and its accessibility. In timber floors the insulation can be placed between the joists. The methods described below refer to maintaining and upgrading the existing ground floor. Additional possibilities exist if the ground floor is to be reconstructed.

Measure	Description	Strategy	Material	Function	Limitations	Variations
Insulation on top of ground/first floor slab	Insulation on top of the heated space floor slab	Add-in			Insulation material of adequate compression resistance. Eliminates thermal mass effect Limitations in height	
Insulation under existing floor	Insulation under first floor slab, or between floor joists (in timber floor construction)	Wrap-it	Insulation, floor finishing	Heat protection: No heat loss from first floor through basement ceiling	Application depends on existing construction. Limitations of height	Different insulation types and thicknesses
Additional floor	Basement heated. Insulating basement floor and walls advised	Add-in			Basement needs to be insulated Similar to insulation on top or the slab	

Table 4.11
Overview of ground floor retrofitting measures

Insulation on top of slab

When the occupied space is adjacent to ground, the ground floor will have to be upgraded with added insulation a new floor deck on top of the existing floor. The insulation material needs to have adequate compression resistance, along with providing the required thermal performance. A damp-proof membrane should be applied between the insulation and the floor finishing.

Although the method is provides a simple and easy way to upgrade the thermal performance, minimum height requirements can be a preventing factor, particularly in apartment buildings. Even if the occupied space is high enough, the extra height can cause problems at stairs and doors thresholds. Moreover, the thermal mass effect becomes unavailable.

Insulation under slab

Inserting the insulation below the ground floor is also a possibility, if the space is accessible. This measure has the benefit of leaving the floor thermal mass exposed and the space height intact.

In case of timber floor construction, insulation can be applied between the joists. Mineral wool of rigid insulation boards, of the same depth as the joists, can be used to fill the in-between space. If a basement exists underneath, the insulation might be installed from below.

Thickness of insulation is less restricted than for an above-slab condition. However, if the basement is used, a certain height to allow accessibility is necessary and, thus, there might be limitations to the thickness of the insulation placed under the basement ceiling.

§ 4.5 Conclusion

Chapter 4 presented an overview of refurbishment state-of-the-art solution to refurbish the aging building stock. This overview was important to organise and support the decision-making process for refurbishment design. Moreover, the systematic organisation of options is a necessary step to integrate the energy performance of the building into the design phase of refurbishment.

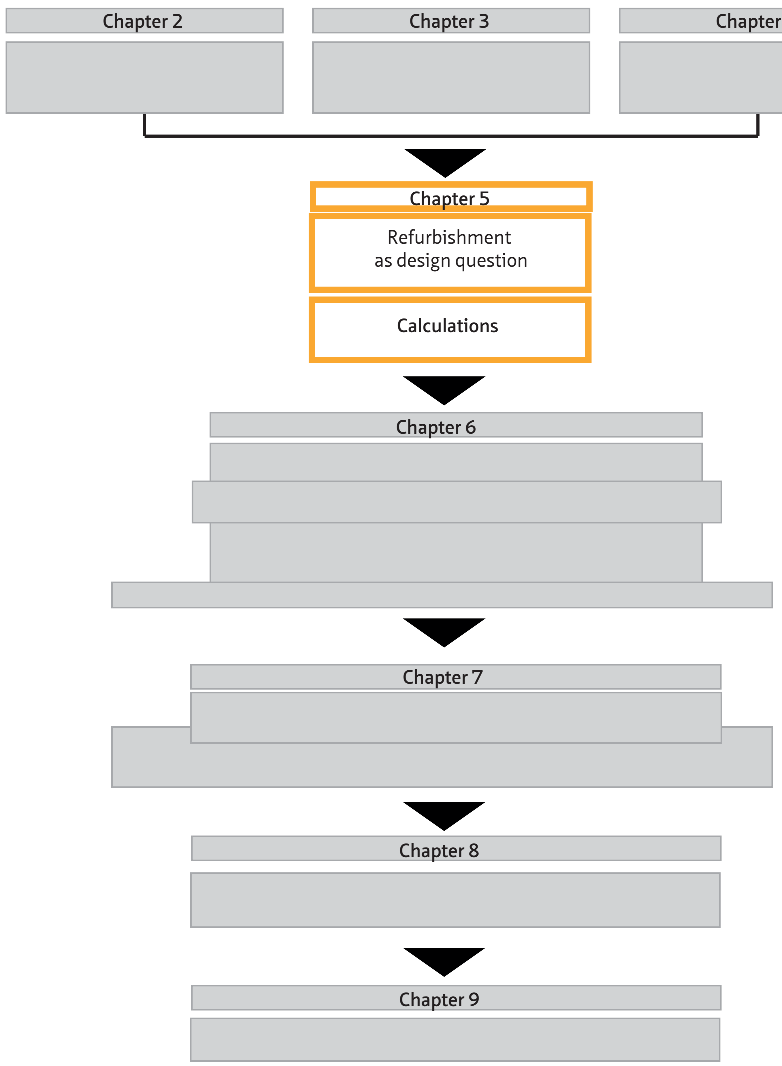
The solutions presented strategies, material and technologies that are the most common in refurbishment practice, with regard to the energy upgrade of the building envelope. They can be combined with additional measures to fix damages and components deterioration, as well as interventions to the structure and floor plan layout, which, however, are not the focus of the research.

Refurbishment interventions can be classified in 5 strategies: replace, add-in, wrap-it, add-on and cover-it. Each strategy has a range of intervention levels that all have a basic principle in common. The strategies result in improvement of the energy performance, along with other modifications to the building's function and layout. An overview was presented in Table 4.1.The purpose of the overview is not to present all possibilities, but categorise them by identifying the basic principle and highlight benefits and limitations in each case, in order to help deciding on the type of intervention, which is a first important step to shape the refurbishment solution.

Materials and technologies refer to the specific retrofitting measures and they are interrelated. They are discussed, however, in separate sections, as it is possible for one material to be used in different measures and the same measure to be realised with different materials. For examples, several insulation materials can be applied as external insulation, while the same insulation material can be used both in internal and external insulation system.

The compilation of solutions was based on analysis of examples, discussion with refurbishment practice stakeholders, investigation of the market and literature research. The specific compilation covers a wide range of solutions. However, it does not exclude possible additional solutions. Given the diversity of available solutions, the decisions that will form a successful refurbishment strategy are not always obvious. However, the purpose of the chapter is not to dictate optimal solutions. In practice, the refurbishment strategy has to fit the individual project and the decisions related to every of the discussed measures have to be investigated for their feasibility and suitability on the specific building.

Each refurbishment option can fulfil an environmental design principle, as as they were discussed in the previous chapter. Apart from the desired function, the choice of measures depends on the existing construction. Therefore, considerations on construction types, as presented in Chapter 2, are necessary. The three chapters are related to the stages of the design process: first,the existing contition and the problems of the buildings are investigated(Chapter 2); then the desired function and performance is deternimed (Chapter 3); finally possible solutions are discussed (Chapter 4). Based on the discussions in Chapters 2, 3 and 4, the suggested approach to answer the research question will be developed in the following chapters.


Chapter 2
Chapter 3
Chapter 4
Chapter 5
Refurbishment
as design question
Calculations
Chapter 6
Chapter 7
Chapter 8
Chapter 9

5 The Façade Refurbishment Toolbox Approach

After discussing refurbishment in terms of existing building stock, possible strategies to enhance building performance and current refurbishment practice, Chapter 5 looks at the design process of refurbishment projects and proposes an approach to support decision-making and improve the design's effectiveness. The first part of the chapter introduces the refurbishment potential and the design process that determines the final result. The thesis proposes an approach to support this process. It is called the "toolbox approach", as it consists of a database of different refurbishment "tools" that the designer can select from. Section 5.3 explains the "toolbox" in more detail, along with the systematic compilation of a matrix that organises the database, including the key components of integrated refurbishment and solutions for each one, respectively. This is the first step in the approach development. In the following section 5.4, the method to quantify the different tools is presented. Simulation software is used to calculate the energy demand before and after retrofitting measures are applied. The simulation set-up is explained in 5.5. Section 5.6 calculates existing building stock and its variations in energy consumption, which is necessary to evaluate the possible reduction of the toolbox refurbishment options, simulated for different measures and different buildings in section 5.7.

§ 5.1 Introduction

The potential of refurbishment to upgrade existing buildings and save energy has been addressed not only by the building industry, which is already busy with refurbishment, but it has also been well researched. The studies are often initiated by regulatory bodies, such as the European commission, research institutes, such as the BPIE, and associations, such as EURIMA (European Insulation Manufacturers Association). The potential of refurbishment to upgrade the energy efficiency of the building stock and resulting savings in CO_2 emissions has been well reported. The BPIE (2011a) in the report "Europe's buildings under the microscope" has calculated possible savings in energy up to 2896TWh/annum and 939 $MtCO_2$ /annum in 2050, which is a reduction of 71% and 90% respectively compared to the 2010 levels. Considering European high-rise buildings alone, achievable energy savings are substantial, ranging from approximately 70% to 80% of the heating demand, corresponding to approximate emissions reduction of 35 $MtCO_2$ (Waide et al., 2006).

Additional studies have concluded that deep renovation has the potential to be the preferred solution from an ecological and economic point of view. EURIMA, in the study "Economics of deep renovation" suggests that the energy related costs per saved kWh for deep renovation can be equal or lower than the actual energy costs, while "shallow" renovations significantly increase the risk to miss the climate targets (Hermelink & Müller, 2011). The study considers deep renovation to offer 70-90% savings and shallow renovation 30-50% savings in energy. BPIE (2011a) has come to similar conclusions, with regard to the depth of the renovation and the potential to reach the 2050 EU CO_2 reduction targets. The study identified four different renovation levels, with the respective energy savings; minor, up to 30%, moderate 30-60%, deep 60-90%, and nZEB more than 90%. Based on these levels, different scenarios have been developed and modelled, projecting the renovation path to 2050 and calculating energy and CO_2 savings, investment and cost savings. Only two of the scenarios achieved the ambitious 2050 EU reduction target. The first scenario suggests a rapid shift towards deep renovation and a growing share of nZEB in the coming 40 years, while the second scenario is two-stage renovation, assuming minor to moderate renovation between 2010-2030 and upgrades 20 years later with additional savings. In both cases, the level of deep renovation should be achieved.

Although the potential and the action to be taken have been identified and appreciated by institutions, researchers and the industry, guidelines come in the form of general suggestion regarding energy savings and benchmark thermal properties that fail to address the diversity of each project. In practice, the detailed implementation of the measures has to suit the individual project (Nemry et al., 2010), in terms of a building's existing construction, location, project specifications, client's ambition, and the architect's decisions. Refurbishment of the aging residential buildings is a complicated task encompassing a number of parameters such as the architectural design, construction and energy efficiency, along with political support and incentives, socio-financial effects and users' behaviour. The design process needs to address all different parameters, which ultimately define the decisions to be taken. Throughout this process and the various constrains to be considered, often energy upgrade is not one of the main consideration. Even though it is part of the project requirements, it is typically calculated towards the end of the design process, in the form of regulatory or voluntary certificates (Dakwale et al., 2011) mostly to be used for official and marketing purposes. In this way, the performance evaluation comes after the strategy has been developed, without influencing the decisions made.

However, the earlier the design decisions are made, the bigger impact with lower cost they can have. Bogenstätter (2000) states that the potential to influence substantial decisions related to construction and operating costs is the highest in the early design process. Evaluation of the performance has proven to be very effective while decision-making amongst various available options (Dakwale et al., 2011). Design cannot easily predict the impact of decisions on building performance and cost. If the designer is provided with an indication of how efficient refurbishment measures are, it is possible to apply them as part of an integrated strategy rather than try to add measures at later stages, after the strategy has been developed. During the early design stages the benchmarking and the possibility to compare alternatives is more important than evaluating absolute values. The ideas-generation phase is iterative and comparative. Most existing tools do not emulate this process and focus on post-design evaluation (Attia, 2012).

To address the aforementioned issues and answer the research question, the current thesis aims at proposing a methodology to evaluate different retrofitting possibilities and provide an evaluation of energy performance in the early stages of the design, when the refurbishment strategy is still under development. This chapter explains the approach development, which starts with analysing the refurbishment design process and looking at existing methodologies to support it. Furthermore, an approach to support decision-making by integrating energy saving potential in the process is proposed. It is referred to as the "toolbox approach", because it includes organising and quantifying different retrofitting measures for each component, which are the "tools" for an integrated refurbishment strategy. A substantial part of the approach development is the quantification of the different measures, by means of energy reduction before and after application. The chapter explains the quantification methodology and presents the results.

§ 5.2 Design process of refurbishment strategies

Achieving energy savings in buildings is a complex process. Reducing the energy demand requires the deployment of effective solutions, which in turn makes it necessary to understand what affects people's decision-making processes (BPIE, 2011a). In order to systematize the decision-making process, researchers have identified different phases in the design and execution of refurbishment strategies. Ma et al. (2012) reviewed the main phases of a sustainable refurbishment program and identified five steps, starting with the project setup and pre-refurbishment survey and ending with validation and verification of the refurbished building. Similarly, Ferreira et al. (2013b) defines five steps that include definition of refurbishment scope, diagnosis real building's conditions, identification of alternative scenarios according to client's choices, technician's experience etc., assessment of the scenarios and optimisation. These stages are present not only in the case of refurbishment, but the construction process in general. Cooper et al. (2008) set up a process protocol model that breaks down the design and construction process into 10 phases that can be grouped into four broad stages; pre-project, which includes determining the need for the project solution, pre-construction, when an appropriate design solution is developed, construction,

which produces the project solution and finally post-construction, which aims at monitoring and maintenance of the project.
Refurbishment design and construction process have been divided in the five phases, shown in Figure 5.1. The phases described are typically encountered, but variations are possible. There are cases that involved a more interdisciplinary process. The design team consists of different experts from the early phase, which blurs the boundaries of which decisions and evaluations were made in each of the phases. Nevertheless, the phases are considered indicative both in interdisciplinary design teams or more traditional team composition. The design phases were concluded based on literature review, such as the above mentioned examples, as well as experience with refurbishment stakeholders, developed during the case studies execution, described in Chapter 6, and the interviews described in Chapter 7.

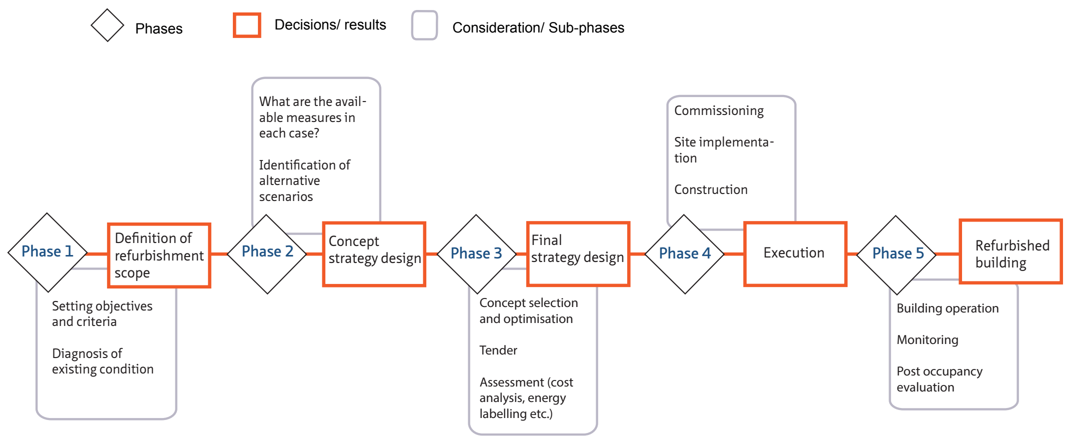


Figure 5.1
Typical phases in refurbishment projects.

Refurbishment projects start with the pre-design, which is Phase 1. This is when the requirements that the refurbished building need to fulfil are defined. It begins with identifying the need to intervene, which then initiates the refurbishment project. The building owner typically makes the decision, according to regular refurbishment cycles, as well as reported problems and users' dissatisfaction. Subsequently, the specific requirements of the project are set. They include the degree of intervention, the building programme, the ambition for performance, such as achieved energy label, the position of tenants during renovation, all in relation with the respective cost and benefits. Requirements are formed by the building owner, typically a housing association or individual homeowners. During this phase, often architects or other experts are involved providing assessment and advice on the building's existing condition and improvement possibilities.

After the requirements for the refurbished building have been established, the design stage begins. More than 80% of the building performance, both in terms of energy savings, generation, and cost, is set during this stage (Ad-Hoc, 2012). The design can be divided in two phases: the concept and the final design. During the concept design (Phase 2), the team looks at the possible measures to implement and identify possible scenarios, which are evaluated in order to select the scenario to be further developed in the final design phase. The scenarios and the decisions that shape the strategy are typically developed by an architect, who has to take in to account the parameters defined in the previous phase; such as building programme, architectural qualities, and depth of refurbishment. At this stage, the architect searches for information to support the design direction (Attia et al., 2012). The various scenarios are then discussed with the building owner, who normally decides on the direction of the strategy, based on costs and benefits of the solution. At this moment, an evaluation is needed to support the decision-making. The evaluation concerns the performance in general, such as energy, comfort, spatial and aesthetical benefits, together with investment aspects. The final design begins after the design team has chosen the strategy concept (Phase 3). It includes the optimisation of the selected concept, preparation for the construction phase, along with assessment of cost and other performance. The assessment of energy use, often in the form of energy certificates, occurs at this stage.

When the design has been finalised and the assessment has resulted in the desired performance, the execution phase begins. It refers to the realisation of the designed intervention, which is the construction on the building site, including demolition of components to be replaced, fixing of damages, acquisition and installation of new components and material etc. Finally, the execution (Phase 4) results in the refurbished building and the last phase of the project, which is the operation by the users (Phase 5).

The interest of the present thesis lies on the first three phases, as they are more influential for the building energy upgrade. User behaviour in the final phase is important for the final energy consumption, but it is beyond the research scope, which focuses on supporting the design of building envelope upgrades. Requirements for energy performance are usually already set in Phase 1, the pre-design phase. The assessment, however, often happens in Phase 3, when the different options have been investigated and the design is being finalised. To deter¬mine the energy performance of a building, architects typi¬cally rely on the input of outside experts, which can slow down the design process (Riether & Butler, 2008).

A wide variety of tools and methodologies are already being used to predict and evaluate a building's performance, in order to support design and construction. Effective Building Performance simulation (BPS) has the potential of reducing the environmental impact, improving indoor quality and productivity and facilitating future innovation and technological progress in construction (Hensen & Lamberts, 2012).

Simulation models assume dynamic and continuous in time boundary conditions and they are based on numerical methods, in order to provide an approximation of real-world complexity. Consequently, model simulation provides a powerful tool to analyse the performance, support iterative design investigations and enable new knowledge. There is a wide range of tools available. Comparison of capabilities of several BPS tools can be found in Crawley et al. (2008) and Attia (2012). US Department of DOE (2012) and IEA Annex31 (2001) provide databases that list tools for BPS.

Refurbishment potential assessments

As far as refurbishment is concerned, the analysis process of Building Performance Simulation (BPS) can be used to support the design of buildings retrofitting. Moreover, a large number of methodologies and tools that focus on refurbishment decisions are available. Ferreira et al. (2013a) provided an overview of 40 decision support systems comparing them in terms of type of building (residential or service; refurbished or new) and in terms of sustainability areas included. They can be classified into discrete decision problem approaches, where a finite group of alternatives is assessed, and continuous or mixed decision problem approaches, which analyse a much wider group of alternatives, often using genetic algorithms. They also have different levels of applicability, varying from simply guidelines to methodology or software.

Furthermore, several European research projects deal with the issue of refurbishment, aiming at providing information for effective evaluation. Some are included in Ferreira et al. (2013a). These methodologies present variations in the scope, objective, methods and results, but they are based on the same principle. They aim at bringing together knowledge and experience of different countries regarding the condition of the existing building stock and possibilities to upgrade it. Below, the methodologies that influenced the development of the present research approach are highlighted. Knowledge of these research projects was used both in the analysis of existing construction types and the investigation of possible measures, and they have already been cited in previous chapters.

Within the scope of a 2-year European research project, involving seven research institutions, EPIQR (energy performance, indoor air quality, retrofit) developed a new evaluation method to define the overall situation of a residential building, regarding its construction, energy consumption and quality of indoor environment (Balaras et al., 2000). The key component of the EPIQR method is the description of the building for which retrofitting and refurbishment is planned. The EPIQR method deals with four technical aspects related to the assessment of the building condition and recommendations for refurbishment. These are indoor environmental quality (IEQ), energy use, costs, and retrofit measures. Retrofit actions have been compiled as a result of discussions with local authorities, housing associations and other large scale apartment building owners who have been involved with retrofitting activities in the past. The methodology developed aimed at assisting apartment building owners who are considering refurbishing their building stock (Jaggs & Palmer, 2000). The results have been translated into a computer based program which identifies the most appropriate refurbishment or retrofitting actions, together with an initial cost estimate, taking into account energy and IEQ issues (Flourentzos et al., 2000; Wetzel, 2012).

COST Action C16 (2011) on the topic of "Improving the quality of existing urban building envelopes" focuses on multi-storey residential blocks of the post-war period, and aims at improving techniques and methods to adapt the envelopes of buildings. The study is based on description and analysis of factors influencing urban buildings envelopes, analysis of how buildings have changes, survey of existing engineering techniques that can be used to upgrade the envelopes and synthesis of possible global approaches leading to guidelines on how to reach maximum value for money in relation to the desired quality. Relations between the most frequently used refurbishment solutions and their impact on sustainability have been worked out.

TABULA (2012) aims at creating a harmonised structure for European building typologies. Each national typology will be a set of model residential buildings with characteristic energy related properties. These will each represent a certain construction period of the country and a specific building size. The European project EPISCOPE (2014) has been launched in April 2013 as a follow-up of the TABULA project. Based on the typology concepts and contents developed during TABULA, the building stock models are elaborated to assess refurbishment processes and project the future energy consumption, in order to result in a concerted set of energy performance indicators.

The European SUSREF project focuses on the exterior wall and aims at a systematic and effective development of new solutions for sustainable refurbishment. The systematic approach develops a common outline of performance aspects in order to facilitate comparing different refurbishment concepts, iterating and optimising between alternative solutions, setting targets for the refurbishment of exterior walls (Häkkinen, 2012). The project that ran from 2009 till 2011 delivered sets of relevant performance specifications for sustainable refurbishment and gave recommendations on sustainable process management for the building industry and standardisation bodies and policy makers (Häkkinen(ed.), 2012).

Finally, within the scope of IEA-ANNEX 36 Retrofitting in Educational Buildings, an energy concept adviser for technical retrofit measures was developed (Barton, 2007). The project identified that currently there is often a lack of understanding of the energy efficiency choices can be made during the retrofit process, and aimed at developing a tool, so that the energy saving potential of different measures could be fully appreciated and appropriate action taken during retrofit. Seven retrofitting options for the building envelope were chosen, including insulating windows, high levels of insulation, solar walls, post-insulation of external walls and roofs, over-cladding systems and doors sealing and insulation. Those options, together with options for heating, cooling and ventilation systems were calculated and combined in an electronic interactive source book (Energy Concept Adviser).

§ 5.3 The toolbox approach

Estimating the refurbished building performance is essential during the decision-making for refurbishment and methodologies to this effect have already developed. Building Performance Simulation (BPS) computer software provides this opportunity. However, only 1% of these tools targets architects during the early design phases, while architects consider these tools non-user-friendly and are reluctant to integrate them into the early design phase of high performing buildings, even though decisions taken during this stage can determine the success or failure of the design (Attia et al., 2012). An analysis of some tools has identified the level of performance feedback in relation to a specific design phase as problem (Riether & Butler, 2008), as they are often used for post-design evaluation (Attia, 2012). There is a need for decision support tools that integrate energy simulation into early design in the architectural practice.

To address the need to support refurbishment decision-making, the literature review included existing methodologies mentioned in the previous section. Research in this direction is important and thus serves as a starting point for the thesis approach development. Nevertheless, in many cases conclusions come more in a form of general suggestions and potential savings. This information is not always easy for the designer to incorporate in the decisions. Moreover, the user's target group of the methodologies often includes the occupants, owners and public authorities, who are parties that influence or even determine the decisions made, but do not actively participate in the actual designing of the strategy.

To improve these aspects, the present thesis focuses on the architect of a refurbishment strategy who makes decisions on the design quality. Based on the analysis of state-of-the-art refurbishment practice, different design options can be found, that go beyond the mere thermal transmittance coefficient upgrade. Furthermore, the present study addresses refurbishment as a design issue that varies in every case. The study sought for an approach that would support the decision-making and enable the development of refurbishment strategies in different cases and for different specifications, without limiting or dictating designers' choices. According to Míguez et al. (2006) an effective rating of the performance must take into account the freedom in designing architectural aspects and installations. Therefore the rating must not punish design components, or judge whether one system is better than another, but should merely assess the quality in each case. Based thereupon, the proposed approach enables the designers of refurbishment projects to know the impact their choices will have and, thus, provide a decision-support instrument.

Depending on the objectives of each project, different strategies can be found. They can range from the basic thermal update of the envelope to comply with energy efficiency regulations to more integrated and sophisticated solutions, in which extra space is added and advanced options for energy upgrade (e.g. renewable energy sources) are available. The first step to enable the evaluation of the different measures is to systematically compile and organise them, according to the building envelope component they address. The result is the refurbishment option "toolbox", which is presented in section 5.3.2.

§ 5.3.1 Systematic organisation of building envelope components' retrofitting measures

In order to be able to assess the energy performance of the refurbished building in the early stages of the design phase, refurbishment options have to be systematically compiled. In this way the designer has an overview of retrofitting measures for the building envelope component, which supports organising his ideas and motivates to address all components, resulting in an integrated strategy. The options compiled aim at offering design solutions to upgrade the thermal envelope and translate the general design principles and performance benchmarks into specific retrofitting measures. After identifying the key components for an integrated refurbishment strategy, as it was defined in 4.1, solutions are given for each one. The measures are state-of-the art refurbishment solutions being used in refurbishment. Different measures are proposed for each component, based on refurbishment practice and experience, analysed in Chapter 4, as well as literature review of research projects on refurbishment, such as EPIQR (Flourentzou et al., 2001), TABULA (2012), SUSREF (Häkkinen, 2012), IFORE (Sdei et al., 2013), and other (Nemry et al., 2010).

The following tables present the systematic compilation of component retrofitting measures, leading to the composition of the toolbox database and matrix. The options for each component are organised in separate parts for the existing condition and the retrofitting measures. Moreover options referring to renewable energy source (RES) or spatial interventions, such as the addition of elevators or extra floors, are mentioned separately. The chapter providing more information on each option is also specified. The component options referring to existing construction can be found in Chapter 2, while retrofitting measures were discussed in Chapter 4. At this point of the thesis the objective is not to explain technical details of the measures but to organise them, which is the first step in the approach development.

The thermal transmittance coefficient U-value used for each construction and measure application has taken into account the legislation requirements set by the EPBD and its translation in the countries' national legislation. Table 5.1 presents the maximum U-values required in different countries and sets benchmark values, also used in the calculation in the next step of the approach development. Looking at the development of requirements in time, the tendency is to lower the U-value coefficient (Hegger et al., 2008). ECOFYS (2007) recommended optimum U-values based on cost-efficiency and energy targets that, in most cases, are more ambitious than current national standards, suggesting that U-value requirements in most Member States should be made more demanding (BPIE, 2011a).

Based on the above discussion, the benchmark for the U-value that the applied measures aim at achieving is 0.2 W/m^2K for opaque elements and 2.0 W/m^2K for transparent ones, which is equal or lower than the requirements in the countries within the thesis focus. As the U-value can vary depending on the exact detailing and thickness of the component construction, the way to achieve the benchmark U-value in the calculations is described in section 5.7.

		Portugal (1)	Greece (1)	France (1)	Belgium (1)	Netherlands (2)	UK(1)	Germany (3)	Denmark (1)	Finland (1)	Toolbox benchmark
Wall	U-value (W/m^2K)	0.50	0.40	0.43	0.35	0.28	0.30	0.24	0.20	0.17	**0.2**
Window		3.30	2.60	2.00	2.20	2.20	2.00	2.00	1.8	1.00	**2.0**
Roof		0.40	0.35	0.43	0.27	0.28	0.20	0.20	0.15	0.09	**0.2**
Floor		0.40	0.70	0.43	0.35	0.28	0.25	0.30	0.12	0.16	**0.2**

(1) (BPIE, 2011a, Figure 2B7), (2) (BRIS, 2012), (3)(EnEV, 2009)

Table 5.1
Benchmark U-value for the building envelope, in different countries and the toolbox approach

External wall

In buildings considered for refurbishment, the external wall is the one of first component to be addressed, as the thermal resistance characteristics in old buildings are far from adequate, compared to current standards for energy efficiency. The measures proposed can be generally grouped in two categories of intervention. The first includes measured that improve the thermal resistance and, thus, reduce heat flow through the wall. This is achieved with the application of additional insulation on the outside, inside or in between the wall. The resulting thermal performance, expressed by the thermal transmittance coefficient U-value, need to comply with the benchmark set in Table 5.1.

The second group refers to measures that create a thermal buffer between the wall and the external environment. This buffer zone is realised as a second façade, which is a new cladding constructed on the outside of the existing wall. The exact construction depends on the condition of each building and design of the refurbishment strategy. It may be suspended by the existing structure or self-supported on new foundations. Moreover, the size of the cavity between the existing wall and the new cladding can vary, from a small cavity to bigger depths that can accommodate new functions, such as a corridor. Finally the new space can be completely incorporated in the thermal envelope, acting as an addition to the existing dwelling. The thermal performance of the façade, including the new layer, cannot be translated in the required U-value for external wall, as it is mostly a buffer, unheated space. Furthermore, the solar heat gains are an important factor to the internal temperature and the heat flow, which defines the energy demand of the dwelling. The U-values in Table 5.2 refer to the coefficient of the new façade. When possible, the best practice thermal conductivity of Table 5.1 is adopted for the retrofitted component.

Window

Window is the best-known form of "opening closure elements" that regulated the building envelope permeability (Herzog et al., 2004). It regulates air exchange in the interior space, daylight, solar gains, view etc. Windows are one of the first components to be addressed in retrofitting, as they are the building envelope component with the highest thermal transmittance. The majority of the windows found in the building stock, normally single glazed or early, uncoated double glazed (Glass for Europe, 2011), have a U-value around 6 or 3 W/ m^2K respectively, which is far over the minimum requirements, presented in Table 5.1.

There are different measures available to retrofit windows, as presented in Table 5.3. Replacement of the existing window with new, better performing is the easiest way to reach the required performance, both for the frame and the pane. It is recommended action in most cases. When replacing the window, enlarging it is also an option, if the construction and the design allow. There are different glazing technologies that can be used to increase thermal resistance, as discussed in Table 4.4. The solar factor g-value also varies, regulating the solar heat gains. The choice depends on the required performance, budget and design. When replacing the complete window is not possible or desirable, less radical measures, such as changing only the existing window pane with an upgraded pane one, or apply a secondary glazing to create a thermal buffer without affecting the existing window.

	Construction		Chapter referred	U-value (W/m2K)
Existing construction	Masonry/ cavity wall no insulation	Masonry of solid brick or stone, 250-400mm/ two leaves of masonry with intervening air cavity. Loadbearing walls. Inadequate thermal resistance	Chapter 2	1.7
	Lightweight concrete/hollow brick, no insulation	Lightweight masonry units, often cladded with additional layer. Non-loadbearing walls. Inadequate thermal resistance	Chapter 2	1.1
	Cavity wall or pre-fab panels with little/outdated insulation	Two leaves with intervening insulation 30-50mm. Inadequate thermal resistance	Chapter 2	0.8
Retrofitting measure	Cavity insulation	Loose or foam insulating material ejected in the existing cavity between inner and outer wall leaf. Increases thermal resistance. Performance depends on existing cavity depth	Chapter 4	0.6 (1)
	Internal insulation	Insulation on interior of wall sheathing with plaster or plasterboard. Increases thermal resistance to required level	Chapter 4	0.2
	Exterior Insulation and Finishing Systems (EIFS)	Rigid insulation boards on exterior of wall sheathing with plaster. Increases thermal resistance to required level	Chapter 4	0.2
	Ventilated façade	Rigid insulation boards on exterior of wall, with panel for finishing. Substructure for the panels needed. Increases thermal resistance to required level	Chapter 4	0.2
	Timber-frame wall	Timber self-supporting structure with insulation infill and panelling. Increases thermal resistance to required level	Chapter 4	0.2
	Second Façade/ Single glazing	Cladding with single glazing, 0.50-2m away from the existing wall. Aluminium frame structure. Thermal buffer, unheated space	Chapter 4	4.3 (2)
	Second Façade/ Double glazing	Cladding with double, insulated glazing, 0.50-2m away from the existing wall. Aluminium frame structure. Thermal buffer, unheated space	Chapter 4	2.0 (3)
RES	BIPV's	Photovoltaic panels installed on the wall, as cladding. BIPV	Chapter 3	n/a
Spatial interventions	Additional space/ Second façade integrated	Additional construction adjacent to existing floor. Possible to be structurally independent, with the loads to be transferred in new structure. Create extra usable, heated space. Prevent heat loss through adjacent façade	Chapter 4	2.0 (3)
	Lift addition per porch	Addition of lift in existing stairwell. Provides access with no significant adaption of the circulation system. May require more than one lift per building	n/a	n/a
	Lift addition per block (access through gallery)	Addition of one lift via new or existing gallery. May require adaption of the circulation system	n/a	n/a

(1) A 50mm cavity is considered,
(2) Referring to single glazing,
(3) Referring to double glazing

Table 5.2
Refurbishment options for external wall

	Construction		Chapter referred	U-value (W/m2K)
Existing construction	Single glazing	Single glazed window panes, g=0.87 (Ug=5.8). High heat losses	Chapter 2	6.0
	Early, double-glazing	Double glazed window panes, g=0.75 (Ug=2.8). Inadequate thermal performance	Chapter 2	3.3
Retrofitting measures	Upgrade windows	Double glazing applied on existing window frame. Increases thermal resistance of window pane	Chapter 4	2.0
	Secondary single glazing	Secondary single glazing window pane, in the inside. Creates thermal buffer. External appearance unchanged.	Chapter 4	4.3
	Secondary double glazing	Increase thermal resistance to required level. Creates thermal buffer. External appearance unchanged.	Chapter 4	2.0
	Replace windows with double glazing	Replace the existing glazing and frame with S-o-t-A double-glazing windows. Increases thermal resistance and ait-tightness.	Chapter 4	2.0
	Replace windows triple glazing	Replace existing glazing and frame with triple glazed windows	Chapter 4	1.6
	Shading fixed	Shading devices placed outside the window pane, in form of overhang, fixed louvers etc.	Chapter 3,4	n/a
	Shading adjustable	Shading devices placed in or outside the window pane, in form of movable louvers, venetian blinds etc.	Chapter 3,4	n/a
Spatial interventions	Enlarged windows	Existing window and parapet removed and replaced with enlarged, improved window pane. Higher solar heat gains	Chapter 4	2.0

Table 5.3
Refurbishment options for windows

Balcony

The balcony is a critical point in the majority of thermal performance upgrades of building envelope, because of the thermal bridging in the cantilevering slabs (Giebeler, 2009). Thermal bridge is a substantial problem, not only because of heat losses but also for condensation risk and effect on occupants' comfort. Retrofitting of the balcony aims at two types of actions; prevent thermal losses through the slab itself, or closing the balcony to turn it into a buffer zone. Finally, a common practice in refurbishment projects is to enlarge existing or add new balconies, to improve the quality of the dwelling with external spaces.

	Construction		Chapter referred	U-value (W/m2K)
Existing construction	Continuous slab, no insulation	Concrete slab projected as a cantilever, balcony structurally connected with internal floor. Thermal bridge	Chapter 2	1.96 (1)
	Separate slab no/little insulation	Balcony constructed as a separate slab, connected with internal floor but not structurally. Thermal bridge	Chapter 2	1.96 (1)
Retrofitting measures	Insulate balcony slab	Insulation applied to all balcony surfaces (top and below)	Chapter 4	0.2 (1)
	Cut off balcony	Cut off the existing balcony and insulate the floor edge	Chapter 4	0.2 (2)
	Balcony cladding single glazing	Cladding with single glazing. Aluminium frame structure.	Chapter 4	4.3 (3)
	Balcony cladding double glazing	Cladding with double glazing. Aluminium frame structure.	Chapter 4	2.0 (4)
Spatial interventions	Balcony space integrated	Cladding with double glazing. Aluminium frame structure.	Chapter 4	2.0 (4)
	New balcony	New, possibly bigger balcony suspended on existing wall, or on independent construction. Thermal break between new balcony and existing envelope. No effect on thermal performance of envelope.	Chapter 4	n/a

(1) Referring to concrete slab,
(2) Referring to thermal break,
(3) Referring to single glazing,
(4) Referring to double glazing

Table 5.4
Refurbishment options for balcony

Roof

Heat loss through the roof is the cause of high energy consumption and lack of comfort in the loft spaces and top floor apartments. Retrofitting of the roof is an essential measure in every refurbishment strategy. Different options can be applied to upgrade the roof. The choice depends a lot on the construction of the roof and the function. In the case of an existing pitched roof, for example, different measures can be applied, whether the attic space is occupied and heated or not. Moreover, there is always the possibility to remove the existing roof and apply a different construction, or even an additional floor. As those measures result in extra loads, the structural feasibility has to be investigated in each project. The U-value refers to the thermal envelope component. For example, if the attic is heated and the coefficient refers to the pitched roof. On the other hand in unheated attics, if the insulation is applied on the top floor slab, the benchmark U-value refers to the slab.

	Construction		Chapter referred	U-value (W/m2K)
Existing construction	Pitched roof, timber rafters no insulation	Rafters, sheeting, Counter battens, roof covering, Plaster-covered, and no insulation in cavity. Inadequate thermal resistance	Chapter 2	2.50
	Concrete slab, no insulation	Plaster, 130-160mm reinforced concrete slab, screed. Inadequate thermal resistance	Chapter 2	1.96
	Little/outdated insulation	Plaster, 130-160mm reinforced concrete slab, 20-40mm insulation, screed. Inadequate thermal resistance	Chapter 2	0.8
Retrofitting measures	Pitch roof insulation	Insulation between rafters, lining. Increases thermal resistance to required level. Advised for heated attic	Chapter 4	0.2
	Insulation of top floor slab	Insulation on attic floor. Advised for unheated attic. Prevents heat loss through top floor slab to unheated attic space.	Chapter 4	0.2
	Flat roof	Additional insulation on roof slab, waterproofing. Increases thermal resistance to required level	Chapter 4	0.2
	Green roof	Additional insulation on roof slab, waterproofing, soil and plants. Increases thermal resistance to required level	Chapter 4	0.2
RES	Photovoltaic	Photovoltaic panels installed on the roof, preferable at optimal angle	Chapter 3	n/a
Spatial interventions	Additional floor	Additional construction on top of existing floor. Possible to be structurally independent, with the loads to be transferred in new structure	Chapter 4	0.2

Table 5.5
Refurbishment options for roof

Ground floor

Refurbishment needs to address the heat loss through the heated first floor. Several variations can be encountered. Firstly, the occupied, heated space floor can be adjacent to the ground. In this case, there is heat flow to the ground, as it has lower temperature than the occupied space. If there are unheated spaces such as storage or garages, heat flows from the first floor to the unheated spaces below. Those spaces can be partly underground, as basements.

To prevent heat loss, the floor slab of the heated space must be insulated. Depending on parameters such as the construction, the height availability etc., the slab can be insulated on top or underneath. Insulation thickness and type can vary, based on project specification. When an unheated space exists, the heat loss can be prevented if it is converted into heated space. Proper insulation of basement walls and floors is then necessary. Apart from the energy benefits, extra usable space is added to the dwelling. Similarly to the roof, the U-values in Table 5.6 refer to the thermal envelope component, which is either the floor adjacent to the ground or to an unheated basement.

	Construction		Chapter referred	U-value (W/^{m}2K)
Existing construction	Slab on ground, no insulation	Reinforced concrete slab or wooden beams construction. Heat loss from first floor slab	Chapter 2	1.96
	Basement unheated. Concrete slab, no insulation	Reinforced concrete slab or Wooden beams construction. Heat loss from first floor through basement ceiling	Chapter 2	1.96
	Little/outdated insulation	Reinforced concrete slab or wooden beams construction with 20-40-50mm insulation on top. Heat loss from first floor through basement ceiling	Chapter 2	0.6
Retrofitting measures	Insulation on top of ground/ first floor slab	Insulation on top of the heated floor slab. Increases thermal resistance to adequate level	Chapter 4	0.2
	Insulation under existing floor	Insulation under first floor slab. Increases thermal resistance to adequate level	Chapter 4	0.2
Spatial interventions	Additional floor-occupied basement	Basement heated. Insulating basement floor and walls advised.	Chapter 4	0.2

Table 5.6

Refurbishment options for ground floor

Building technical systems

Retrofitting the building technical installation to provide high efficiency for heating, cooling and ventilation is an integral part in refurbishment planning that aims at upgrading the energy performance. Therefore, they are included in the systematic compilation of refurbishment measures. Different technologies for the building technical installations and renewable energy sources (RES) have been discussed as active measures for environmental design in chapter 3. An overview is given in Table 5.7.

The measures to upgrade the building envelope components and retrofit building services are not competing to each other. On the contrary, they are complementary and their application should be parallel. Firstly, the upgrade of the building envelope aims at minimising the energy demand, which will be covered by the integration of RES, such as PV panels and solar collectors, if possible. The building serviced will then need to supply the remaining demand as efficient as possible, which is the third step in the "Trias Energetica" (AgentschapNL, 2013).

Often, it is possible to include building technical installation and RES in the design of the building envelope. This is the case in BIPV in the façade, solar collectors on the roof, ventilation inlets in the window frames, or even more complicated and advanced option integrating the services in the envelope components. Such an example is the concept developed by Fraunhofer Institute for Solar Energy Systems ISE. It consists of prefabricated façade components that integrate external wall insulation system with heating, ventilation and air conditioning components (Coydon et al., 2013).

Therefore, along with options for the building envelope the toolbox includes options for ventilation and heating. The design of the technical installations retrofit is not described in detail, as the research focussed on the building envelope. Nevertheless, the installations are an important part to be considered; that is why they are included in the toolbox. Moreover, certain options, such as ventilation system and PV cells, are connected with the building envelope construction and it is necessary to be included in the overview of building envelope.

	System	Description	Function
Ventilation	Natural ventilation	Air movement through the façade's openings, driven by the climatic forces	Exchanges the heated internal air with cool outside air. Cooling effect
	Trickle ventilation	Adjustable openings on window frames	Constant minimum air supply
	Natural inlet/ mechanical exhaust	Air is supplied and/or extracted from the building or both by a fan and using exhaust air terminal devices, ducts and roof /wall outlets	Providing fresh air to occupants and removing pollutants from a space
	Mechanical inlet/ natural exhaust		
	Mechanical ventilation		
	Ventilation system with heat recovery (HR)	Heat exchangers heat or cool incoming fresh air, recapturing 60 to 80% of the conditioned temperatures	
Heat source	Gas or biomass stove	Heat produced and directly transferred to the space	Generate heat
	Fossil fuel boiler in each dwelling	Transfers the heat liberated during combustion into the heating system	Generate hot water for hydronic heating systems and DWH
	Fossil fuel boiler per block		
	Replace existing boiler in each dwelling, high efficiency	Transfers the heat liberated during combustion into the heating system. Efficiency >80%	
	Replace existing boiler per block, high efficiency		
	CHP installation	Provide simultaneous generation in one process of thermal energy and electrical and/or mechanical energy	
	Heat pump	System to transfer heat from the source by means of electrical or thermal energy at a high temperature to the heat sink	
	Biomass boiler	Transfers the heat liberated during combustion into the heating system, using biomass fuel	
	Solar collectors	Convert direct solar radiation into an other forms of energy	
	Geothermy	Water is pumped down a borehole in the ground and back to the surface, allowing the heat to be transferred by simple conduction from the ground to the water	
	District / community heating	Heat is generated in a central source and delivered on demand as hot water to group of buildings	

Table 5.7
Building systems retrofitting options

§ 5.3.2 The toolbox matrix

The compilation of the options of Table 5.2 until Table 5.7 results in the Façade Refurbishment Toolbox. This toolbox is essentially a database of possible measures that can be implemented in refurbishment projects. The information is organised in a matrix, as presented in Table 5.8. The refurbishment solutions are organised according to the key components of the building envelope. The measures can be combined depending on the specific requirements of every project and design, resulting in the integrated refurbishment strategy. Addressing solutions for all the above composes integrated refurbishment strategies. The measures are scaled according to effort and level of intervention. In this way, each project can be located on the top, middle or bottom of the table according to requirements. Moreover, it is possible to combine various levels, for example apply a more complex solution for the wall and a simpler one for the rest the components. Moreover, the toolbox matrix is organised according to the efficiency of the measure and the level of intervention, based on preliminary calculation (Konstantinou & Knaack, 2011, 2013). This helps to easily identify the possible options depending on the projects ambitions and, thus, facilitate the selection.

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

Table 5.8

The toolbox matrix

§ 5.4 Method to quantify the toolbox

The previous section introduced the toolbox approach and concluded to the systematic compilation of retrofitting measures for building envelope components, which was the first step in the approach development. The second step is the quantification of the different tool. Providing a number of how much energy can be saved by the measure application gives an indication of the measures quality and characteristics and makes them comparable, supporting the decision-making of refurbishment strategies. This section explains the boundary conditions and the methodology to quantify the toolbox retrofitting measure.

§ 5.4.1 Boundary conditions of the toolbox quantification

The toolbox approach aims at providing an assessment of refurbishment options impact on the energy performance of residential building. Buildings performance refers to a number of parameters, such as thermal comfort of occupants, energy conservation features, solar energy utilization, incorporation of recycled materials, reduced building construction waste, etc. In the present study, the building performance is assessed in terms of energy efficiency. The comfort of the users is taken into account, as a precondition in the calculation. Adequate ventilation rates and comfort temperatures are ensured in the thermal performance simulation of the dwelling, as part of the inputs to be explained in section 5.5.1. The resulting energy consumption depends on these conditions.

The energy efficiency indicator in the present study is heating demand, as it accounts for the largest percentage of the energy consumption in residential buildings. Namely, more than half of the final energy consumption of residential buildings in the EU is used for space heating, reaching up to 70% in some countries (BPIE, 2011a; Itard & Meijer, 2008). Water heating also plays a major role, accounting approximately for one fourth of energy use in dwellings. Even though the importance of water heating is addressed by the toolbox, e.g. with the use of solar panels, it is not considered in the energy efficiency calculation in the current study. Cooling loads, if necessary are included in the energy demand. However, in the case of residential buildings cooling is not as important as in non-residential, as most dwellings rely on natural ventilation (Itard & Meijer, 2008), particularly in the areas and climate within the scope of the study (BPIE, 2011a). The usage patterns prior to and after the refurbishment are assumed to be comparable; thus, for example, no significant change in the use of appliances is expected.

The impact of retrofitting measures is quantified as the reduction in the current heating energy demand. It is expressed by the percentage of the reduction in current demand, calculated with the following formula: [100x (Current demand-New demand)/ Current demand] %. This suggests that the lower the resulting energy demand is, the higher the reduction and, thus, the percentage would be. The energy efficiency of the building is therefore improved, as thermal comfort is achieved with less energy. To determine the energy demand, the thermal performance of the building is simulated. Dynamic simulation is considered as the appropriate method for the purposes of the research, as it can provide hourly data on internal temperature and heating demand throughout the year. In this way, not only the annual heating demand is measured, but also the internal thermal comfort is ensured.

The software used for the thermal simulation is DesignBuilder. There is a wide variety of software for building energy analysis (DOE, 2012) and a number of comparative surveys of energy programs have been published (Attia, 2011; Crawley et al., 2008). DesignBuilder was chosen as appropriate for the purpose of this study, because it can generate a range of environmental performance data such as: energy consumption, internal comfort data and HVAC component sizes. It provides a modelling interface, integrated with EnergyPlus, which is the U.S. DOE building energy simulation program for modelling building heating, cooling, lighting, ventilating and other energy flows. Output is based on detailed sub-hourly simulation time steps using the EnergyPlus simulation engine (DOE, 2012). The software calculates heating and cooling loads using the ASHRAE-approved "Heat Balance" method implemented in EnergyPlus (DesignBuilder, 2012).

The rating applied is classified as "Tailored rating", according to European Standard EN15603 (2008). The actual data for the building's size and construction were used, data for the location climate were input and occupancy data were based on the building's function. The simulation is based on European standards for thermal comfort for required temperature, overheating and ventilation (EN15251, 2007). The inputs are explained in detail in section 5.5.1. The use of European standards for can increase the accessibility, transparency, comparability and objectivity of energy performance calculations (Dijk, 2012)

The energy calculated refers to energy need for heating, namely the heat that needs to be delivered to or extracted from a conditioned space to maintain the intended temperature conditions during a given period of time (EN15603, 2008). Thus, the savings are in the heating energy need, or thermal energy. Primary energy savings can be addressed, if we consider the current and retrofitted systems efficiencies and the primary energy factors of the area and fuel used. This information is difficult to be generalised and differs in each building. Moreover, within the study's scope, comparing the heating energy need is more adequate to understand the improvements in the building envelope, because the reduction in primary energy is influenced significantly by the system and fuel type.

An important limitation to be considered is the unavoidable uncertainties in the simulation. Any building performance assessment and simulation is based on assumptions about the building's function. Logical as these assumptions might be, the actual operation can differ significantly, resulting in different actual energy demand than predicted (Haas et al., 1998; Hens et al., 2010). For this reason, it is very difficult to come up with a specific, reliable number for the real energy demand. Expressing the improvements on building performance as a percentage of reduction in the current energy demand has the advantage of tackling the uncertainties of the simulation. When comparing current and new energy demand, an assumption is that the usage patterns will not change significantly. Even though this may not always be the case, as differences in usage patterns after refurbishment have been observed (Herring & Roy, 2007), the comparison of the demand before and after, expressed in a percentage, is still indicative of the improvement that can be applied in different buildings with similar characteristics.

An apartment is used as the reference dwelling. The position of the apartment in an apartment block is important for the energy demand. The approach uses the results of the typical apartment as reference for retrofitting measures effect. Typical is the type of apartment that is repeated more times and its energy savings are then more important for the total savings of the block. In apartment buildings, typical in most cases is a middle apartment, in a middle floor, which is type T2 in the thesis methodology (Figure 5.3). Moreover, typical is the apartment where a measure has more effect, because it is then an appropriate reference to identify and isolate the measure quality. Identifying the typical apartments is part of the methodology in section 5.6.2. With regard to measures for the external wall, window and balcony, the typical apartment is the middle T2. For roof and ground floor retrofitting measures, typical are considered the top (T3) and ground (T1) apartment respectively. Nevertheless, apartment with different position are simulated, because it is necessary in order to calculate the energy savings in a whole building or in different buildings types, such as row houses. The need for information of typical or other types of dwellings depends on how the information will be used and varies in every design process. In the approach development and quantification discussion, the typical apartment is used, unless otherwise indicated.

The energy demand is calculated in kWh/m^2 per year and it refers to the living and bedroom of the dwelling. The two rooms are adjacent to each other and to the same façade (as seen in Figure 5.2.c). They will be further referred to as model room. Using the energy demand of those two rooms as oppose to the apartment average is more suitable for the research purpose that requires isolating the effect of each measure and each orientation. In this way, the results can be generalised in dwellings with only one orientation or in cases where different measures are applied in the different facades of the same dwelling. If the whole apartment were used as reference, instead of the model room, the total energy consumption would be influenced by solar gains in more than one orientation, as well as internal gains in different zones and, thus, would not be indicative to isolate the effect of specific measures on specific orientation.

Finally, as the calculations are generic, to address a wide range of building variations, the simulations are not of high resolution. This suggests that the objective of the simulation is not to obtain an optimised performance, which would demand more specified information about building construction, operation etc., but show the retrofitting measures performance under similar conditions, in order to render them comparable. The information provided by the approach must be perceived as an indication for the resulting thermal quality, in order to evaluate the measure.

§ 5.4.2 Methodology

To evaluate and compare refurbishment measures, each option needs to be quantified separately. Since this quantification is expressed as reduction in current energy demand, the method used to isolate the impact of each option has two distinct steps. First the existing building's condition needs to be simulated, to determine the current energy demand and, subsequently, the building after the application of the refurbishment measure, to evaluate the impact on energy demand.

1 Determine current energy demand

Since the impact of each refurbishment measure is expressed as the percentage of reduction in current energy demand, the first step is estimating this demand. The building stock is not uniform and the existing condition of a building determines the energy demand. The toolbox calculations aim at covering a wide range of buildings and, therefore, a number of models where simulated, based on variations of the construction, position in the apartment block, window-to-wall ratio (WWR) and orientation. The variations of the existing dwelling models are explained in section 5.6. They have resulted in 288 models. Each model, also referred to as building type, is the combination of one variation for each parameter of construction type, apartment position, window-wall ration, and orientation. Even though these variations are not exhaustive, they are important to the future toolbox application, as any building can be associated with one of the existing models, to provide the indication of refurbishment impact.

2 Estimate refurbishment option impact on energy demand

To isolate the measure effect, every option is simulated separately, by changing only one component in the model of the existing building. This would suggest that every option of Table 5.8 should be applied to all 288 existing building models, resulting in a vast amount of models and respective results. However, variations of the existing building do not always result in different reduction of the energy demand, depending on the kind of variation and the component to be retrofitted. In order to effectively calculate and use the results, it is, hence, necessary to identify the relevant variations and the important factors in each refurbishment measure and for each component. The methodology followed to define the variables to simulate the toolbox refurbishment options has several steps. The following steps are applied for each one of the toolbox retrofitting measures of Table 5.8.

A. Measure variations

Firstly, variations for each retrofitting measure are simulated, applied in one of the existing building types. This building type consists of a combination of characteristics determined in the first step in the methodology. The apartment position is typical, as it will be further explained. The orientation is east or west, to avoid the effect of high solar gains or their absence in south and north. The energy demand calculated is compared to the existing energy demand of the specific building type. The variations depend on the specific measure and concern different material, for example insulation material or glazing, material thickness, windows shading and operation etc. The variations are compared and whose resulting in significant differenced on the energy reduction will be further simulated, in different construction types, opening proportions and orientations, in step D.

B. Construction types variation

One of the measure variations is applied in several building types. The selected models differ in key construction variables, according to the measure tested. For example, models with different wall construction are simulated with regard to external wall retrofitting measures. Similarly, measures concerning window upgrades are compared in models with different construction of existing windows. The results on the energy reduction are compared, in order to conclude which building types will be further simulated, on the basis of significant differences on energy reduction. If different building types result in similar percentages of reduction, only one will be simulated in step D.

C. Window-to-wall ratio

The models with different construction types are also checked for different WWR, to establish if the impact on energy demand is significant. Steps B and C often happen together, as described in section 5.7. After comparing the energy reduction in the building types, the most relevant are selected for the final simulation.

D. Final calculations

The previous steps have concluded with each measure specifications and the building types that are relevant to simulate. These models are then simulated for four orientations and six apartment types. This results in the toolbox database, consisting of a range of reduction percentages, corresponding to different building types.

Next sections describe in detail the process followed to calculate the energy demand before and after the application of the toolbox refurbishment options. Section 5.5 explains how the simulation was set up. This includes the inputs provided to the simulation software, such as comfort requirements, dwelling function etc., as well as the simulation outputs that are generated, namely the energy demand of each dwelling modelled and the indoor temperatures. Subsequently, section 5.6 presents the existing dwellings variations that are simulated, as the first step in the methodology described above. Finally, the steps 2.A-D used for the toolbox options calculations are explained in detail for each component in the section 5.7.

§ 5.5 Simulation set-up

In order for the any thermal performance simulations software, such as Design Builder used in this case, to do the calculations, certain inputs are required. The information needed refers to climate, building geometry, size and function, occupancy patterns, components construction and energy supply systems. Within the scope of the thesis that focuses on building envelope upgrade, the key parameter for the thermal performance is the construction of the components. These are the main input to be changed to model different refurbishment options. Details on the construction and opening types will be described further in the chapter, along with the respective model.

The simulation set-up included defining the information to be used as input, as well as determining what information is needed for the tools quantification. Section 5.5.1 explains the inputs that stay constant for all the models, unless otherwise indicated and they are related to climate data, model geometry, activity in the simulated zones, function of HVAC systems and equipment. The main output to estimate the measures' effect is the heating energy demand section. Moreover the internal temperatures are checked to be within thermal comfort limits.

§ 5.5.1 Simulation inputs

The input categories are organised according to the requirements of the simulation software used, Design Builder. Different simulation software might organise the input categories differently, but the nature of the data would be similar. They were decided based on European standards, for example in the case of indoor comfort and ventilation, as well as assumption, such as for the apartment occupancy.

Climate

Part of the research's boundary conditions is to focus the approach on one type of climate, the North-West European climate, encountered in countries such as the UK, Germany, and the Netherlands. The reason for this decision is to reduce the complexity of the Toolbox as a decision support instrument. However, the proposed methodology to support decision-making does not exclude its applicability in different climates. Nevertheless, the numerical output of the toolbox calculations is expected to be different.

The weather data used as an input for the simulation refer to Amsterdam, the Netherlands. The data are available by the U.S. Department of Energy, in order to be used in EnergyPlus Simulation Software (Data, IWEC2012). According to Köppen Climate Classification System (Peel et al., 2007), the Netherlands climate is classified as Moist Mid-latitude Climate, with adequate precipitation in all months and no dry season (Cfb). Climates with the same classification are encountered in Germany, France, United Kingdom, Austria and European countries, as seen in Figure 1.2 (Kottek, 2006, fig. 1). Heating demand is the main concern, as extra energy for heating is needed during 2/3 of the year (Climate Consultant2011), to provide comfortable temperatures inside the dwelling.

Geometry

The geometrical characteristics of the simulated dwelling are modelled in the software interface. Design Builder provides a user-friendly modelling environment that works with building models. A typical apartment (Figure 5.2.c) was designed and then copied to make a block, consisting of ground, middle and top-floor apartments. The floor plan in the model was based on typical floor plans in post-war apartments, found in literature such as Priemus and Elk (1971). Even though the room dimensions and the external wall to floor area ratio determine the energy demand, it is not possible to model every combination. To address the uncertainties of the exact room and dwelling size, the energy demand is referred in kWh/m^2.

Zones

Thermal simulation software uses zones to simulate interior, as oppose to the outside, environment (Crawley et al., 2008). Spaces with similar characteristics can be grouped as one zone. The complexity of the simulation increases when multiple zones are modelled. In the present model, each room is modelled as a separate zone. This is because each room has different function in terms of occupancy rate and schedule, ventilation rates etc. Furthermore, the different function affects the internal gains. Table 5.9 summarises the different zones and the respective inputs.

Activity

The activity that takes place in each zone is essential, as it determines the internal heat gains. Information regarding activity includes the occupancy levels, in terms of people per m^2 and the time during which the zone is occupied. It also includes HVAC systems temperature set-points and gains from lighting and equipment.

Schedules

The schedules define the hours of the day that the respective input takes effect. Apart from describing the hours when the zone is occupied, determining the metabolic internal gains, schedules also indicate the use of light and other equipment, as well as the HVAC systems.

The occupancy schedules can vary significantly in different dwellings. The differences between assumed and actual usage patterns are the main cause of uncertainties in building performance simulation (Branco et al., 2004; Haas et al., 1998; Hens et al., 2010; Majcen et al., 2013). Detailed electricity and thermal demand profiles for domestic housing are an important prerequisite for the accurate analysis. Richardson et al. (2008), for example, developed an approach that generates statistical occupancy time-series data to be used as input to any domestic energy model. Looking at the patterns of their approach, a wide range of variations in occupancy schedules can be found.

The simulations executed for the toolbox calculations are not high-resolution to require diverse occupancy data, such as the aforementioned approach. To give a generic, indicative value on the energy demand and, most importantly, to be able to compare the results for different options, one schedule that can be considered as representative was applied to all simulations.

The occupancy schedule is not always the same with the schedules applied in equipment and HVAC systems. When the schedule is set to "on", the input that it refers to is always applicable, unless other parameters affect its applicability, for example a temperature set-point. To understand the schedule settings in Design Builder, Figure 5.2.e and f present as an example the occupancy schedules for living-room and bedroom zones. It is expressed in percentages of the total value. This means that since 4 people are assumed to occupy the apartment, all of them are in the living room when the percentage is 100% from 18.00 to 21.00, while only 2 are there when the percentage is 50%. Similarly, the 2 people accounted in the bedroom occupancy are there from 0.00 to 7.00 and only 1 from 7.00 to 8.00.

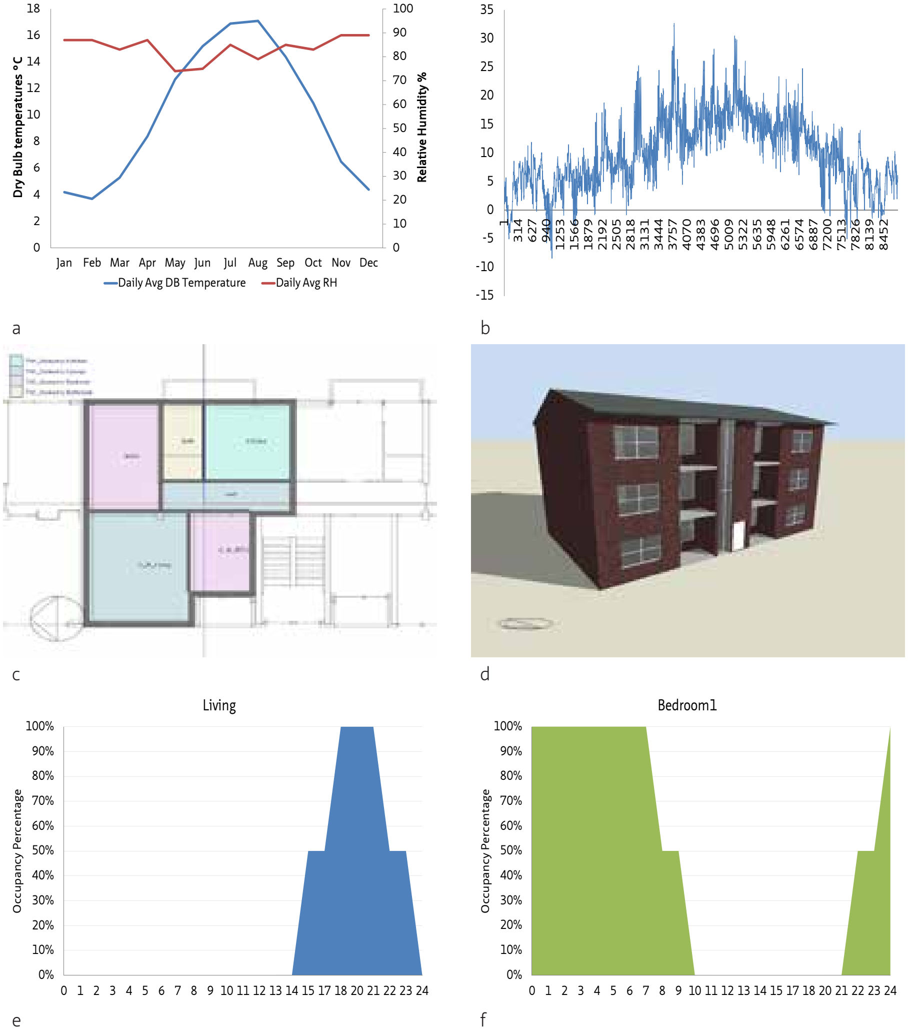


Figure 5.2

(a) Average temperature and relative humidity and (b) hourly Dry Bulb temperature (oC) data base on weather data (Data, IWEC2012)
Floor plan (c) and 3d impression of the model (d) in Design Builder.
Occupancy schedule (e) the living room and (f) bedroom

HVAC

Defining heating and cooling thermal comfort criteria, such as minimum room temperature in winter and maximum room temperature in summer, are used as input for the calculations. These criteria are usually specified in national building codes for design and dimensioning of systems (EN15251, 2007). As the present thesis does not focus in one country in particular, the values are based on standards issues by the European Committee for Standardization, or other literature sources. European standards give, in informative annexes, recommended input values for several categories of expected performance. The category used in this case is II, according to Table 1 of EN15251 (2007), which refers to normal level of expectation for the building performance and should be used in new buildings and renovations.

Table 5.9 summarises the simulation inputs to the respective zones. These inputs remain the same in all current model simulation, unless otherwise indicated. The inputs that vary in different models of existing buildings are explained in section 5.6. In the refurbishment options simulation, some are modified with regard to the specific measure. For example, when double glazed windows with new frames are applied, the infiltration rate is reduced, as the building becomes more airtight. Details on each measure modelling are described in section 5.7.

Heating

Heating energy is necessary to achieve thermal comfort and the heating energy demand is the main indicator for energy efficiency, according to our methodology. To calculate the heating demand through the simulation, heating function should be turned on. A standard hot water radiator system is used. The heating energy demand is the main indicator for energy efficiency in the thesis scope and it is further explained in section 5.5.2 on energy output. The temperature set point for heating is 20°C for bedrooms and living-room and 18°C for kitchen and bathrooms (EN15251, 2007, Table A.3).

Ventilation/ Infiltration

The existing building is naturally ventilated. Thus mechanical ventilation and cooling are excluded from the current condition simulation. In the refurbished building, however, the ventilation is changed to mixed mode, natural inlet-mechanical outlet. Natural ventilation is provided through the modelled openings. The ventilation set point is 23oC, suggesting that if the interior temperature rises over this point the windows open. The percentage of windows opening varies depending on the measure. The objective is to avoid overheating and to this end the percentage of opening can change to achieve comfort temperatures.

	Living	Bedroom1	Bedroom2	Kitchen	Bathroom	Hall	Basement	Roof
Zone type	Standard, conditio-ned	Standard, conditio-ned	Standard, conditio-ned	Standard, conditio-ned	Standard, conditio-ned	Standard, conditio-ned	Semi-ex-terior, unconditi.	Semi-exterior, uncondit.
m^2	19.5	18.4	13	7	5.2	11	0	0
Occupancy	4	2	2	2	1	2		
Density (people/m^2)	0.2	0.1	0.15	0.28	0.19	0.181	0	0
Schedule	15-23	22-9	22-9	24, 7 days 0.2	24, 7 days 0.1	24, 7 days 0.2		
Metabolic	0.8	0.8	0.8	0.8	0.8	0.8	0	0
Environmental Control (1)								
Heating Set-point Temperature	20	20	20	18	18	18	n/a	n/a
Cooling Set-point Temperature	26	26	26	26	26	26	n/a	n/a
Natural Ventilation	23	23	23	23	23	23	n/a	n/a
Mechanical Venti-lation	low	low	low	low	low	low	n/a	n/a
Minimum Fresh Air (2)								
Fresh air l/s/person	7	7	7	10	15	7	0	0
Mechanical ventilation per area l/s/m^2	0.42	0.42	0.42	0.42	0.42	0.42	0	0
Lighting								
Lux (3)	200	100	100	500	200	100		
W/m^2 (4)	9	9	9	9	9	4.5		
Equipment intern. gain W/m^2 (5)	5	5	5	30	5	0	0	0
Airtightness								
Infiltration rate m^3/h per m^2 exposed surface (6)	5	5	5	5	5	5	5	5
(1) (EN15251, 2007) Table A.3								
(2) (EN15251, 2007) Table B.5								
(3) (EN12464-1, 2011) Tables 5.1.3, 5.12.5, 5.2.4, 5.36.17								
(4) (GPP, 2012) Tables 3.2								
(5) (CISBE, 2006) Table 6.2								
(6) (EN15242, 2007) Table B.1								

Table 5.9
Inputs for each zone

The ventilation strategy, according to EN14788 (2006), is to provide a continuous, relatively low background ventilation air flow rate, to deal with the background pollutants together with a higher intermittently operated extract air flow rate provided in the activity rooms to deal with most of the specific pollutants, such as the kitchen and the bathroom. To simulate this principle, constant mechanical ventilation to the minimum 0.42 $l/s/m^2$ is set, according to Table B5, EN15251 (2007). In practice this constant air flow will be achieved either by trickle ventilators or by windows 'cracked' open (CISBE, 2006). To select the ventilation rate for the residence, we are based on the required rate per floor area and the number of occupants (EN15251, 2007, Table B5). The higher value should be selected for the total ventilation rate of the residence. Outdoor air is supplied primarily to living rooms and bedrooms. The air is exhausted from the kitchen, bathroom and toilets, according to the air flow rates in column 4 of Table B.5 in EN15251 (2007).

With regard to infiltration, the value for an average leakage levels is used. This is 5 m^3/h per m^2 outer envelope at Q50Pa, according EN15242 (2007), table B1. Even though higher infiltration rates can be assumed in existing buildings, extreme infiltration rate were not used in the simulation, to avoid affecting considerably the results and the comparability of the options. In refurbishment options simulation, the leakage level in sometimes improved (e.g. to 3 or 2.5 m^3/h per m^2 outer envelope at Q50Pa), depending on the type of refurbishment measure.

Cooling

The cooling temperature is set at 26°C, according to European standards (EN15251, 2007). It is also the upper limit for acceptable thermal comfort benchmarks (ISO7730, 2005). However, the cooling function is not applied in the models as long as the overheating hours are within acceptable thresholds. The upper temperature limit is 26°C, which is the cooling set-point, and should not be exceeded for longer that than 3-5% of the time according to Annex G of EN15251 (2007) or 300h according to Herpen (2007). Evaluating overheating risk is part of the simulation output that will be explained in section 5.5.2. If the simulation with natural ventilation results in overheating outside acceptable thresholds, the cooling function should be applied.

Lighting and equipment

Lighting specifications are important in terms of energy consumption. Not only do lights account for a percentage of the energy consumption of a household, but also they increase the internal gains, with respective results on the heating and cooling loads. To address this issue, the lighting requirements and use are considered in the simulation. Both required illuminance in lux and heat gains in W/m^2 are used in the simulation. The lighting schedules are based on the activity schedules set for each zone and the time of the day. This means that lights are used to provide adequate illuminance only during the time that the zone is occupied, but during the night a smaller percentage of use (20%) is assumed even in the space is not occupied. The requirements are set according to European standard for lighting (EN12464-1, 2011), as indicated in Table 5.9. The lighting control is switched on, so that the lighting is balanced with daylight to achieve the required illuminance. The lighting energy in W/m^2 for residential buildings is set according to EU Green Public Procurement (GPP, 2012). Lighting specifications remain the same prior to and after the renovation. The output may be different though for measures that affected the solar radiation penetration, such as shading or enlargement of the windows.

§ 5.5.2 Simulation output

In dynamic simulation the energy consumption is calculated on an hourly basis (EN15251, 2007). For the purpose of the thesis' research, annual simulation was used. Based on the information used as inputs, hourly data on the building performance throughout the year were generated. Design Builder can generate a wide range of simulation data, including energy consumption broken down by fuel and end-use, internal air, mean radiant and operative temperatures and humidity, underheating and overheating hours distribution curves, heat transmission through building fabric and other (DesignBuilder, 2012). Out of the complete range, the data used to evaluate the current building condition and refurbishment measures, based on the methodology of the toolbox quantification explained in section 5.4, are heating energy demand and internal temperature.

Energy demand

Heating energy demand is the heat that needs to be delivered to a conditioned space to maintain the intended temperature conditions (EN15603, 2008). The heating energy need, or thermal energy, depends directly on the quality and design of the building envelope, as it is influenced by fabric, ventilation and infiltration heat losses and solar heat gains (McMullan, 2002). The improvement in the building envelope achieved with the refurbishment has, hence, a significant effect on the heating demand, which is how the methodology evaluates the efficiency a retrofitting measure.

Heating energy demand should not be confused with primary energy demand. Primary energy savings can be calculated, taking into account the current and retrofitted systems efficiencies and the primary energy factors of the area and fuel used. This information is difficult to be generalised and differs in each building. Moreover, within the study's scope, comparing the heating energy need is more adequate to understand the improvements in the building envelop, because the reduction in primary energy is influenced significantly by the system and fuel type. To ensure that the output is the energy demand and not the Primary energy, the system efficiency is set to 100%. Based on the information generated by the toolbox approach, the PE can be calculated for each specific building.

The simulation has as an output the energy demand in watts (W) for every hour of the year. The sum of this demand, divided by the area of the zone gives the annual demand for the zone in kWh/m2. This demand is expressed as a percentage of reduction in the demand of the building as simulated in its original condition, according to the following expression:
(original demand-demand after refurbishment)/ original demand %.
The values refer to the living room and the bedroom zones. This was preferred to the whole apartment, in order to isolate the effect of different orientation, as in the simulated apartment layout those rooms are adjacent and have the same orientation. Moreover, it is considered more important for the purpose of the research to focus on the main rooms, with similar function, activity levels and ventilation rates, rather than all the rooms of the apartment where the different function can affect the energy demand and make it more difficult to identify the refurbishment influence.

Operative temperature and overheating

The internal temperature of the zones, as simulated in an hourly basis, is also checked, in order to ensure thermal comfort. According to ASHRAE Standard on thermal environment conditions for Human occupancy, the comfort zone is defined in terms of a range of operative temperatures that people find thermally acceptable (ASHRAE, 2004). Operative temperature, which is one of the simulation outputs, is defined as the average of the air temperature and the mean radiant temperature weighted, respectively, by the convective heat transfer coefficient and the linearized radiant heat transfer coefficient for the occupant (ASHRAE, 2004).

Comfort zone depends also on humidity, air speed, metabolic rate and clothing insulation (ASHRAE, 2004), as well as the external temperature if we consider the adaptive approach to thermal comfort (EN15251, 2007). However, for the purpose of this research, which is to evaluate refurbishment measures and not fully elaborate on the residential buildings thermal comfort, the thermal comfort is simplified in terms of operative temperature limits. Acceptable thermal comfort limits, according to ISO 7730, Table A.5, are considered 24,5 ±1.5ºC for summer and 22.0 ± 2.0ºC (ISO7730, 2005). In naturally conditioned spaces, such the residential buildings simulated, where operable windows are easily accessed to and occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions (EN15251, 2007).

The lower limit (20ºC) is achieved by setting the heating set-point temperature. The temperature should not be over the upper limit (26ºC) for more than a limited amount of time, which would be 3-5% of the time according to Annex G of EN15251 (2007) or 300h according to Herpen (2007). If the simulation results in temperatures outside of comfort zone, some inputs (e.g. window set-point temperature) are modified to ensure thermal comfort. These modifications may result in higher energy demand. This means that the value for energy demand considered in the options evaluation, presupposes thermal comfort.

§ 5.6 Existing buildings' current condition and energy demand

To evaluate refurbishment energy savings, the first step is to know how much energy the building initially needed. The potential improvement depends directly on the existing condition and energy demand. To calculate current demand, the identified construction types of the building envelope, based on the building stock analysis, were simulated, along with variations in the opening proportions and different apartment's positions. This section analyses and compares the results of the different existing dwellings models. The critical analysis and comparison will help understanding the importance of each parameter and its effect on energy demand. The first part explains which parameters are investigated through simulating existing buildings variations. Subsequently, the differences in the models are compared, according to results on energy demand.

§ 5.6.1 Variations in existing buildings' models

The existing building's condition and construction result in different impact of the retrofitting measures. Moreover, the position of apartment and window-wall-ratio (WWR) determine the external surfaces where heat is transferred and as a result affect the energy demand and the reduction through refurbishment. For the evaluation of refurbishment measures based on the energy demand reduction from the original situation we need to have an overview of those key variations of the existing building and how they affect the energy demand. These variations are important for further applicability of the approach, in order to associate each building with the calculated models, as it will be explained in Chapter 8.

Construction

The first part of the research (Chapter 2) investigated construction types of the building stock. Typical constructions were presented in Table 2.2. Modelling all types of constructions and their combination would increase the number and complexity of the approach and a method to simplify the simulations, while still covering a range of different options, was sought. To this end, construction types that share similar thermal transmittance characteristics have been grouped into categories. Each category is modelled as one construction type. This resulted in two types of construction for wall, window and roof, as shown in Table B.1. The internal, basement and balcony slabs are assumed to be the same concrete slab construction. Combining components' construction types resulted in 6 model types to be simulated as presented in Table 5.10.

Models	External wall	Window	Roof
M1	Masonry wall	Single glazing	Pitched roof
M2	Masonry wall	Double glazing	Pitched roof
M3	Lightweight blocks	Single glazing	Pitched roof
M4	Lightweight blocks	Double glazing	Pitched roof
M5	Lightweight blocks	Single glazing	Flat roof
M6	Lightweight blocks	Double glazing	Flat roof

Table 5.10
Model variation, according to relevant combinations for components original construction, based on variations presented in Table B1

Apartment types

The methodology is based on simulation apartments in apartment blocks. The apartments are modelled with the same layout. The energy performance is expressed in kWh/m^2; as a result the apartment size is not of great significance. The main parameter affecting the energy demand of each apartment is its position, as it determines the area of external surfaces, through which the heat is transferred. Figure 5.3 presents the different types of apartments according to the position in the apartment block.

Six types are modelled, varying in their horizontal (middle or edge of the block) and vertical (ground, middle and top floor) position. Determining the energy demand for all types is essential for the methodology. The different building envelope components have different effect in different apartment types. For example, retrofitting of the roof affects mainly the top apartments, or insulating the wall has a bigger effect on corner apartments, as they have larger external wall surfaces. Moreover, results of all apartment types are necessary to apply the results in other building types, or to estimate the potential energy savings for the whole apartment block.

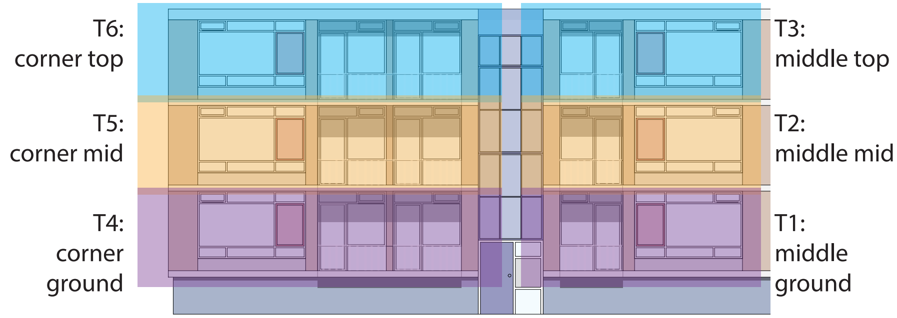


Figure 5.3
Apartment types in the building, according to their position

Window-wall ratio (WWR)

The percentage of transparent to opaque component of the façade, referred to as window-to-wall ratio (Aksamija, 2013), is an important characteristic, as it determines the area of each construction and the respective heat losses. On one hand, the glazed parts have usually lower thermal resistance than the opaque parts of the wall; on the other hand, more solar radiation is admitted the biggest the glazed area, increasing solar gains but also overheating risk. This principle affects both the energy demand of existing buildings and the impact of refurbishment measures (Konstantinou & Knaack, 2013). As a result, WWR has a high effect on the performance obtained by rehabilitations (Cetiner & Ceylan, 2013). Therefore, simulating different WWR in existing buildings is important to define the effect of refurbishment.

1. 30% WWR

2. 60% WWR

Figure 5.4

Examples of building with different opening proportions. A 30% and 60% ratio opening to wall has been identified as the most representative..

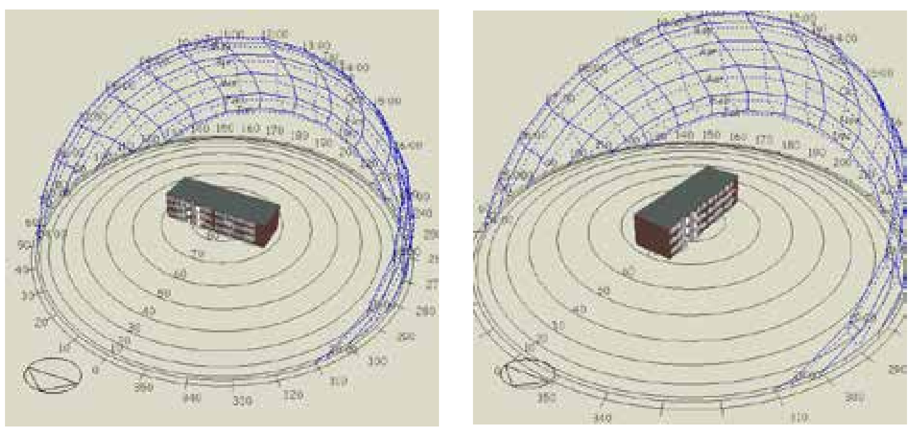
In the building stock, a range of opening proportions can be found, that reflect the specific construction and design, as well as the climatological conditions. As it is not possible to simulate all the range, they have been simplified. In residential buildings with loadbearing walls the openings size is restricted to the structural limit of the lintels. In non-load bearing walls, larger WWR can be found. However, taking into account the structure, parapets, frames etc., the façade cannot be considered 100% transparent.

As far as energy consumption is concerned, Bokel (2007) has concluded that an optimal window size for this office simulation is around 30 %, while for WWR over 50 %, the advantage of a larger glass area, the total energy load increases. Other studies on low energy houses (Persson et al., 2006) suggest that the optimum regarding space heating demand can be found somewhere between a reduced area of 20 and 50%.

Taking into account the commonly encountered ratios in the residential building and the effect on energy demand, two WWR are chosen to be simulated as variations in the existing residential buildings: 30% and 60%. These values are considered to be representative. Buildings with other WWR should refer to the closest percentage of the two simulated.

Orientation

The orientation influences the amount of solar heat gains as well as the hours of insolation. Hence, it affects the energy demand for heating and the overheating risk. Moreover, orientation is an important parameter in refurbishment measures evaluation, as it is one of the constrains that cannot be modified in existing buildings. It is, hence, important to consider the façade's orientation in the decision-making process for refurbishment measures. To determine the effect of different orientation on current and reduced energy demand, four orientations are simulated. Even though, the reference building has facades of two orientations (Figure 5.5), the model room is each time oriented towards the North, South, West or East. In this way, the effect of the different orientations on the energy demand and the effect of refurbishment measures can be isolated.



1. 30% WWR

2. 60% WWR

Figure 5.5

Different orientation of the model in relation to the sun path. The E-W orientation of the modelled apartment block results in South and North facades while the N-S orientation in west and east facades, respectively.

§ 5.6.2 Existing buildings' models simulation results

The variations explained in 5.6.1 and their combinations resulted in 288 models to be simulated (Table B.3). Overall there are six building types with regard to construction, six apartment types with regard to position, two window-to-wall ratios and four orientations. The simulation results discussed in this section include the heating energy demand of the existing buildings in kWh/m^2 per year, as well as comparison between the different models.

The numerical output of existing building types is important, as it will be used as the reference to quantify the impact of refurbishment measures. Moreover, different types of apartments, in terms of construction and position, are compared, based on the numerical output for energy demand. This information can be useful to housing associations and users during decision-making on refurbishing of buying apartments.

Finally, the systematic comparison, which is comparing models that differ only in one variable, can determine the effect of specific variable on energy demand. The comparisons are also useful to determine the typical apartment and the models to be compared in the refurbishment options (step 2.B in the methodology). The variables are described in 5.5.1 and they concern the position of the apartment, opening proportions, components construction and orientation. Further in section 5.5.2, the comparison based on these variables is elaborated and conclusions on current condition simulation are drawn.

Position of the apartment

The position determines the area of the exposed wall and, thus, the area though which the heat flows. There are 6 different types of apartment, as shown in Figure 5.3. For further reference in the discussion, horizontal position refers to whether it is a corner of middle apartment, while vertical position refers to the floor. In the comparison with regard to position, we examine the percentage of higher energy demand of different apartments of the same building type. The apartment differ either in horizontal or vertical position, according to the variable investigated. Percentages of all modelled building type are presented in Appendix B.

After comparing differences in energy demand, a first remark is that the different WWR does not affect the comparison between apartments with different position. As shown in Figure B.2, the percentages of difference in energy demand between the apartments are very similar for building types with WWR 60% and 30%. Moreover, the bigger differences are found in the middle apartments. When comparing middle to corner apartments, the percentages range from 26% to 33% in the middle (types 2 and 5), while they range from 4% to 10% in top apartments (types 3 and 6). Similarly, with regard to the vertical position, the differences between middle apartments are bigger than corner apartments. This is because in apartments with more external surfaces than the middle apartments, the additional heat losses affected the heating demand. This observation is important for further toolbox calculations, as it suggest that the middle apartments are affected more from the individual variables, which make them appropriate for investigating the effect of individual refurbishment measures.

Figure 5.6 presents an overview of the comparison for the typical apartment. This means that, when comparing middle to corner, only the middle floor in considered, while in the comparison of vertical position, T2 was compares with T3 and T1 respectively. The percentages refer only to 30% WWR and are averages of all orientations. This overview of building types suggests that the different constructions are not important when comparing apartments with different positions in the block. The only variation is between the pitched roof and the flat roof models, as the heat losses through the flat roof are significant less.

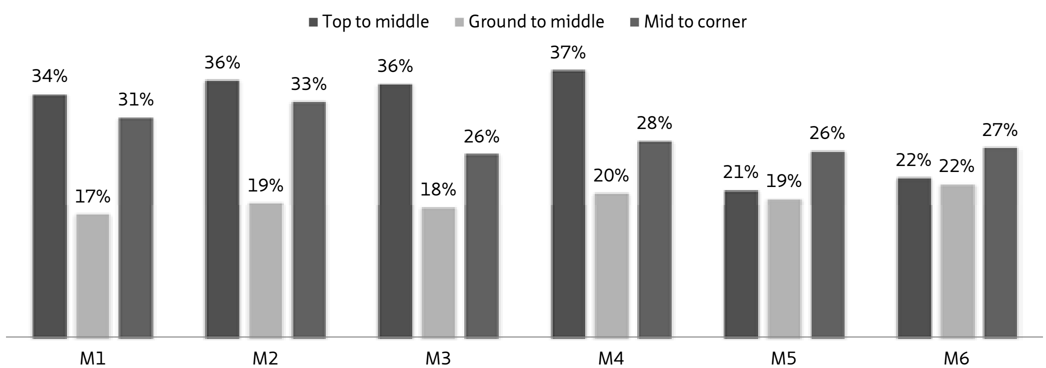


Figure 5.6
Overview of heating demand comparison with regard to position, for typical apartment (T2: MID_Mid)

Window-to-wall ratio

Two different window-to-wall ratios were simulated. Table B.8 presents percentage of energy demand of the apartment with 30% to apartments with 60% WWR, for the same position in the block. Figure 5.7 shows the comparison only for the typical apartment, which is a middle apartment in a middle floor. The difference between buildings with 30% and 60% WWR is up to 5%. Even though the difference is not significant, it is interesting to notice the pattern between models with single and double glazing. In models with single glazing the difference is negative, meaning that in buildings with single glazing, the bigger openings increase the energy demand. In models with double glazing, we see the reverse effect of bigger openings resulting in lower energy demand.

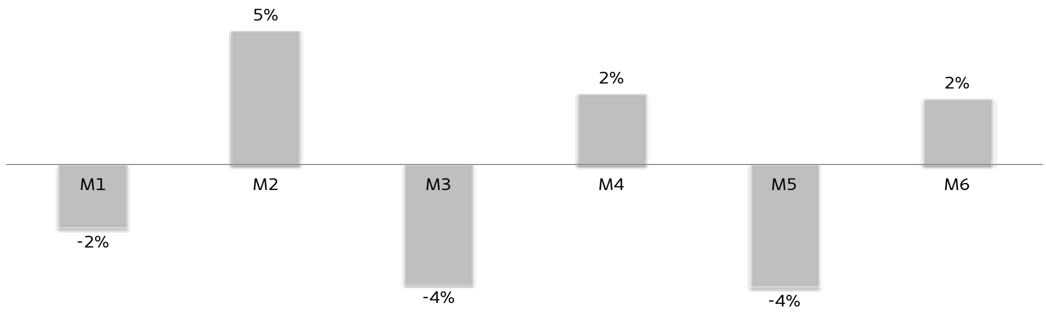


Figure 5.7
The percentage of heating demand of apartments with 30% to apartments with 60% WWR, for typical apartment, T2.

Construction

To evaluate what is the effect of different construction on the energy demand, we compare models that differ in only one type of construction. Table 5.11 shows the models that were compare with respect to each component and their construction. The comparison refers to the external wall, window and roof component, as they have been modelled with variations. The comparison is expressed in percentage of difference in energy demand, according to the last column of the table.

Component	Model	Construction	Model	Construction	Percentage
Wall	M1	Masonry wall	M3	Lightweight blocks wall	(M1-M3)/M1
Window	M1	Single glazing	M2	Double glazing	(M1-M2)/M1
Roof	M4	Pitched roof	M6	Flat roof	(M4-M6)/M4

Table 5.11
Comparison of apartment with regard to construction

In order to understand what it the effect of a different wall type in the heating demand we compare building types M1 and M3. Those types have the same construction of window and roof and they only differ as far as wall type is concerned. Figure 5.8a shows the percentage of how much more heating energy type M1 demands in comparison to M3, for the respective apartment types. The difference in energy demand between dwellings with different wall construction is on average 10%. Since the one wall has a better thermal transmittance than the other, the differences in heating demand are bigger in corner apartments (T4-6), where the wall surface is bigger. Similarly, in 30% WWR models, where the wall surface larger, the percentage is bigger, around 2%, than in 60% WWR. The above observation suggest that in the next step when identifying the models to be simulated with the application of wall refurbishment measures, different wall construction and WWR need to checked, as well as both middle and corner apartments types.

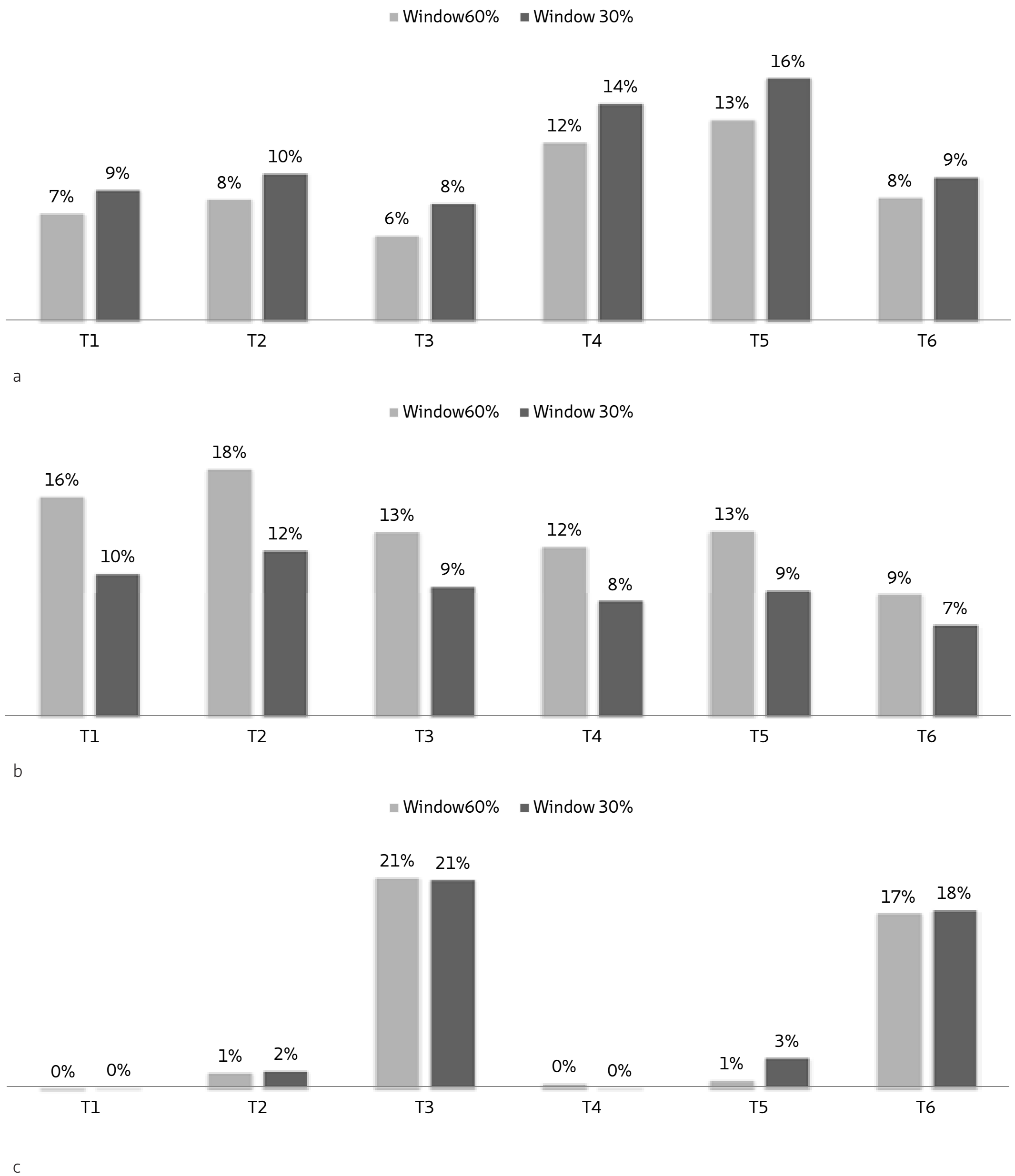


Figure 5.8

(a) The percentage of difference in heating demand between building with masonry wall (M1) and lightweight block wall (M3) .(b) The percentage of difference in heating demand between building with single glazing (M1) and double glazing (M2) (c)The percentage of difference in heating demand between building with pitched roof (M4) and flat roof (M6)

Similarly to the wall types, building types M1 and M2 are compared to evaluate the effect of different glazing types. Figure 5.8.b presents the percentages of difference in heating energy demand between the dwelling with single glazing (M1) and double glazing (M2), for the respective apartment types. The two building models are identical apart from the glazing; M1 has single glazing while M2 double glazing. In this case, double-glazing should not be confused with a suggested refurbishment measure. It refers to early uncoated glazing, mostly applied in existing building in the 1980's, which is already out-dated and needs to be addressed as part of the existing building construction. Still, it has improved performance than the single glazing, resulting in M1 having up to 18% higher heating demand of the building, as shown in the table. The bigger differences are found in the apartments where glazing affects more the heat losses, which are the apartment with the higher WWR (60%), as well as middle floor apartments (T2 and T5) .

To evaluate the effect of the roof construction to the energy demand, building types M4 and M6 were compared. Those models have the same wall and window construction, while M4 has a pitched roof and M6 a flat roof. Figure 5.8.c shows the difference percentages for the respective apartment types and WWRs. The main conclusion of is that different roof construction affect only top floor apartments, while the impact is zero or insignificant in other floors. Therefore, the apartment that is considered typical with regard to roof retrofitting measures is the top, middle apartment, T3 in the thesis methodology. In the case of roof construction comparison, different WWRs are not so important.

Orientation

The differences in energy demand in building with different orientation are mainly due to the received solar radiation. Figure B.4 and Table B.12 present the percentages of difference in heating demand between different orientations of the same building type. The differences are bigger when the glazing area is larger, accounting for up to 28% more heating demand to north than south-orientated rooms. East and west oriented rooms have similar heating demand.

§ 5.6.3 Conclusions on existing building models

After investigating the range of building and construction types of the building stock, calculating the energy demand of existing building was the first essential step in order to evaluate the potential effect of refurbishment measures. The variations in existing buildings resulted in a number of different building types, also referred to as models in the thesis. They are important not only for their numerical output that is used to define the savings after the application of the retrofitting measure, but also for the applicability of the approach, as each building to be refurbished should be associated with the relevant building type. The conclusions refer both to the quantitative data on the energy demand itself and the qualitative analysis, which is useful for the further steps of the research.

Quantitative

The numbers calculated for the energy demand of existing buildings are used as the reference to calculate the potential percentage of reduction in energy demand after the refurbishment measure application. The minimum and maximum percentage of difference observed can give an indication on the range of energy demand in existing buildings.

	Difference between:	Maximum difference	Minimum difference
Position	Middle and corner apartment	33%	4%
	Middle and top apartment	38%	2%
	Middle and ground apartmen	22%	10%
WWR	30% and 60% WWR	5%	1%
Construction	Different wall construction	14%	6%
	Single and double glazing	18%	6%
	Pitched and flat roof	21%	17%

Table 5.12
Summary of maximum and minimum differences in the systematic comparison of existing building types

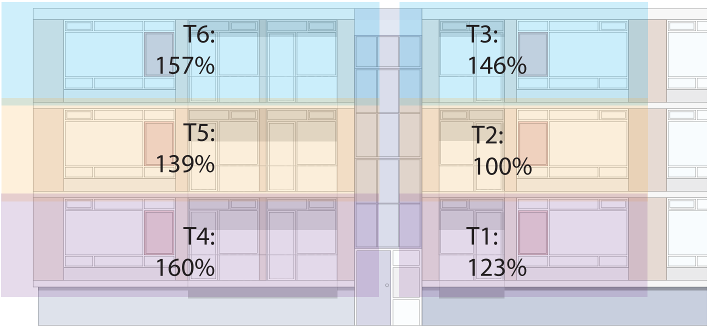


Figure 5.9
Comparison of the heating demand for different apartments, in percentages to the typical apartment (T2)

Qualitative

Comparing the demand of the different types is useful for understanding the existing condition of the stock and determining key parameters. The models developed are also important for further reference in the toolbox approach. Table 5.10, together with Table B.1, Table B.2 and Table B.3 should be used to understand the building type referred in the approach development and the pre-calculated model to be associated with the real building characteristics.

For further evaluation of refurbishment option, the approach focuses on the typical apartment. When comparing the middle apartments of different building types, the differences are bigger. They are, thus, more appropriate to evaluate the individual options as the energy demand is not influenced by additional external surfaces as in corner, top and ground apartments. For this reason, middle apartments are considered as typical and they are used to indicate the reduction potential of a measure. Moreover, middle apartments (T2 in Figure 5.3) are more common in an apartment block. Their number depends on the number of building floors and the number of apartments in each floor. With regard to roof retrofitting measures, top middle apartment (T3 in Figure 5.3) is considered typical, while ground floor middle apartment (T1 in Figure 5.3) is typical for ground floor retrofitting measures.

A generalised expression of differences in energy demand, based on the typical middle apartment is shown in Figure 5.9. The percentages have considered average calculated heating demand for all building types. When comparing apartment in different position in the block, models with different construction and WWRs have similar percentages, as shown in Figure 5.6. According to the comparison, a corner apartment has approximately 40% higher energy demand than the typical middle apartment, a top apartment 45% and a ground floor apartment 23%. This suggests that if the calculated energy demand is associated with the energy label ranges, the difference of energy demand can result in up to two scales difference in the energy labelling of different apartment in the same building.

In terms of thermal conductivity of the envelope, building type M1 is the worst model and M6 is the best. Building type M1 comprises solid brick masonry wall, single glazing and pitched roof, while M6 is modelled with a wall of lightweight concrete blocks, double glazing and flat roof construction. Their potential reduction can give us the minimum and max reduction of a retrofitting measure.

Finally, some remarks can be made on how each component construction affects energy demand. The heat losses through the roof in the main factor for energy demand in top apartments. The other variation parameters are not so important. In buildings with single glazing, the bigger openings increase the energy demand, but with double glazing they reduce it, compared to the same building type with smaller openings. This suggests that, when the apartment has single glazing, it is better to have smaller openings. However, if the building already has double glazing, even the early uncoated type, the bigger openings result in lower energy demand than in the same building type with single glazing. The wall type alone is not the most influential variable on the energy consumption. This is because even the worst performing wall type, typically found in the building stock, does not have as bad thermal resistance as other components, such as the window. However, major problem with bad performing wall is thermal bridging, which is not expressed by the calculations. Thermal bridging is an important issue not only for heat losses but also for the resulting condensation and related problems. Thus, upgrading the external wall should not be neglected.

The calculation of existing buildings energy demand was necessary for the approach development, as the toolbox options quantification is expressed in percentage of reduction in current demand. The following section proceeds with calculating energy demand after application of the retrofitting measures.

§ 5.7 Retrofitting measures quantification

This section covers the second part of the methodology to quantify refurbishment measures, which is an integral part of the approach development. Simulating the toolbox refurbishment options has various steps. The evaluation of the options was based on comparing the upgraded energy demand to the existing situation of buildings. The range of existing building is extensive, as already analysed in section 5.6. To make the simulation process more efficient and simplify the toolbox approach, as described in the methodology in section 5.4.2, the following steps were followed:

A Measure variations were simulated in one building type.
B Building types variations were simulated for one measure variation
C Window-to-wall ratio were simulated in the building types of step B, for one measure variation
D Final simulations, including the variations identified in steps A-C, all apartment position and all orientations

Steps A to C aim at reducing the number of models, by identifying the important factors that determine the effect of each component refurbishment measure. If the difference in energy demand was significant, translated in a threshold of 5%, the variations defined in these steps were further simulated in step D. The results of the final simulations are the energy demand and percentage of reduction in current demand after each measure application. They are included in Appendix C. The following sub-sections on each component measures simulation make reference to the respective tables.

Regarding the apartment type, the effect estimation refers to typical apartment. For measures on the wall, window and balcony typical is a middle apartment in a middle floor, which is T2 according to Figure 5.3. Nevertheless, all apartment types are simulated and the possible reduction in existing energy demand is calculated. Estimating the effect for all apartment types is necessary for further application of the toolbox calculations in different building types, as well as blocks with other apartment number than the reference model, as it will be explained in Chapter 8.

The current section elaborates on the variations investigated for each refurbishment measure and building type, in order to choose the ones that were further simulated. It needs to be clarified that the section presents refurbishment measures in terms of the simulation process and the effect quantification. Some general technical aspects of the measures have been covered in chapter 4, while the detailed implementation depends of the specific product and project specification.

§ 5.7.1 External wall

A External wall options variations

Since simulating every material and design choice of external wall refurbishment options is not the objective, the first step is to define indicative variations. For this purpose, different materials were simulated for each option, based only on one building type, namely model M6 with East orientation and WWR 60%. The building type is not so important at this stage, as the simulation needs to compare the effect of different materials and thickness on the energy demand. Different building types were evaluated as the next step According to the differences in energy demand reduction, the options to be further simulated were chosen. Interventions on the external wall can be grouped in those that add to the thermal resistance of the component and those that create a thermal buffer.

Cavity insulation

Cavity insulation refers to insulation between the two leaves of the external wall. In most existing buildings the cavity is filled with air, or the insulation is insufficient and out-dated. A common refurbishment practice is to fill the cavity with new insulation, mostly in form loose or foam material. A drawback of the method is that the resulting insulating thickness is limited to the depth of the existing cavity. In the simulation, the air cavity of the wall construction was replaced by an insulation layer of the same thickness. Different insulation materials of the same 5cm thickness were simulated, resulting in different U-value of the external wall.

Internal insulation

Internal insulation of the wall was simulated by applying additional layers of insulation and plasterboard on the internal surface of the existing wall. The variations with regard to internal insulation refer to different insulation materials and thickness. The resulting thermal transmittance coefficient was similar to the external application. However, internal insulation requires attention in critical points such as thermal bridges, that are not accounted for by the simulation software (Martin et al., 2011), which should be considered in the final decision.

External Insulation Finishing Systems (EIFS) and Ventilated façade

External insulation of the wall is applied with two ways: External Insulation Finishing Systems (EIFS) and ventilated façade. They were simulated by applying extra layers externally to the wall. The EIFS add a layer of insulation and plaster finishing, while in the case of ventilated façade an aluminium substructure and cladding material was applied. Between the insulation and the finishing material, a cavity where air circulates was created. The variations with regard to external insulation included different insulation materials and thickness, as well as different cladding material for ventilated façade.

New insulated wall

Replacement of the wall, e.g. with a timber frame wall construction, is also a possibility. The new wall needs to be insulated to comply with energy performance. In the methodology, the thermal transmittance coefficient assumed is 0.2 W/m2K, which is the same as in case of wall upgrade. Depending on the construction of the wall, the effect will be the same as internal or external insulation. Therefore, it was not simulated as a different option.

Second Façade (SF)

Second Façade refers to the construction of a second layer on the outside of the wall. The second layer is constructed as a curtain wall, with a large glazed percentage. The glazed part of the envelope allows solar heat gains, resulting in temperature rise in the SF space, which then functions as a buffer zone between the wall and the external environment, preventing heat loss from the inside to the outside. Several variations of a second facade were simulated. The variations were regarding single or double glazing, the percentage of glazed part of the new cladding, the use of shading, the depth of the cavity and its function.

The simulation required modification in the existing situation models, more substantial than changing the wall construction, as in the previous cases of extra insulation. A new zone, adjacent to the existing building, was modelled, which made the bedroom and living room zones windows internal. The internal window should open to allow airflow from the second facade zone. Moreover the required constant ventilation rates are applied. The new façade open 80% when internal temperature is over 22o C for natural ventilation. In the models that shading is used, it is applied when the zone internal temperature is 23o C. The above mentioned inputs were decided on trial simulation, to ensure the resulting internal temperature will be within acceptable overheating risks thresholds.

The construction is the curtain wall with single or double glazing and aluminium structure. Both glazing are Low-E coated. In some models the cladding is 100% glazed and in other 50%. In the 50% glazed models the parapet is a lightweight laminated plasterboard sandwich construction. When double glazing is applied, the infiltration rate is reduced as it is assumed that the new construction complies with higher airtightness standards.

Two different depths were simulated, 60cm and 150cm. The 60cm-deep zone was simulated as a cavity, suggesting that no occupancy or other internal gains are accounted. The 150cm-deep zone was assumed to be used as circulation area and there were internal gains, e.g. from lighting. In most models there was no mechanical installation in the second façade zone. An exception is the FS zone integrated into the thermal envelope, creating an extension to the dwelling habitable space. In this case, the originally exterior walls were removed and the new space was accounted in the heating demand.

Table 5.13 gives an overview of the variations and the energy demand reduction for external wall measures. The specifications of each option are explained in the adjacent columns. The heat transmittance coefficient U-value of each option is the result of the material layers and thickness used in the simulation software. According to the simulation of the different options, the energy reduction depends on the U-value. Options with the same U-value of the wall result in the same energy reduction, e.g. option 1 and option 4. The same thickness of different insulation material does not, however, result necessarily in the same U-value. Ventilated façade options have almost identical result on the energy reduction. This is because the air in the cavity affects the heat transmittance through the wall.

Internal and external insulation options have very similar effect on energy reduction. The application of a certain insulation thickness results in the same U-value whether the insulation is applied on the inside or the outside. The choice, hence, should also consider other parameters such as the possibility to change the building appearance etc. Furthermore, thermal bridging, which is a critical point in insulation application, is not addressed by the simulation. The only significant variation in the options effect happens by the application of cavity insulation. The reason for that is the thickness of the insulation, which is only 5cm, resulting in higher thermal transmittance coefficient than the rest of the option. However, this is necessary, as in reality it is not likely to encounter an existing wall with cavity as wide as 200mm, which is the thickness needed to achieve a U-value of 0.2 W/m^2K.

Regarding the second façade, the variations have resulted in similar reduction percentages. In case the second layer creates a cavity without additional function, it is preferable to use single glazing cladding. The reduction in the variation of SF with single glazing (option 16) is 41%, while it is 34% in the SF with double glazing (option 20). If the cavity is occupied, internal temperature is important. In this case, both glazing types have similar result on the heating demand reduction of the dwelling, but the use of double glazing resulted in lower overheating risk.

To keep the number of simulation as efficient as possible and since no significant fluctuation in the results were shown, one variation for each option for external, internal and cavity insulation will be further simulated. The SF measures include cavity and corridor measure, both with single and double glazing, as well as the option to integrate the SF space into the dwelling. These are in total 5 measures regarding a SF. The selected variations are highlighted in Table 5.13 and summarised in Table C.13.

B-C. Building types and WWR variations

After defining the measures specification, decision on different building types to be simulated needs to be made. The original condition of the building determines the potential energy reduction and, to this end, different existing building types were simulated in the beginning of the study. However, simulating all six types is not necessary to check the effect of improving the external wall alone. For this reason, building types M1 and M3, which are identical apart from the wall construction, were checked. Moreover, type M6 that has the best performance identified in section 5.6, was simulated, to compare it with M1 and identify the minimum and maximum energy reduction potential.

Variation	Construction (inner to outer)						
External Insulation Finishing System (EIFS)			Insulation material	Insulation thickness	U-value W/m²K	Heating kWh/m².yr	Reduction
1	Existing wall Insulation material Plaster		XPS	14 cm	0.2	201	22%
2			XPS	20 cm	0.15	197	23%
3			Wood fibres	30 cm	0.25	204	20%
4			Rockwool	20 cm	0.19	200	22%
5			Wood wool	20 cm	0.34	208	19%
Ventilated façade		Cladding material	Insulation material	Insulation thickness	U-value W/m²K	Heating kWh/m².yr	Reduction
6	Existing wall Insulation material Air cavity (7cm) Cladding	Aluminium	Rockwool	20 cm	0.163	201.27	21%
7			XPS	20 cm	0.13	200.76	22%
8		Wood fibre board	Rockwool	20 cm	0.162	201.25	21%
Internal insulation			Insulation material	Insulation thickness	U-value W/m²K	Heating kWh/m².yr	Reduction
9	Plasterboard Insulation material Existing wall		XPS	14 cm	0.2	197	23%
10			XPS	20 cm	0.15	194	24%
11			Wood fibres	20 cm	0.18	196	23%
12			Rockwool	20 cm	0.19	197	22%
Cavity insulation			Insulation material	Insulation thickness	U-value W/m²K	Heating kWh/m².yr	Reduction
13	Existing wall-inner leaf Insulation material Existing wall-outer leaf		polyurethane	5 cm	0.38	213	18%
14			cellulose	5 cm	0.49	220	16%
15			perlite	5 cm	0.52	222	15%
Second façade (SF)		Cavity, cm	Second façade glazing type	g-value	U-value W/m²K	Heating kWh/m².yr	Reduction
16	Existing façade Cavity Second façade	60	Single Low-E 3mm	0.76	4.3	111	41%
17						116	39%
18						120	37%
19		150				117	38%
20		60	Double Low-E 3mm/13mm Air	0.59	1.79	125	34%
21		60				127	33%
22		150				121	36%
23		150				128	33%
24	Existing façade removed Cavity Second façade	150				107	44%

Table 5.13

External wall measures variations, applied in one building type, M6, WWR 60%, east orientation. Highlighted the selected for further simulation variation numbers

Table 5.14 presents an overview of applying external insulation on the wall of the three building types, for different WWRs. The reduction on energy demand is greater in models with 30% WWR, as a bigger area on the external envelope is improved. The heating demand in M1 and M3 models is the same. Although, the original wall construction was different, the refurbish wall has in both cases the required level of heat resistance. The reduction percentage, however, is different, as the original heating demand in M3 was lower than in M1. The reduction percentage of type M3 is similar with those of building type M6.

Building type	Wall Type	Window type	WWR	Heating (kWh/m².yr)	reduction
M1	Masonry Brick	Single Glazing	30%	184	26%
	Masonry Brick	Single Glazing	60%	202	22%
M3	Lightweight Concrete	Single Glazing	30%	184	19%
	Lightweight Concrete	Single Glazing	60%	201	14%
M6	Lightweight Concrete	Double Glazing	30%	155	20%
	Lightweight Concrete	Double Glazing	60%	159	16%

Table 5.14
The effect of EIFS application on the heating demand of different building types

In order to decide which building types should be further simulated for the second façade options, four different building types were compared for both WWRs. In this case, models with differences in both wall and windows needed to be checked, as the SF is applied in the whole façade. For the same building type the different openings proportion do not affect significantly the potential reduction (1-3%). In building types M1 and M2, which have the same wall and different window type, the heating demand after refurbishment with a second façade (SF) is almost identical. The reduction percentage is different, because the original demand was lower in M2. The conclusion is that the existing glazing type is not important when a SF is applied. For this reason, only M1 will be simulated.

M1 compared with M6 has around 14% lower heating demand, while before the second façade application the demand was 23% higher. Based on this observation, we may consider that the lower thermal resistance of the masonry wall functions better with the buffer zone created in the SF than the lightweight concrete wall. Another explanation can be related to the ventilation heat losses. Due to higher thermal resistance of M6 construction, high temperature that trigger ventilation occurs more often, resulting in higher ventilation heat losses. The simulation has calculated 14.86 kWh/m^2 ventilation heat losses per year in M6 middle apartment while 8.44 kWh/m^2 per year in M1, same apartment.

	Existing facade			Single glazing		Double glazing		Double glaz_ MERGED	
	Wall Type	Window type	WWR	Hea-ting (kWh/ m².yr)	reduc-tion	Hea-ting (kWh/ m².yr)	reduc-tion	Hea-ting (kWh/ m².yr)	reduc-tion
M1	Masonry Brick	Single Glazing	30%	105	58%	116	53%	107	57%
	Masonry Brick	Single Glazing	60%	100	61%	115	56%	107	59%
M2	Masonry Brick	Double Glazing	30%	106	52%	116	47%	89	60%
	Masonry Brick	Double Glazing	60%	101	52%	114	46%	89	58%
M3	Lightweight Concrete	Single Glazing	30%	105	53%	116	49%	87	61%
	Lightweight Concrete	Single Glazing	60%	100	57%	115	51%	87	63%
M6	Lightweight Concrete	Double Glazing	30%	120	38%	130	33%	107	45%
	Lightweight Concrete	Double Glazing	60%	111	41%	125	34%	107	44%

Table 5.15
The effect of second façade application on the heating demand of different models

D. External wall options simulation results

According to the investigation of different external wall refurbishment options and different building types, the models that were simulated for all orientations were M1, M3 and M6. Table 5.10 and Table B.1 give details on building types characteristics. Building type M1 was modelled with masonry wall and single glazed windows, M3 with lightweight wall and single glazed windows and M6 with lightweight wall and double windows. Even though, both models with lightweight wall presented similar reduction when the wall was insulated, in Table 5.14, they are both included in the final simulation as they differ in the performance of a second façade, in Table 5.15. Figure 5.10.a confirms this tendency, observed in step B. When comparing external wall measures impact on energy demand, average in all orientations, the SF application gives greater variation in energy reduction in the different building types. Moreover, both window-wall ratios are simulated, as they influence the area of the retrofitted component and result in different energy demand. Figure 5.10.b shows that the WWR does not influence the reduction of the SF application.

Table C.2 until Table C.7 present the results of the simulation. Even though all apartment types were simulated, the tables present the data for typical apartments, to avoid excessive accumulation of data. The numbers on heating energy demand

and, most importantly, the percentage of reduction can be used for reference in future refurbishment projects, to provide an indication of the potential effect of the refurbishment and compare the different options. The building in question must be associated to the characteristics of the three models in terms of construction and the respective opening proportion, orientation and position.

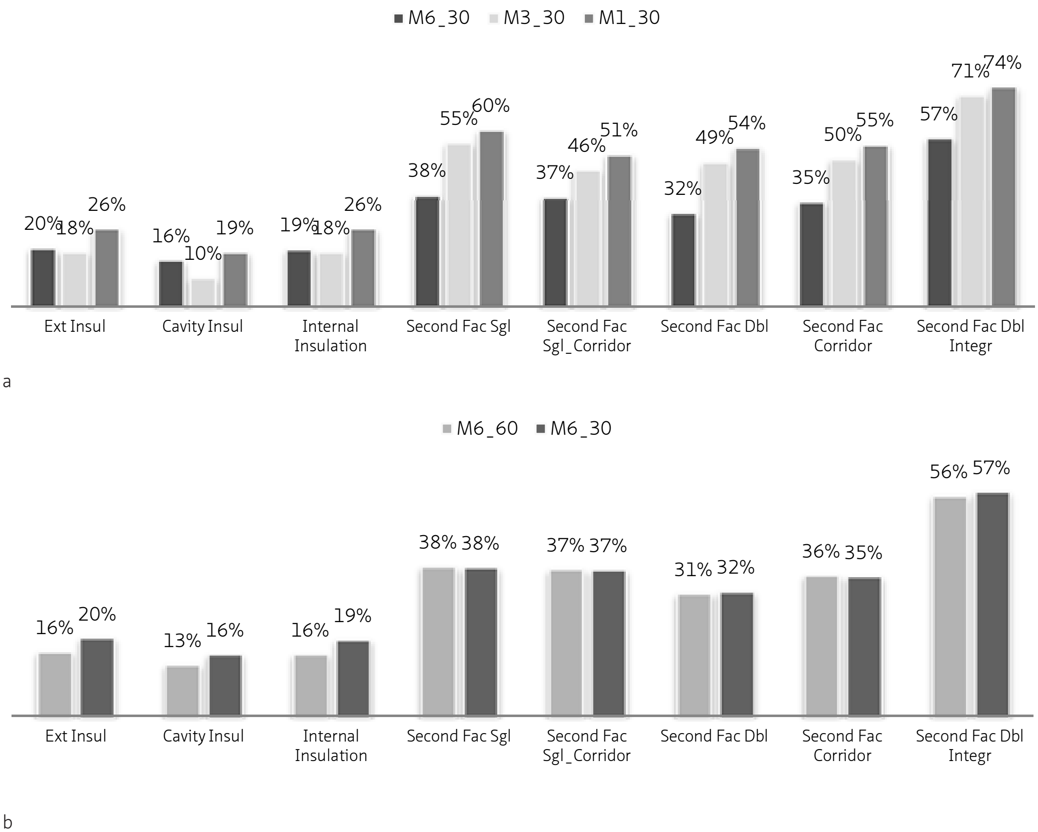


Figure 5.10

Comparison of external wall measures impact on energy demand between:
(a) the different building types.
(b) middle and corner apartment, applied in Model M6, WWR 30%.
The values are the average of all orientations.

§ 5.7.2 Window

A Window options variations

The measures included in the toolbox as far as windows are concerned are upgrading the existing window pane, replacing both frame and window glazing, application of secondary glazing and the use of shading devices. Those options, along with variations for each one, were firstly simulated in one building type, M6, WWR 60%, east orientation. This first set of simulation aims at comparing the effect of the variations, checking for significant differences and decide on the options to be further simulated.

Upgrade window
This option refers to replacing only the existing windowpane, normally from single to double glazing. To simulate this option, the glazing material in the existing building models was changed to double, Low-E coated glazing. The frame was kept the same, as well as the infiltration rate.

Replace window
There are several options to replace the window. They include different technologies of glazing and window frames, as discussed in section 4.3.2. and 4.3.3. In the simulation model, the material of the window components was replaced with the respective technology, as seen in Table 5.16. The window frame was in all cases aluminium with thermal break and the infiltration rate was reduced to 3 m^3/h per m^2 outer envelope at Q50Pa (EN15242, 2007, Table B.1), to address the improved air tightness of the new windows.

When replacing the window, it is also possible to enlarge it, subject to façade design and construction. This option was simulated in the models with a WWR 30%. The WWR was then doubled and the new energy need is compared with the existing model with WWR 30%.

Secondary glazing
Secondary glazing or box window refers to the application of a second glazing inside of the existing glazing. The secondary glazing is often an option in monumental buildings, where the external appearance should not be altered. The advantage of this measure is that it creates a thermal buffer between existing and new glazing, as well as increases airtightness, due to the interior airtight window. The advantage is the same also in case the secondary glazing is applied to the outside.

To simulate the box window in Design Builder, a new block, adjacent to the existing window, is drawn. The new block covered the same area as the existing window and had 30cm width, as the external wall. The application of the new block resulted in the existing external wall window to be part of the inter-block partition. This part was 100% glazed and the construction was that of the new window pane. On the other hand, the external wall of the box window block, 100% glazed as well, was assigned the window type of the existing building. As far as the operation is concerned, the external windows provided natural air inlet when the room internal temperature reached 23o C, to avoid overheating. The inner, secondary window was set always slightly open to allow a constant, minimum ventilation into the room (EST, 2006a). The infiltration rate of the construction is also reduced due to the application of the secondary glazing.

Shading

The option of shading use was applied to the existing model. Although shading is not by itself a refurbishment solution, the simulation aims at identifying if the heating demand can be implored with the use of shading alone. The options tested were regarding fixed shading and movable shading, inside and outside the window pane. They were modelled with the relevant option given in the software. The fixed overhand was 50 cm wide. The movable blinds controls are based on zone's internal temperature and they are applied when it reaches 23oC. Design Builder offers a range of options for the shading controls, such as outside temperature and illuminance. In this study, the internal temperature was considered to be more appropriate, as it is one of the critical parameters that the simulation aims at checking and optimising.

Table 5.16 presents the variations of window retrofitting measures and the respective results and reduction of heating energy demand. The coefficients g and U-value shown in the table were given by the simulation software, based on the International Glazing Database (IGDB) (DesignBuilder, 2012). The comparison of different glazing showed that the reduction depends both on the solar and heat transmittance coefficients. For example, option 4, which is double, Low-E, argon filled glazing results in lower energy demand than option 6, which is triple, Low-E glazing, even though the latter has lower U-value. This can be attributed to the higher solar gains allowed by option 4. The infiltration rate is also important. Variations 1 and 2 have the same glazing type, but the first had higher infiltration rate, assuming that the window frame has not been changed and resulted in higher energy demand. Finally shading does not influence heating demand in the improved glazing, in variations 2 and 3. When it is applied in the existing glazing, it provides a reduction in the heating demand, which can be explained by the reduction of required ventilation. Based on the results and the above discussion, the variations to be further simulated were selected. They are highlighted in Table 5.16 and also summarised in Table C.8.

Variation	Glazing Construction	frame	infiltration m^3/h/m@50Pa	g-value	U-value W/m^{2}K	Heating kWh/m^2.yr	Reduction
Upgrade							
1	Double Low-E 3mm/13mm Air	Existing (wooden)	5	0.59	2.25	172	9%
Replace							
2	Double Low-E 3mm/13mm Air (coating inner pane)	Aluminium with thermal break	3	0.68	1.78	165	13%
3	Double Low-E 3mm/13mm Air Shading		3	0.68	1.78	165	13%
4	Double Low-E 3mm/13mm Argon (coating inner pane)		3	0.68	1.51	158	17%
5	Triple Low-E 3mm/6mm Air (coating inner pane)		3	0.58	1.25	175	8%
6	Triple Low-E 3mm/6mm Air (coating in two panes)		3	0.47	0.99	161	15%
7	Triple Low-E 3mm/13mm Argon (coating in two panes)		3	0.47	0.78	156	18%
Secondary window							
8	Existing glazing Cavity 300mm Single Low-E 3mm	Aluminium with thermal break	3	0.76	4.3	156	91
9	Existing glazing Cavity 300mm Double Low-E 3mm/13mm Air		3	0.59	1.79	154	19%
Shading		**Device**			**Shading set point**		
10	Shading fix	Overhang 50cm		Steel	n/a	184	3%
11	Shading inside	Venetian blinds		Blind with high reflectivity slats	23°C	173	9%
12	Shading out					173	9%

Table 5.16

Window measures variations, applied in one building type, M6, WWR 60%, east orientation. Highlighted the selected for further simulation variation

Building type	Wall Type	Window type	WWR	Heating (kWh/m^2.yr)	reduction
M1	Masonry Brick	Single Glazing	30%	199	20%
	Masonry Brick	Single Glazing	60%	176	32%
M2	Masonry Brick	Double Glazing	30%	199	9%
	Masonry Brick	Double Glazing	60%	176	16%
M6	Lightweight Concrete	Double Glazing	30%	175	10%
	Lightweight Concrete	Double Glazing	60%	165	13%

Table 5.17

The effect of replacing the window with double, Low-E glazing in different models and WWR.

B-C Building types and WWR variations

To evaluate differences in the effect of window variations in different models, three building types were simulated. Since there are two variations- single and double glazing- in existing window construction, models with different glazing must be compared. Building types M1 and M2 have the same construction apart from the glazing type. M1 has single and M2 double glazing. Additionally, building type M6 was also simulated. M6 differs from M1 regarding all components and it is interesting comparison to see the minimum and maximum potential. All building types are simulated for one orientation, east, and for variation 2 of Table 5.16.

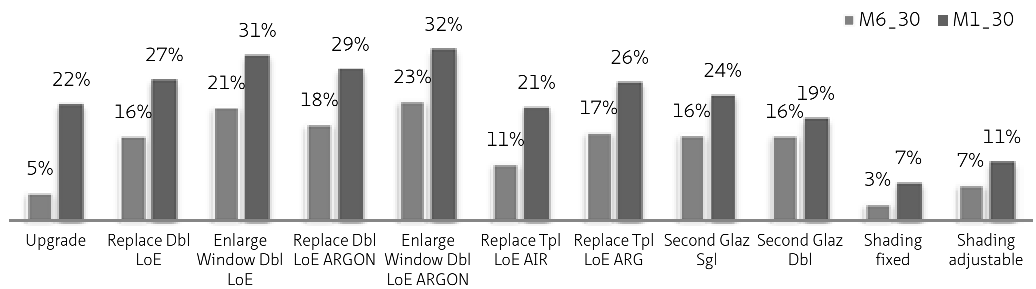
Table 5.17 presents the results of window retrofitting in different building types. According to those results, building types M6 and M2, both having double glazing, have similar energy reduction, within a 1-3% threshold. Window refurbishment options in M1 have almost double potential reduction than in the other two models. Window-wall ration is also important, as there are significant differences in the same model with different WWR. The models with higher WWR (60%) have a higher energy reduction.

D Window options simulation results

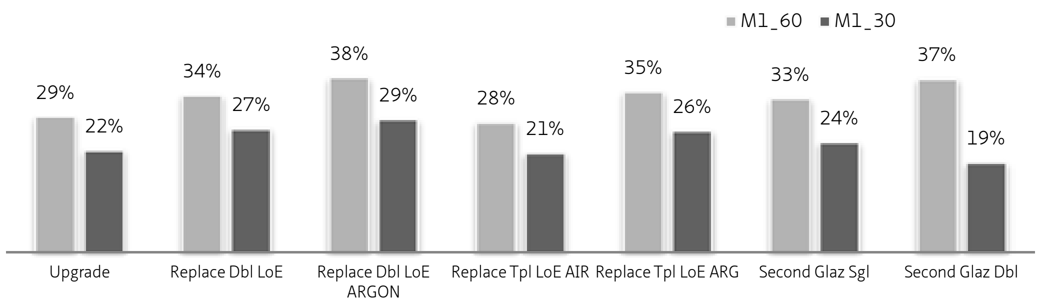
After simulating window options variations and different models, the final window options simulations were executed. The variations simulated were the ones presented in Table 5.16, with the exception of double glazing with shading, because the difference was not significant if the shading is not applied, and the triple glazing with only one pane coated, because the improvement was not big. Also, for the movable shading, only the option of external shading is further simulated. In terms of models, one building type with single glazing (M1) and one with double glazing (M6) are calculated, for both window-wall ratios.

Results of all window measures variations and all orientations for the respective models are available in Appendix C. Figure 5.11.a compares window measures effect on energy reduction between the different building types. A first remark is that the building that features single glazing in the current condition (M1) has a greater potential improvement than the other model that originally featured already double glazing (M6). Moreover, buildings with higher WWR have a higher the energy demand reduction, as shown in Figure 5.11.b, as the improved component covers a wider area in the façade.

With regard to different orientations, east and west orientations have in most cases similar reduction. In the south orientation, the reduction is in general less than the rest of the orientations. A reason is that in the South, solar heat gains are more substantial and the new glazing has lower solar gain coefficient g-value. Another reason could be the higher overheating risk in south orientation, particularly due to lower infiltration for the new windows, which results in higher need for ventilation. However, south orientation has greater reduction when the windows are enlarged, exactly due to the higher solar gains, as shown in Figure 5.11.c. Finally, an interesting observation is that the reduction of double glazing is greater than triple glazing, in both models. This can be explained by the fact that, even though the thermal resistance is higher, triple glazing has a lower g-value, resulting in less solar heat gains.



a



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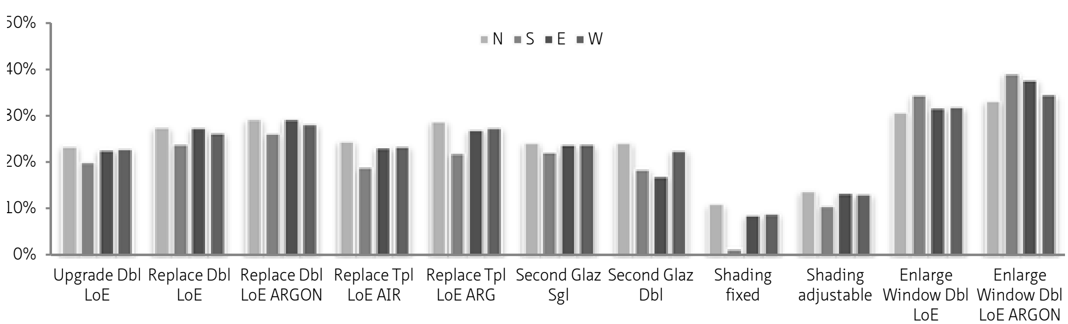


c

Figure 5.11

Comparison of window retrofitting options effect on energy reduction, applied in
(a) different building types, WWR 30%. The values are the average of all orientations.
(b) Building type M1, for different WWRs. The values are the average of all orientations.
(c) D ifferent orientations of the typical apartment in building type M1, WWR 30%

§ 5.7.3 Balcony

A Balcony options variations

Balcony is a major thermal bridge in most existing buildings, as heat flows form the interior to the exterior through the balcony slab. In the simulation, the balcony effect was approximated with the use of sub-surface at the balcony projection on the wall, assigned with material with different thermal properties of the exterior wall.

Balcony retrofitting measures comprise insulating the balcony to prevent thermal bridging or cladding the balcony and insulating the edge, to create a thermal buffer. Firstly, those options, along with respective variations, were simulated for one orientation and one building type, namely model M1 with 30% WWR and oriented to the East. This first set of simulation aim at comparing the effect of the variations, checking for significant differences and decide on the options to be further simulated. Simulating balcony glazing is the options with most variations possible and requires further modification in the simulation models. Therefore, the variations evaluation focuses on the balcony cladding options.

Cut-off balcony and Insulation of balcony slab

The options of cutting- and possibly replace and enlarge- the balcony and insulating the balcony slab, to prevent thermal bridging, have technical solutions, as discussed in section 4.4.3. In terms of thermal modelling, simulating the heat transfer through the wall detail, as the example in Figure 4.16, is necessary to check the insulation thickness to be sufficient. In the model set-up in Design Builder, to calculate the effect on the energy consumption, the measures are approximated by changing the properties of the sub-surface. In the case of cutting the balcony, the sub-surface is removed, so that the previously balcony edge is now continuous wall. In the case of insulating the slab, insulated construction is applied as the surface material. As the simulation set-up does not provide a wide range of variation in balcony thermal break measure, the aforementioned two measures are directly used in the final simulation in step D, for the building types decided in steps B and C, based on the balcony cladding measure evaluation.

Balcony cladding

There are two types of applications regarding balcony glazing. The first is the creation of a winter-garden and the second the integration of balcony space into the thermal envelope. The main difference is that in the first case the balcony space is not heated. However, it functions as a thermal buffer as the glazed cladding allows solar radiation to increase the temperature inside balcony zone and, thus, the heat losses from the heated space to the balcony are reduced compared to the outside space.

In the winter-garden simulation, the balcony was modelled as a separate zone. In this way the temperatures in the balcony were checked. As a result, the bedroom zone has no longer external wall and window. The external construction and openings of the balcony zone were assigned the respective construction, while the inter-zone partition kept the construction of existing wall and window. To avoid overheating in the occupied zone, the external window opens when the temperature in the balcony zone exceeds 21oC. The inter-zone window is always partially open, to ensure a low level constant ventilation. Single and double glazing, proportion of the balcony glazed cladding and the room wall insulation was checked as measure variations, presented in Table 5.18 .

The measure of integrated balcony refers to the balcony zone being merged with the occupied zone. When the balcony zone was integrated to the thermal envelope, the balcony became a heated space. Cladding according to external window standards is then required (Table 5.1). The wall between balcony and the room was removed. The same activity and HVAC inputs applied for the balcony as for the living room zone, meaning that the zone is also heated and ventilated according to requirements set in Table 5.9. The transparent part of balcony cladding was 80% open when interior temperature was over 23oC. Double glazing Low-E glazing was applied. The U-value achieved was 1.78 W/m2K, which complies with regulation for external windows. The infiltration rate of the construction was also reduced, assuming that the new cladding has improved airtightness.

a b

Figure 5.12

Visualisation of M1 model building with balcony glazing. The balcony space as winter garden (a) and integrated in the apartment space (b). When it is integrated the wall between balcony and internal space doesn't exist anymore.

Table 5.18 presents variations and respective results, as far as the heating demand the overheating is concerned. The coloured values show the parameter that varied in every model. According to the results, the variations of balcony glazing applications did not have significant different effect on the heating energy demand of the apartment.

The reason is that the glazed balcony creates a heat buffer to reduce the heat loss form the adjacent conditioned zones. The reduction is achieved by maintaining higher temperatures in the balcony than outside, due to solar heat gains. The simulation has shown that the variations in the balcony converted into winter garden, have similar reduction (24%). When double glazing winter is applied, the reduction is again the same, but less overheating hours occur in the balcony zone. When balcony is integrated in the thermal envelope, higher reduction 37% was calculated. Based on the results, the options to be further simulated are three: single glazing and double glazing cladded winter-garden and integrated balcony, highlighted in Table 5.18.

variations	Glazing type	infiltration $m^3/h/m^2$ @50Pa	g-value	U-value	proportion transparent %	Shading	WWR	Existing wall	Reduction	Balcony overheat (h per yr)
1	Single	5	0.76	4,3	100	no	60	masonry	24%	243
2	Single	5	0.76	4,3	100	inside-blinds	60	masonry	24%	230
3	Single	5	0.76	4,3	100	no	30	masonry	24%	251
4	Single	5	0.76	4,3	50	no	60	masonry	24%	237
5	Single	5	0.76	4,3	100	no	60	masonry, 10 insul	24%	254
6	Double	3	0.68	1.78	100	no	60	masonry	24%	153
7	Double	3	0.68	1.78	50	no	n/a	n/a	37%	n/a

Table 5.18
Overview of balcony options variations for Model M1

B-C Building types and WWR variations

After checking the different variations for the same model, different building types and WWRs were tested for one of the variations, in order to which models should be simulated to correspond with different buildings in the stock. The parameters that needed to be considered are the characteristics of components adjacent to balcony space, namely the wall and window construction, as well as the window-wall ratio. For this reason, models that differ in those parameters, as shown in Table 5.19, were simulated. Simulation considered both single and double glazed balcony cladding and the output was the reduction in current energy demand in the occupied space and balcony overheating hours. The 60% opening models had an overheating problem. To avoid this and achieve acceptable overheating hours, the ventilation scheme was slightly modified that the 30%-models.

All three models showed similar tendencies both in the energy demand reduction and overheating of the balcony. Hence, the difference in wall and window construction is not of great significance to the effect of balcony glazing. The WWR on the other hand does make some difference, with the reduction being 24-21% and 19-16% for the 30% and 60% WWR respectively. This can be explained by the ventilation scheme simulated and the area of the operable opening between balcony and internal zones. Moreover, WWR does make a difference, probably due to the higher overheating risk. Based on the above discussion, one building type, namely M1, will be further simulated is building type M1, for both WWRs.

	Existing			Single balcony glazing		Double balcony glazing	
	Wall	Window	WWR	Reduction	Balcony T>26°C (h per yr)	Reduction	Balcony T>26°C (h per yr)
M1	Masonry Brick	Single Glazing	30%	24%	243	24%	153
	Masonry Brick	Single Glazing	60%	19%	244	19%	156
M2	Masonry Brick	Single Glazing	30%	22%	268	23%	174
	Masonry Brick	Single Glazing	60%	16%	270	17%	176
M3	Lightweight Concrete	Single Glazing	30%	21%	242	22%	158
	Lightweight Concrete	Single Glazing	60%	18%	245	19%	160

Table 5.19
The effect of balcony glazing application on the heating demand of different models

D Balcony options simulation

The results of balcony measures energy reduction for the typical apartment can be found in Appendix C, Table C.14 and Table C.15. As also shown in Figure 5.13.a, a remark is that measures of balcony cladding save considerably more energy than insulating the balcony slab or create a thermal break. This can be understandable since the latter measures only prevent heat loss due to thermal bridging, while the balcony cladding reduces the heat flow through the whole façade that is adjacent to balcony space. The potential reduction of 2%-4% by insulating the thermal bridge is consistent with studies on thermal breaks found in the literature (Goulouti et al., 2014).

An important consequence of balcony cladding is that the temperature in the balcony is possible to be maintained within thermal comfort zone for more hours, as shown in Figure 5.13.b, making the balcony a winter-garden and reducing the heat flow between the heated space and the balcony zone. The higher reduction was calculated in the case where the balcony space is integrated in the thermal envelope. However, it needs to be noted that the reduction is calculated per m^2 and the balcony integration adds m^2 to the conditioned space. So the percentage of reduction for the whole dwelling is determined ultimately by the total area.

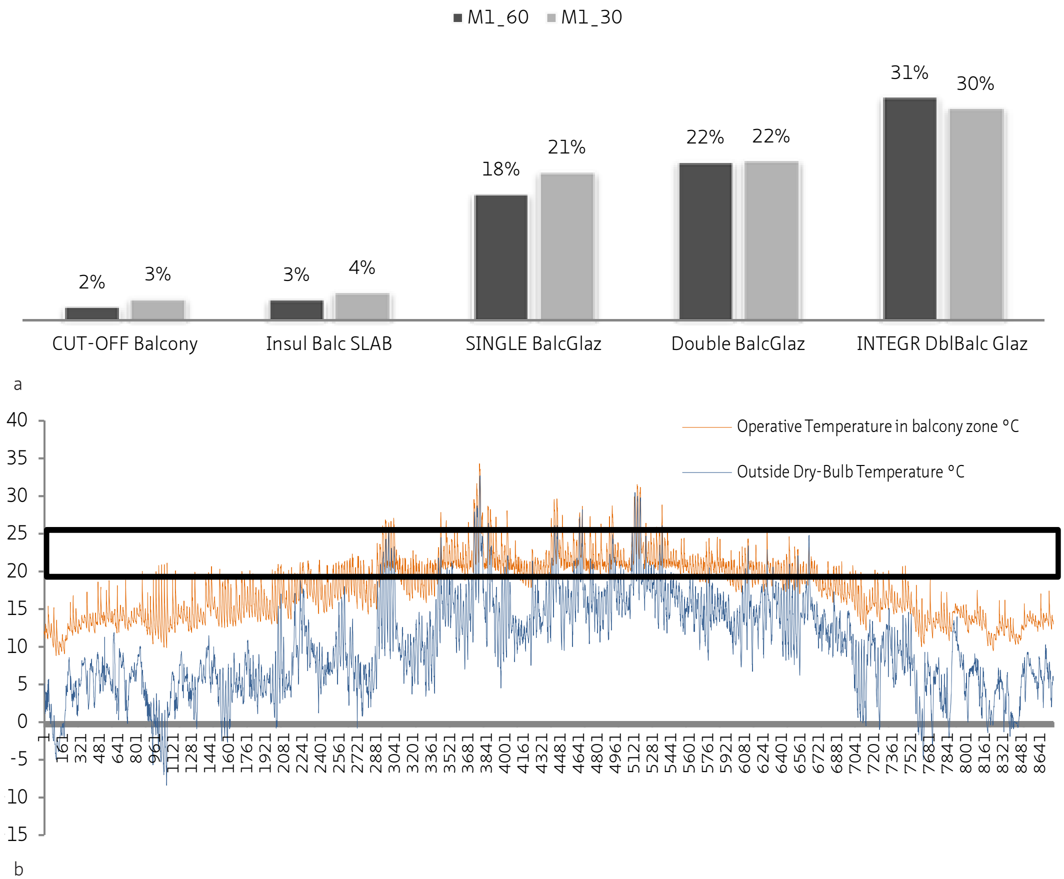


Figure 5.13

(a) Comparison of balcony measures' effect on models with different WWR. The values are average demand for all orientations

(b) Comparison of the outside temperature to the operative temperature in balcony after the application of single glazing cladding to the balcony in the East façade. 3017 more hours per year are within comfort zone after the application of the glazing. The comfort zone temperatures are highlighted

§ 5.7.4 Roof

A Roof options variation

Several measures are possible to upgrade the roof thermal performance. The technical details of the measure implementation depend on the specific roof construction and have been discussed in section 4.4.4. Building type M1, with 30% WWR and east oriented façade, is used to simulate the roof measures variations, as it gives the possibility to apply the measures for pitched roof. In the case of roof retrofitting the typical apartment is the top, which is T3 in Figure 5.3. The reason is that the energy demand reduction in middle and ground floor apartments is insignificant, as shown in Figure 5.14.

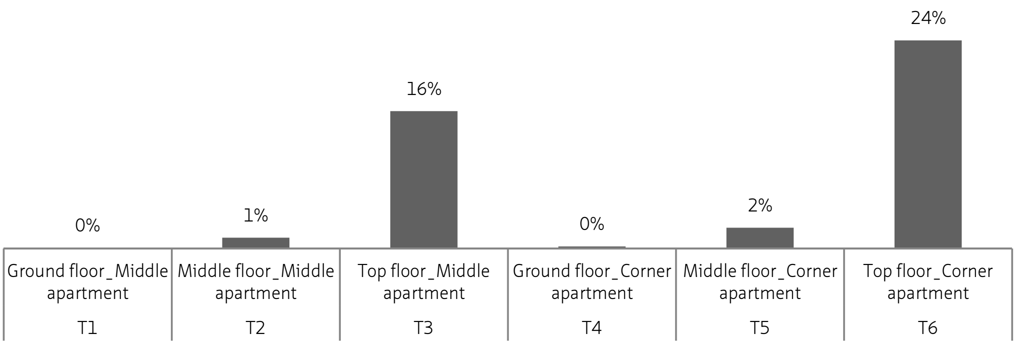


Figure 5.14
Heating demand reduction after the application of flat roof insulation in different apartment types in M1 building type, with 30% WWR and east oriented façade

Pitch roof and top floor slab insulation
An important factor that determines the type of measure and potential energy reduction is whether the loft space is occupied or not. Pitched roof insulation refers to increasing the thermal resistance of the roof component. In the simulation, this was achieved by applying a construction that included insulation material. In options 1 and 2 of Table 5.20, this construction was assigned to the roof component. The difference between the two options is that in the second case the loft space is occupied and, thus, the heat transfer through the top floor slab is eliminated, as both occupied spaces have comfort temperatures. In option 3, the loft space is also occupied, but the roof is not insulated.

When the loft space is not occupied, insulation can be applied on the top floor slab. To simulate the measure, a layer of insulation was added to the top floor. Different insulation material and material thickness were tested, resulting in different thermal transmittance coefficient and energy demand reduction. The loft space remained unoccupied, as specified in the simulation input, in Table 5.9.

Flat roof insulation and green roof
In building types with an existing pitched roof, such as M1, the roof was assumed to be removed and the top floor slab was insulated. An insulation layer is added to the slab construction, together with waterproofing and covering. The zone of the roof space no longer exists. Similarly, the pitched roof is removed and the top floor slab construction is changed, to include the necessary layer for a green roof construction. In building types with existing flat roof, the same constructions were applied to the roof component.

Table 5.20 presents the roof measures variations with the respective energy demand reduction for the typical top floor apartment. A first remark is that in case of unoccupied, the saving is much greater if the top floor slab, rather than the roof, is insulated. This happens in option 1 of the table, because even though the roof is insulted there is still heat flow through the top floor slab, as the loft space is unoccupied and has lower temperature that the occupied top floor apartment. When the loft space is occupied, as in options 2 and 3, the energy demand of the top floor dwelling reduces. In general, the energy demand and the respective reduction depend on the resulting U-value after the application of the measure. Measures with similar U-values provide similar reduction. The measures to be further simulated in the step D are highlighted in the below table and summarised in Table C.16.

B-C Building types and WWR variations

After the measures' variations comparison, different building types are compared. The most important is to compare buildings with different roof construction, which are types M1 and M6. Moreover, additional models that differ in wall and window construction are checked. The models with pitched roof construction have similar result and, thus, only M1 building type is further simulated. Additional, M6 type is simulated, to address building with existing flat roof construction.

As far as window-wall ratio is concerned, Figure 5.15 shows that different opening sizes do not play a significant role when comparing the effect of roof retrofitting. Therefore only the 30% WWR is further simulated.

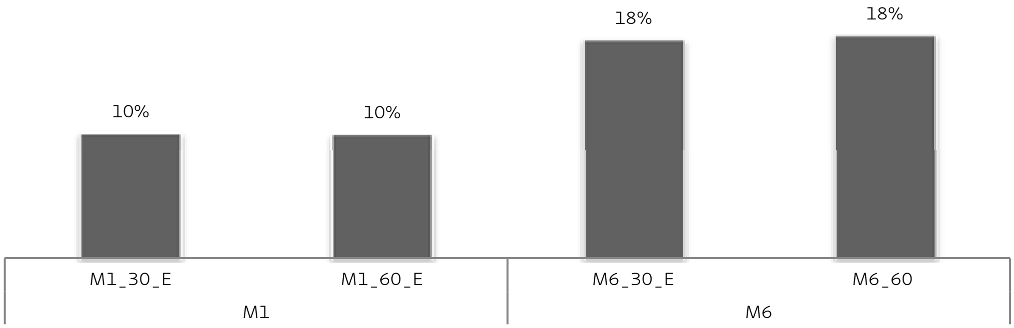


Figure 5.15

Heating demand reduction in current demand after the roof insulation in M1 and M6 building type with 30% and 60% WWR respectively.

Variation	Construction (inside to outside)	Loft space	Insulation material	Insulation thickness cm	U-value W/m²K	Heating demand of top floor kWh/m².yr	Reduction
Pitch roof insulation							
1	Plasterboard Insulation between timber rafters Hard board, bitumen membrane	Unoccupied	Rockwool	20	0.3	345	9%
2		Occupied/ additional floor	Rockwool	20	0.3	253	34%
3	Plasterboard Timber rafters Hard board, bitumen membrane	Occupied/ additional floor, no insulation on the roof	n/a	n/a	2.4	264	31%
Top floor slab							
4	Existing concrete slab Insulation material	Unoccupied Insulation on the top floor slab, under pitched roof	XPS	14	0.19	244	36%
5			perlite	20	0.2	245	36%
6			Rockwool	20	0.21	246	35%
7			Wood wool	20	0.4	266	30%
Flat roof insulation							
8	Existing concrete slab Insulation material Waterproofing Fibreboard, asphalt	Pitched roof removed in M1-M4	XPS	20	0.15	256	33%
9			Rockwool	20	0.3	322	16%
10			Rockwool	10	0.37	357	6%
Green Roof							
11	Existing concrete slab Waterproofing Insulation material Thick plastic sheet Gravel, Soil	Pitched roof removed in M1-M4	XPS	20	0.14	255	33%
12			XPS	6	0.37	279	27%
13			Rockwool	20	0.184	262	31%

Table 5.20

Roof retrofitting measures variations for building type M1, 30% WWR, east orientation

	Roof type	Existing wall type	Existing window type	Top slab insulation - RW20		Flat Roof insulation - RW20	
				Heating demand kWh/m².yr	Reduction	Heating demand kWh/m².yr	Reduction
M1	Pitched roof	Masonry Brick	Single Glazing	246	35%	322	16%
M2		Masonry Brick	Double Glazing	215	38%	308	19%
M3		Lightweight Concrete	Single Glazing	222	37%	286	19%
M6	Flat roof	Lightweight Concrete	Double Glazing	n/a	n/a	196	22%

Table 5.21
The effect of roof improvement on the heating demand of different models

D Roof options simulation

The final roof retrofitting measures simulation included variations for pitched rood insulation, whether the lost space was considered occupied or not, one option for the top slab insulation, flat roof insulation and green roof. For the building type with existing flat roof, the options that assume a loft space are not applicable. Different roof make important difference, with the pitched roof having more potential for improvement, indicated in Figure 5.16.a. The reference for the reduction is the top floor apartment, type T3, except from the last option that refers to the reduction in the demand of the loft space, when the roof is insulated. The different orientations do not have a significant influence, as shown in Figure 5.16.b. The south orientation presents in general higher reduction that can be explained by higher solar heat gains, while reduced heat losses through the new roof.

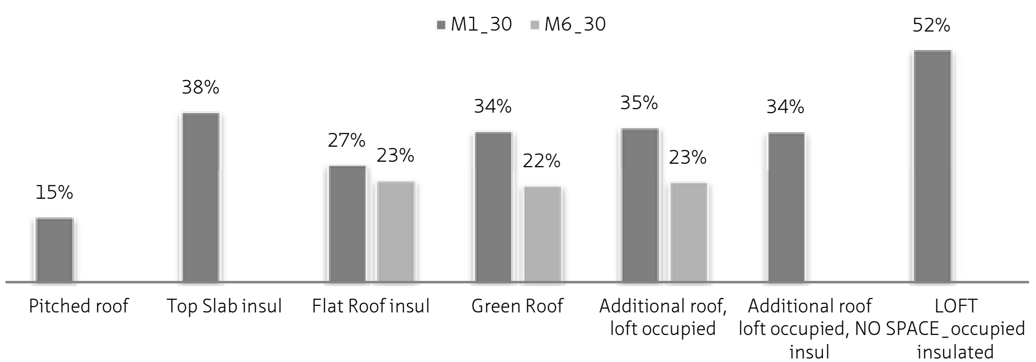
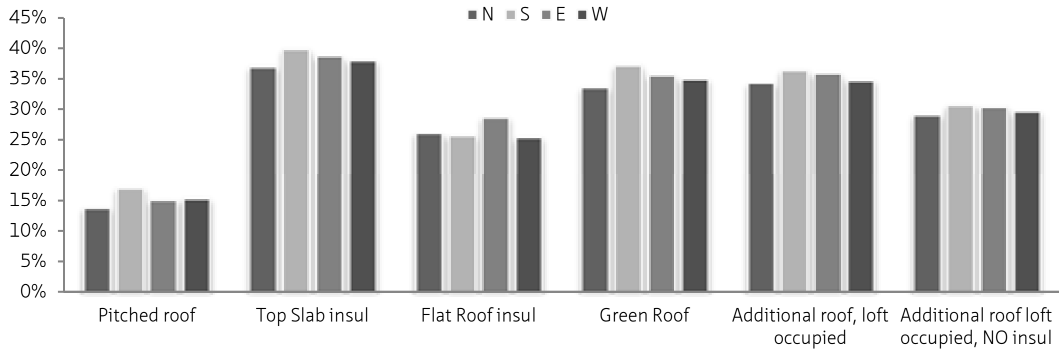


Figure 5.16
(a) Overview of roof retrofitting measures for building type M1 and M6, average values for all orientations
(b) Comparison roof measures effect on the different orientation, for building type M1

a



b

Figure 5.16

(a) Overview of roof retrofitting measures for building type M1 and M6, average values for all orientations
(b) Comparison roof measures effect on the different orientation, for building type M1

§ 5.7.5 Ground floor

A Ground floor options variations

Ground floor retrofitting refers to the floor of the first occupied storey. The component may be adjacent to the ground, but often it is on top of an unheated space, such as a basement, parking garage or storage space. To identify if there are differences between the heating energy of the occupied space, whether it is adjacent to the ground or an unheated space, these two cases of existing building types were modelled and compared. Table 5.22 shows that in both cases the heating demand is similar, with differences within a threshold of 3%. Therefore, only building with unheated space will be further simulated, as they serve better the purpose of applying various retrofitting measures. The reduction that was calculated in step D is considered to be the same in apartments adjacent to the ground.

	T1	T2	T3	T4	T5	T6
	Ground floor_Middle apartment	Middle floor_Middle apartment	Top floor_Middle apartment	Ground floor_Corner apartment	Middle floor_Corner apartment	Top floor_Corner apartment
Building with unheated basement	303	250	381	416	369	409
Heated space slab on ground	313	244	380	426	363	408
Difference between two models	-3%	2%	0%	-2%	1%	0%

Table 5.22

Heating demand in kWh/m2.yr for the same building type, with and without basement

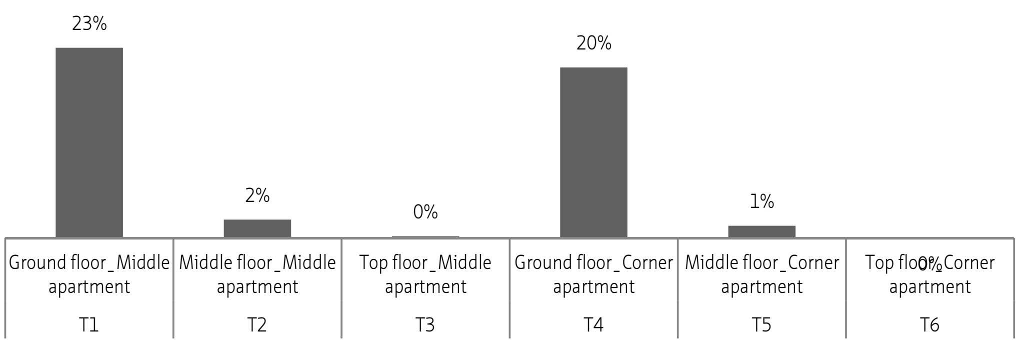


Figure 5.17

Figure 5.17: Heating demand reduction after the insulation of basement slab in different apartment types in M6 building type, 30% WWR, east orientation.

Regarding different apartment types, Figure 5.17 proves the logical assumption that only the ground floor apartments are affected by changes in the ground floor slab (23% and 20% in the middle and corner apartment respectively). Therefore the ground floor middle apartment is considered typical for ground floor measures. Moreover, the heating energy demand of the ground floor apartments after the retrofitting is very similar with that of middle apartments.

Insulation of the slab

To prevent the heat loss the ground floor, two types of slab insulation are possible, depending on the position of the added insulation. The exact detailing depends on the specific construction, as discussed in section 4.4.5. In general the insulation can be applied on top or under the slab. The measures were simulated with the addition of an insulation layer to the construction assigned to the ground floor.

Measure variations of insulating opaque elements, such as the external wall and the roof, has shown that the application of different insulation material have very similar effect on the energy demand reduction, as long as they have similar thermal transmittance coefficient (Table 5.13 and Table 5.20). Based on those findings, only one insulation material with variation in the thickness and the resulting U-value were simulated.

The variations' results showed that the reduction is similar for both measures, depending on the insulation thickness. Appling insulation of 20 cm, in both cases, was chosen for the final simulation, as the resulting U-value complies with the benchmark in Table 5.1.

Additional floor- Heated basement

If the space under the first occupied floor is heated, the heat loses through the floor slab are eliminated. Even though it is not exactly a retrofitting measure, occupying the space that was previously unheated, reduces the energy consumption of the ground floor apartment. The apartment becomes then a middle floor apartment. To calculate the reduction in energy demand, the current demand of apartment type T1 is compares to the demand of apartment type T2. The results are included in the final simulation in step D.

	Construction (inner to outer layer)	Insulation material	Insulation thickness cm	U-value W/m²K	Heating demand of top floor kWh/m².yr	Reduction
Insulation ON slab						
1	Floor covering Insulation Existing floor slab	Rockwool	20	0.2	187	23%
2		Rockwool	10	0.37	199	19%
Insulation UNDER slab						
3	Existing floor slab Insulation	Rockwool	20	0.2	187	24%
4		Rockwool	10	0.37	195	21%

Table 5.23

Basement slab insulation variation for M6 building type with 30% openings

B-C Building types and WWR variations

Since the existing ground floor was not simulated with variations, the existing building types to apply the measures were M1 and M6, which differ in all construction variations, providing the lower and the higher thermal transmittance of the building envelope. Nevertheless, according to Table 5.24, the potential reduction on the energy demand as the result of insulating the basement slab is similar for both building types. Moreover, the WWR of the façade does not affect the potential reduction and, thus, only 30% WWR was simulated in step D.

Model	Wall Type	Window type	WWR	Heating (kWh/m².yr)	reduction
M1	Masonry Brick	Single Glazing	30	236	22%
			60	238	23%
M6	Lightweight Concrete	Double Glazing	30	187	24%
			60	182	24%

Table 5.24
The effect of insulating the basement slab on the heating demand of different models

D Basement options simulation

Step A concluded with two measures for ground floor insulation, along with the addition of a heated space. Those measures were applied in the two building types of step B. Since only the ground floor apartment is affected by the basement refurbishment, this is the typical type with regard to basement refurbishment option. The results for all orientations are presented in section C.5, Appendix C. Based on the results we can conclude that the different orientations do not present significant differences with regard to ground floor options. Figure 5.18 compares the energy reduction in the two building types, which was found to be similar within a 3-5% threshold. This can be explained by the findings of existing building types comparison, which concluded that the ground floor apartment has 16%-22% more heat losses that the middle apartment, regardless of the façade construction (Table B.7).

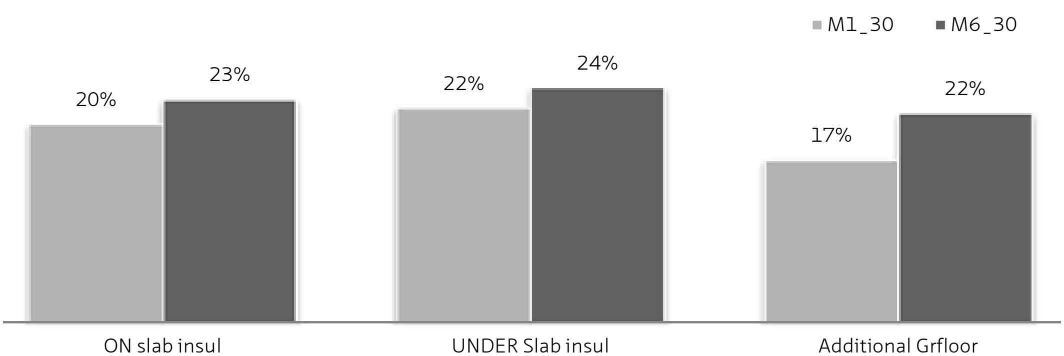


Figure 5.18
Heating demand reduction in current demand after the insulation of basement slab in different building types.

§ 5.8 Conclusion on toolbox calculation

This chapter developed the first two steps of the methodology that answers the research question and makes the integration of energy performance in the early stages of the decision-making process. After identifying the need of designers to have support in the early stages, in order to make informed decisions, the refurbishment toolbox approach was introduced. The toolbox is a database of refurbishment options, organised in a matrix, which addresses each building envelope component. The first step to the approach methodology was the systematic compilation of refurbishment options. The compilation was presented in section 5.3 and it was based on the research developed in the previous chapters, including building stock analysis, energy design principles and refurbishment practice.
The second step in the methodology was the quantification of the options, in order to give a numerical indication of the possible energy reduction that enables the comparison and supports the refurbishment strategy design. The quantification methodology comprised assessment of existing buildings energy demand, discussed in 5.6 and the assessment of energy demand reduction after the measure application, presented in 5.7.
The main outcomes of the present chapter are the introduction of the toolbox approach and the numerical output of the measures quantification. Both results are intended to be used in the early design stage of refurbishment projects, providing insights on retrofitting measures' quality and impact on energy demand to support the decision-making on refurbishment strategies.

Overview of quantification results

The toolbox options calculations generated specific figures on energy demand reduction related to each retrofitting measure. An overview of the numerical output is available in Appendix C. The importance of those figures lies in their further applicability on specific projects. Based on the specific building characteristics, they can provide an indication of the measure effect, expressed in percentage of heating energy demand reduction compared to the current demand.

Figure 5.19 presents a general overview of heating demand reduction after the application of retrofitting measures in the respective components. The code names given to the measures are descriptive of their properties, but were kept short. Details of what each measure simulation were explained in section 5.7 and they are summarised in the respective tables in Appendix C. More information of technical details were discussed in Chapter 4 and summarised in the tables in section 4.4.

The values in Figure 5.19 refer to typical apartment and they are average for different building types, WWRs and orientation. A range of potential reduction, mostly due to different building types, is presented in Figure C.1. It also shows that the general tendency is similar, even though the precise number varies. Overall, the refurbishment toolbox quantification overview has different reduction numerical output for each specific building. To extract the specific information, each building can be associated, in terms of component construction, WWR and orientation, to the pre-calculated building types and the respective reduction that the measures achieve in each case.

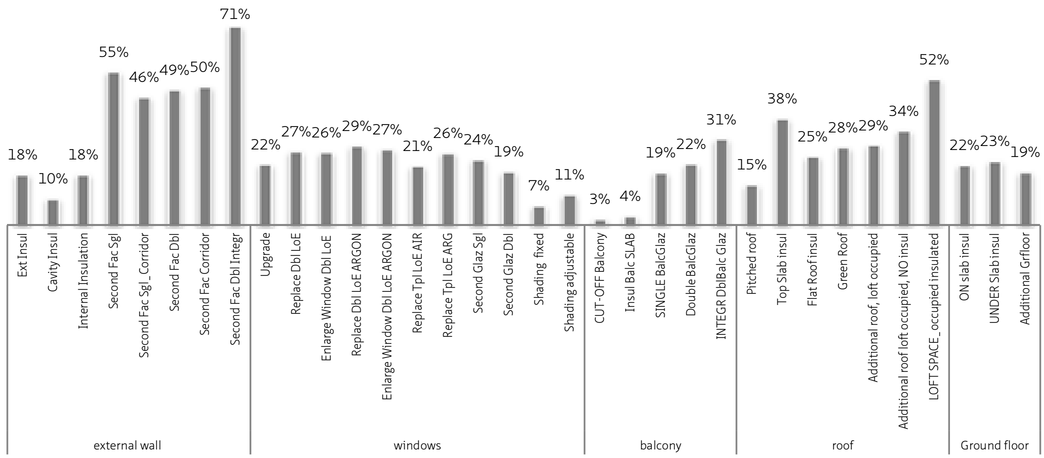


Figure 5.19

Overview of heating demand reduction after the application of retrofitting measures in the respective components. The values refer to typical apartment and they are average for different building types, WWRs and orientation.

A general remark based on the toolbox calculations results is that the worse building envelope has bigger the potential of improvement. In the modelled building types, as they are described in Table 5.10 and Table B.1, type M1 is the one with the worse thermal transmittance, comprising a masonry wall, single glazing and a pitched roof. Building type M6 consisting of lightweight concrete walls, double glazing and flat roof, has the better performing envelope. The reduction achieved in those building types set the boundaries of the measures quantification. The characteristics of the existing building types derived from the building stock analysis in Chapter 2.

Measures that add space, like the Second façade or the balcony integration, have resulted in high potential saving, accounting per m2. The percentage of energy demand reduction for the whole dwelling is determined ultimately by the total area of the heated space, which is increased by the application of the measure. For example, an existing model room in building type M1, WWR 60% and east orientation has an energy demand 259 kWh/m2.year, which results in 7493 kWh/year for the 28.93 m2 occupied space. The energy demand per m2 is 66% reduced after a second façade construction that integrated additional 15m2 to the occupied space. The total demand is then 3928 kWh/yr. Comparing the room energy demand before and after the extra space integration, the reduction is 48%, which is lower than the 66% calculated per m2. Nevertheless, it is still a substantial reduction.

Regarding the orientation of the building, for some measures the effect is similar, while in other, differences occur, depending on the type of measure. In general, when the measure performance is sensitive to high heat gains, overheating and high ventilation through open windows as a result, there are notable differences in each orientation. The south orientation presents in general higher reduction in measures that increase the thermal transmittance of opaque components, such as the wall and roof insulation. This effect can be explained by high solar heat gains in the South, while reduced heat losses through the retrofitted component. On the other hand, in measures that influence the solar gains, such as replace of the window with glazing of lower g-value, of shading application, resulted in lower energy demand reduction, compared to other orientations. In measures regarding the roof and ground floor, the orientation and WWR do not play a significant role in differences in energy demand for different models. This is logical, as orientation and WWR are characteristics of the façade.

An important remark is that the reduction percentage corresponding to each measure cannot be added up when combined in an integrated strategy. To assess the total energy reduction of a combined strategy, additional, specific performance simulation is required. When all the components are upgraded they all influence the heat losses reduction, which differs to the toolbox simulation set up that aimed at isolating each component effect. This was a choice in the methodology development, because simulating all possible measures combination would lead to a vast number of result and complicate the approach. Moreover, the toolbox information aim at supporting the decision by giving information and make comparable measures quality and effect, which will then lead to the combined strategy and the total energy upgrade assessment. Examples of combined strategies and the respective energy reduction are presented in case studies in the following chapter.

Finally, it must be highlighted that the simulation is not high resolution, as it aimed at comparable results for all option. Basic assumptions on ventilation, shading and openings function are based on European standards and they were kept the same in all as and have the main objective of avoiding overheating internal temperatures. Further optimisation in the performance is possible by applying different and more detailed inputs for the building operation.

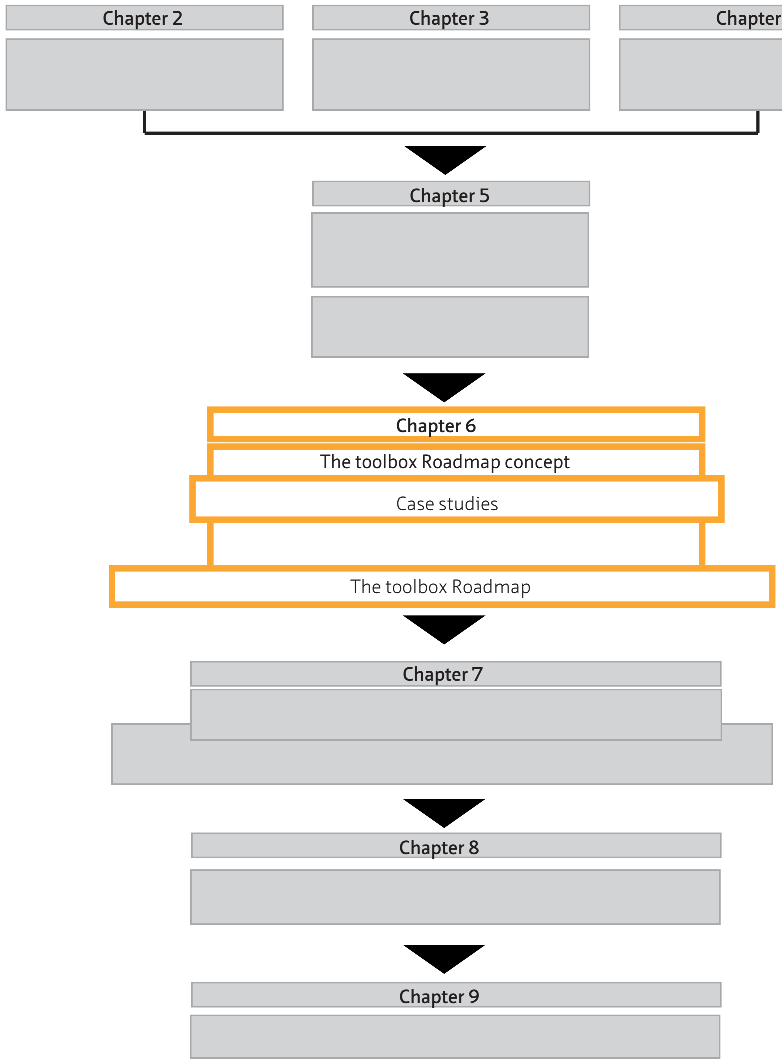
Further Applicability

The toolbox calculation results can be used in refurbishment project, based on the existing building characteristics. Table 5.25 shows the model types where the toolbox measures were applied. They were determined throughout the process of finding relevant models, described in section 5.7. Based on those, the potential reduction of each measure was calculated, for different cases. The model reference names are described in Table 5.10 and refer to the existing building types.

In future projects, the building to be refurbishment must be associated with the pre-calculated models according to each component construction and referred to the relevant tables, included in Appendix C. Subsequently, average or according to orientation potential reduction can be estimated, to be used during the design process. This design process and how the toolbox can support it are explained in the following chapter. Chapter 8 further demonstrate the process of associating different buildings to the toolbox calculations. Aside from the toolbox information association to future projects, the last step in the approach development aims at understanding the parameters that shape decision and highlighting when the information of the possible energy reduction can be useful for the designer. To achieve this, the following Chapter 6 investigates refurbishment strategies decision process determines when the input of the toolbox can be used, creating a roadmap to use the refurbishment toolbox.

Compo-nent	Existing construction	Additional parameter	Component U-value (W/m2K)	WWR (%)	Model
External wall	Masonry of solid brick or stone, 250-400mm two leaves of masonry with air cavity (30-50mm)	n/a	2.5 - 1.4	10-45	M1_30
				45-80	M1_60
	Cavity. Inner leaf with lightweight masonry units	Single glazing	1.4-0.6	10-45	M3_30
	Perforated brick masonry			45-80	M3_60
	Prefabricated concrete panels, insulation 50mm	Double glazing		10-45	M6_30
				45-80	M6_60
Window	Single glazing	n/a	6,5-5	10-45	M1_30
				45-80	M1_60
	Double glazing		4,0-2.8	10-45	M6_30
				45-80	M6_60
Balcony	Various construction (concrete slab, steel structure) with no insulation, inducing thermal bridges	n/a	2.0-0.8	10-45	M1_30
				45-80	M1_60
Roof	Pitched roof, Timber rafters, no insulation in cavity	n/a	3.8-2.0	all	M1_30
	Flat roof, plaster, 130-160mm reinforced concrete slab, 20-40mm insulation , screed		0.6-1.0		M6_30
Ground floor	Various construction (concrete slab, steel, timber structure) with no insulation	External wall type 1 (masonry, cavity)	2.0-0.8	all	M1_30
		External wall type 2 (lightweight masonry)			M6_30

Table 5.25
Building construction association with toolbox calculation models


Chapter 2
Chapter 3
Chapter 4
Chapter 5
Chapter 6
The toolbox Roadmap concept
Case studies
The toolbox Roadmap
Chapter 7
Chapter 8
Chapter 9

6 Refurbishment strategy Roadmap

After developing the "toolbox" as an approach to evaluate refurbishment options at the early stages of the design, this chapter sets off to highlight how these data can be integrated in the design process. Based on five case-study buildings, the key questions occurring during the refurbishment strategy development are identified and used to determine the decisions that shape the final solution. As a result, a roadmap to the refurbishment toolbox is composed, which highlights when the approach can be used to support the design process. The chapter first introduces the roadmap concept and the methodology to its development. Section 6.3 analyses the current condition of each building, the problems identified and the requirements for the refurbishment. Subsequently, in section 6.4, the refurbishment options are organised according to the toolbox matrix and the design choices for each component are explained. Finally, section 6.5 develops the roadmap, combining the key questions and processes followed in the case studies and determining the impact of the toolbox information.

§ 6.1 Introduction

The previous chapters elaborated on the idea of using the Façade Refurbishment Toolbox to support the decision-making process for the design. Based on the theoretical background regarding existing housing stock, its energy use, and current refurbishment practice, several retrofitting measures to apply on the building envelope components were systematically organised into a toolbox. Moreover the options were quantified in terms of energy demand reduction. In this way the energy performance of each measure can be considered in the early stages of the design.

Every refurbishment project is different, not only in terms of the existing building's condition and the relevant energy savings, as they were calculated in Chapter 5, but also regarding the project specifications. Those specifications include the required performance of the refurbished building, modifications of building's appearance, function and layout, as well as investment and changes in the occupants' situation. Since the toolbox is a systematic approach to support decision-making in the design process, it is still crucial to understand what the parameters that shape decision are and when the information of the possible energy reduction can be useful for the designer. Important as the systematic compilation of options provided by the toolbox may be, not all of them are applicable to every case. Furthermore, the designer needs to know at which points throughout the process the information come together and what are the available options then.

To address these issues, the approach investigates how refurbishment strategies are developed, highlights decision-making points and determines what the input of the toolbox can be. In this way a roadmap of how to use the toolbox information is created. The concept of a roadmap to Facade Refurbishment Toolbox and the methodology to develop it are explained in section 6.2. Refurbishment strategies development is investigated through case-studies. Each project has different design process, as the parameters that affect decisions differ. The toolbox information supported the selection of retrofitting measures. Combining these processes creates a roadmap to refurbishment strategy design process. The selection of case-study buildings and their existing conditions are explained in section 6.3, while section 6.4 develops refurbishment strategies for each case. Every component of the building envelope is addressed separately and a retrofitting measure presented by the toolbox is selected for each one, composing the integrated refurbishment strategy. The selection depends on several aspects related to the building existing condition and the project specifications. Based on this process, section 6.5 concludes on the key questions and consideration that occur and how the toolbox information can support the answers, leading to the final measure selection and strategy composition. The roadmap to the façade refurbishment toolbox is then created.

§ 6.2 The Roadmap concept

Given the necessity to support the design decisions at the early stages, as already discussed in Chapter 5, the approach points out what decisions are made during the refurbishment strategy development and what are the parameters affecting them. Those parameters are related not only to the original condition of the building, but also the specific requirements of each project. Such requirements and limitations are, amongst others, the monumental status, that allows for modification of the appearance or not, the building program of the project, e.g. if extra space is required, the budget and the lifespan of the investment, the user position during and after the refurbishment, and the energy efficiency of the refurbished building.

Every design process has to consider and give solution to several requirements. In order for the designer to use the information provided by the toolbox approach, they need to know how the information contribute to their design process. Organising the steps where impact of the information is possible leads to a roadmap to refurbishment design process. This roadmap highlights what and when decisions are made and the parameters that are important, focusing on building envelope, as it is the target of the research and the most influential building component in terms of energy efficiency. Last but not least, is clarifies when the toolbox information are able to support the decision-making.

The toolbox approach intends to give an indication of the effect of refurbishment measures in the early stages of the design, before the final design is developed. For this reason, different possibilities, addressing all building envelope components are suggested and calculated. Nevertheless, not all the options are applicable to every case. The roadmap helps to determine the relevant options for each project.

Based on the toolbox information, the roadmap presents the decision process by addressing each building envelope component separately, namely the external wall, windows, roof, ground floor and balcony. In reality, the design development is not linear, as each decision affects various aspects, it may need to be revisited or be determined by factors outside the building envelope. In order to create a roadmap to determine when information of the energy efficiency is crucial, the process has been simplified, addressing the individual components.

To develop the roadmap, key considerations that determine the refurbishment strategy are identified. The design process is not linear and it is unique depending on the specific project and design team. The roadmap does not attempt to reproduce the design process, but show when the toolbox information can be referred to, supporting the decision-making.

The key questions appearing during the study of the building envelope components are connected, first of all with the existing condition of the building. It determined the decision of components that need to be upgraded and it is also necessary to associate the building with the generic toolbox calculations, in order to specify the potential energy reduction. Moreover, the specific project requirements need to be taken into account. Such requirements include the possibility or not to change the external appearance or the need for bigger dwellings, handicap access etc.

With regard to the potential energy reduction, these figures can be used to compare different options, in order to select the more efficient. However, in some cases choosing the more efficient is not possible, due to technical, financial or other reasons. Even then, knowing the potential reduction is useful in order to justify certain choices and provide information about the quality of a measure. The orientation is necessary to provide the actual number of the energy reduction, simulated in the toolbox calculations.

Nevertheless, the final decision is mostly taken according to the level of intervention and the intended investment. The level of intervention depends on the project's budget and ambition. The toolbox supports the evaluation of the measure and points out when the decision is influenced by the investment. Furthermore, the investment can be conceived not only in terms of budget, but also in terms of energy. Some measures are more energy intensive than other, as far as the energy for the material manufacturing and transport, a.k.a. the embodied energy, is concerned.

Energy generation should be mentioned as an additional possibility. The decision to include energy generation technologies-mainly with the application of solar collectors and photovoltaic cells- is determined by financial aspects, requirements in order to obtain an environmental or energy certificate or ambition to promote a green image of the estate. Energy generation will be an addition to building envelope upgrades that will further reduce the primary energy consumption.

To investigate what are the key points in the design of refurbishment strategy, how they influence the decision and how it is supported by the toolbox approach, five case-study buildings are used. A case study can be defined as an empirical inquiry that investigates a contemporary phenomenon within its real-life context (Yin, 1994). In the framework of the thesis, the phenomenon is the design of a refurbishment strategy and the context is each specific building, its construction, problems and requirements. The current chapter presents each case study building and explains the decision-making process that forms the refurbishment strategy. This is the next step in the approach development. The first part describes the current condition of the building, the problems identified and the requirements of the refurbishment. Subsequently, the refurbishment options are organised with the help of the toolbox matrix and finally the design choices are explained, creating the toolbox roadmap for each building.

§ 6.3 Case-study buildings

The roadmap is composed based on the decision-making followed during the refurbishment design of 5 case study buildings. The choice of buildings aims at supporting the development of the toolbox approach and the roadmap. Therefore, the buildings needed to have certain aspects in common, to make them comparable, as well as differences, to help identify the different parameters that influence the decisions.

First of all, they building are located in the same climatic zone, within the scope of the research. The climate is a key parameter on the effect refurbishment measures would have on the energy demand. This means that the same measures have different effect in different climates. For this reason, the parameter of climate is eliminated from toolbox calculations to avoid a big amount of data that would not be manageable, or comparable. The research focuses on one climate, the north-west European climate. Nevertheless, the approach of the toolbox and the roadmap to decision-making is applicable to different climates as well. The results of the toolbox calculations would be different, suggesting that the effect of the refurbishment measures has to be simulated with focus on the specific climate.

Secondly, the research sought for buildings of the same type. Multi-residential buildings of the post-war period are the building type in focus. The reason for this decision is that apartments are one of the most common building types. According to Eurostat (2011), 41.5% of the European population lives in apartments (Figure 2.2). Moreover, apartment buildings give the opportunity to investigate dwellings with diverse energy requirements, such as the middle, top and side apartments.

The post-war period buildings are particularly interesting in the refurbishment discussion. The circumstances during that period resulted in a large building stock, almost one third of the total stock (Itard & Meijer, 2008), of poor quality and energy performance. The structure, however, is still active (Andeweg et al., 2007). Demolishing those building would be a waste of energy and capital. Upgrading of the building envelope is the answer to many issues of the post-war residential stock.

Despite the similarities that render them comparable, the selected case-study buildings have differences in terms of existing construction. In this way a wider range of possibilities is covered. Last but not least, the specifications of each project differ, giving the opportunity to demonstrate different decision-making processes.

The first step in developing any refurbishment strategy is to analyse and understand the construction of the building, current condition, problems and requirements that the strategy needs to answer. Consequently, this section analyses the condition of each case-study building, the analysis of the existing buildings is based on the original construction drawings provided by the archive of the housing association, along individual observations. Four post-war apartment building complexes are used as case studies. The first of the complexes is investigated into two different case studies. Even though the both buildings have the same original condition, the specifications differ, resulting in different solutions.

The specifications are given by the housing associations that own and manage each building. Each of the case studies is in the immediate plans of their owner to be upgraded and, therefore, the project requirements, connected with financial scenarios, were already developed. The cases of Breslauer and Platanen complexes were executed as a study initiated by their owner, in order to identify their refurbishment potential. The cases of Suringerflat and Coevordenstraat complexes were analysed as part of master theses in Delft University of Technology, supervised by the author. In all cases, the housing associations were involved, providing information and access to the buildings. A comparative overview of the five case-study buildings, in terms of construction and design characteristics of the existing condition, problems and specific requirements is given in Table 6.1, in section 6.3.5, before section 6.4 proceeds with explaining the refurbishment strategy decision-making.

§ 6.3.1 Breslauer Complex, Krefeld, Germany

General information

The first study is a case-study project, the refurbishment of a multi-residential-building complex of the post-war period in Germany. The subject of the study was assigned by Wohnstatte Krefeld, the housing association that owns and manages the estate. It concerns two residential buildings constructed in 1967, located at the area Gartenstadt at the outskirts of the city of Krefeld. They are part of 3 identical complexes, consisting of two buildings, one 3-storey and one 4-storey apartment block, laid out in an L-shape arrangement.

Based on data given by Wohnstatte Krefeld, Breslauer Complex comprises 120 apartments, most of which are still in their original situation. They are all rented and the only owner is the housing association. Less than 1/5 has renovated bathroom and kitchen, while none is disabled accessible. Moreover, 22% is vacant, which is one of the issues the housing association would like to eliminate with the upgrade of the apartments.

The three-storey apartment block consists of four identical staircases, providing access to six apartments, two in every floor. The block has a north-south orientation, resulting in east and west oriented façades. The four-storey block has two staircases and north, south oriented façades. The south façade overlooks the courtyard.

Building Construction

The structure of the building consists of load-bearing masonry brick walls and concrete, in-situ slabs. The façade is constructed of 24mm lightweight concrete blocks and brick cladding. Balconies are designed either as incised loggias or as a continuous cantilevered concrete slabs. Basement ceiling and the ceiling to the attic consist of a 130 mm thick in situ concrete floor without additional insulation. As shown in the construction details in Figure 6.1.d and e, no insulation has been used on the façade or the floors. The buildings have a pitched roof of a 12° slope, constructed with timber joists and a wooden casing and sealed with bitumen roofing membranes. The original windows were replaced with double glazed, PVC framed windows in the 1980's.

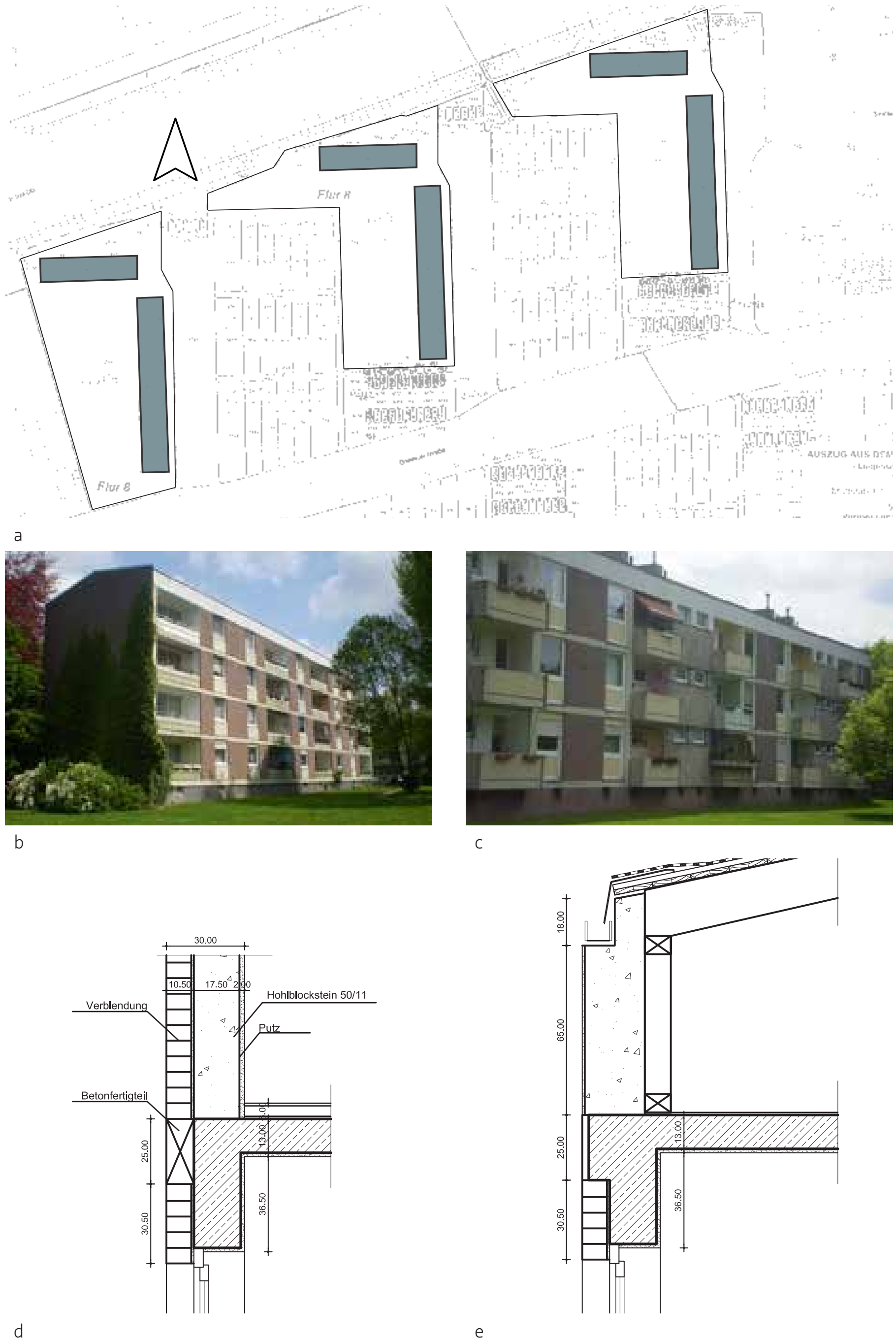


Figure 6.1

(a) Urban layout of the Breslauer complex. (b) The courtyard façades of the three- storey and (c) the four-storey apartment blocks.

Drawings of the original building construction, (d) the external wall and (e) roof respectively.

Current problems and refurbishment requirements

The main problems found during the analysis are related to the building envelope, the spatial quality of the apartments and the condition of the mechanical installation, which are the key technical aspects to the refurbishment approach. In more detail, as far as the components of the façade and the roof are concerned, the problems identified were the complete lack of thermal insulation on external walls and roof, outdated windows and thermal bridging at the balcony slabs. The comparison of the existing components thermal resistance with the minimum required by the German regulations (EnEV, 2009) confirms the incompetence of the current fabric's thermal properties. The external wall for example has a U-value of 1.20 W/m²K, while the current standard is 0.24 W/m²K.

Moreover, there is no sound insulation on the floor, ceiling or walls and parts of the façade and prefabricated elements show signs of deterioration, such as plaster fall-off, reinforcement's corrosion of the concrete parts etc. Additional problems were mould growth on the inside of the external surfaces, related to thermal bridging and insufficient ventilation, and outdated technical installations in most cases. The apartments are not handicap-accessible (no lift, ramps etc.), which is a problematic situation especially taking into account the number of elderly residents. The spaces are considered too small for today's standards, so extra spaces or rearrangements of the layout are needed. Finally, the outside space of the buildings, even though abundant, is currently not used by the residents, due to its nature as a "confused space"- neither public nor private, which is a common problem in this type of estates (Priemus, 1986).

a b

Figure 6.2

Problematic areas of the building envelope, deteriorating parts and mould growth.

The specifications of the project specified different requirements for each the two buildings of the complex. This is the reason each building constitutes a different case-study, with separate strategy developed in the following section. In general, a diverse tenants' population mix is aimed, this is why the building program requires of better quality flats, diverse layouts and an appealing, refreshed design. The current tenants will be removed and the buildings will be empty during the refurbishment construction work.

For the three-storey block, the programme of the housing company for the apartments specified bigger, higher-quality housing with elevator access. The energy upgrade also has to be substantial. The rent price of the refurbished dwelling will be higher, targeting higher socio-economic group than the existing tenants.

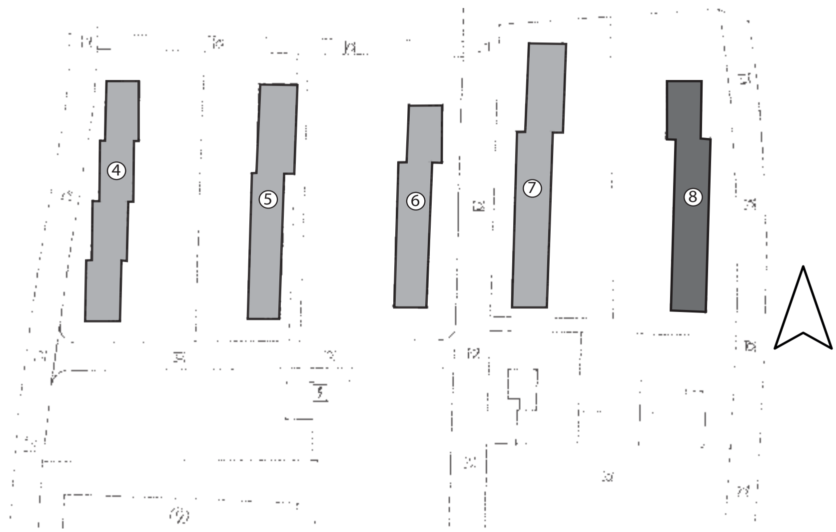
The specifications for the four-storey apartment block, provided by the housing company, were slightly different from the previous one. Diverse sized apartments are required that will be moderate prised, in comparison to the other block. The energy upgrade is set to the minimum normative requirements. Additionally, one of the design requests was the noise protection from an adjacent highway.

§ 6.3.2 Platanen complex, Krefeld, Germany

General information
The Platanen complex consists of 5 building with the same typology with slight modifications. The blocks are parallel to the North-South direction, resulting in East and West façades. Each apartment building consists of 3 to 4 staircases that give access to two, symmetrically laid-out apartments in each floor. The buildings have two to three upper floors and a non-occupied attic. Entrances are located directly on a passable road. The open areas are in relatively private atmosphere among the buildings' rear façade.

Approximately 1/5 of the apartments of the complex have renovated kitchen and bathroom and a 10% have allied internal insulation for soundproofing. The majority of the apartments remain in the original condition and none of them is barrier-free accessible.

The strategy development focuses on block number 8, highlighted with darker grey colour in Figure 6.3. The building is two-storey high, consisting of 16 dwellings. The other building of the complex has the similar lay-out, construction and problems. Consequently, the refurbishment strategy given in section 6.4.3 can be applicable for other buildings of the Platanen complex.



a

b

c

Figure 6.3
(a) Urban layout of Platanen residential complex
(b) Front façade of building 4 (c) and rear façade of building 8 of the Platanen complex

Building construction

The structure of the buildings consists of masonry solid brick walls, both external and internal. The load-bearing walls are made of 240mm Masonry. The longitudinal facades are plastered, while the end traverse wall is exposed brickwork. The floors are in situ, reinforced concrete, 130mm thick, that continue in the loggias. The final floor finishing in the dwellings consists of timber planks, constructed with timber substructure of 100mm height. The roof is a timber-rafter construction, inclined 30°, on top of a raised edge of the concrete ceiling. The roof is covered with clay tiles, which date from the construction period and there is no other lining (Figure 6.4.a), creating an un-occupied attic. Most apartments have been equipped over the years with PVC windows, the age of which is approximately 25 to 30 years.

a b c

Figure 6.4
Details of the roof and bottom part of the external wall

Current problems and refurbishment requirements
The impact occurred at various points (Outer corners /Geometrical thermal bridges) to mould problems, which some tenants in have tried to address individual performance with the application of an interior insulation, also for soundproofing reasons. Similarly to the previous case study, the components thermal conductivity is far beyond the current standards. Energy upgrade of the dwellings, coupled with improvement of interior layout and finishing, is one of the main requirements. Nevertheless, the changes should ensure to preserve the architectural character of the neighbourhood, with low to medium-rise buildings.

None of the considered building of the complex is barrier-free accessible. The building entrance is halfway in the height between first floor and basement, resulting in half staircase to reach the first floor. The addition of lift, ramps or other solutions should be part of the refurbishment strategy.

The floor plan layout and the apartment sizes correspond only partially to current needs set by the housing association. Bigger, better quality apartments, possibly with merging of the existing flats, are one of the requirements for the refurbishment. As significant changes in the layout are expected, current occupants will be removed during the construction works.

Finally, a particular challenge comes from the urban situation. The development with semi-public green space leads to a lack of identification of the open spaces. Neither have the open spaces of a clear public Park character, yet they are clearly associated with individual dwellings. Clarifying and identifying the external open spaces, so that occupants will start using them, should be one of the refurbishment considerations.

§ 6.3.3 Suringarflat, Zaandam, The Netherlands

General information

The case-study building is a representative multi-residential building of the post war period in the Netherlands. It is situated in Zaandam, in the typical post-war district 'Poelenburg', where a number of buildings are already being considered for refurbishment by municipality and housing associations. The building used as case-study was built in 1963 and it is one seven identical residential complexes. Each building consists of two symmetrical wings in an L-shaped layout. As a result, the apartments have 2 orientations. One orientation is North–South with the living room on the South side that overlooks the internal backyard. The other orientation is the East–West orientation with the living room on the East side, looking at the street.

Figure 6.5
(a) Aerial view of Poelenburg district and (b) the L-shaped buildings
(c) Gallery and (d) back façade.
Image courtesy Edwin Tensen

The building is five stories high, storage space on ground level and 4 layers of dwellings. Each wing of the L-shaped building is approximately 100m long, containing 12 apartments in each floor. As a result, the complex consists of 96, four-room dwellings, with an average area of 68m². The individual apartments in the upper floors can be accessed through a walkway along the façade. The gallery leads to a central staircase. This type of apartment building, also known as gallery-flat building, is one of the most common types of multi-residential building constructed in the post-war period in the Netherlands (Priemus & Elk, 1971). The main entrance of the building, located on the corner of the L-shape, gives access to an open gallery on the north and west façade respectively in each building wing. There is an extra staircase at the end of each gallery. The North oriented galleries of the dwellings are located on the street side, while the ones on West façade are orientated to the internal backyard of the housing complex.

Building construction

The construction of the housing block is according to the 'Rottinghuis' building system, a standard industrialised building system, developed in the post war period in the Netherlands The building method of 'Rottinghuis' concept is used for middle-rise building and consists of prefabricated concrete elements for the walls and floor (Priemus & Elk, 1971).

The structure of the building is made of concrete elements. The load bearing walls between dwellings has have a total thickness of 200mm, while the load bearing wall in the dwelling are 160mm thick. The floors are made of prefabricated concrete slabs, with a total thickness of 230mm, 180 mm structural and 50mm finishing layer. The finishing layer is made of 10mm mineral fibres insulation and 40mm lightweight concrete on top of that.

The long façades is a combination of opaque and transparent elements. The opaque wall is prefabricated concrete elements, of 250mm thickness in total. Other opaque element is the parapet of the façade panel, consisting of plywood, 40mm insulation and 100mm lightweight concrete (Figure 6.6). The original wooden frame windows have been replaced with plastic frames and double glazing. The end walls consist of two leaves, 110mm masonry on the outside and 180mm concrete in the inside, with 50mm cavity in between.

In 1992 the housing company 'Rochdale' that owns the estate did some maintenance on the building. Apart from windows replacements, the galleries and balconies are refreshed and some interventions are done on the front doors, staircases and the main entrance. In the interior, kitchen, douche and toilet are renewed.

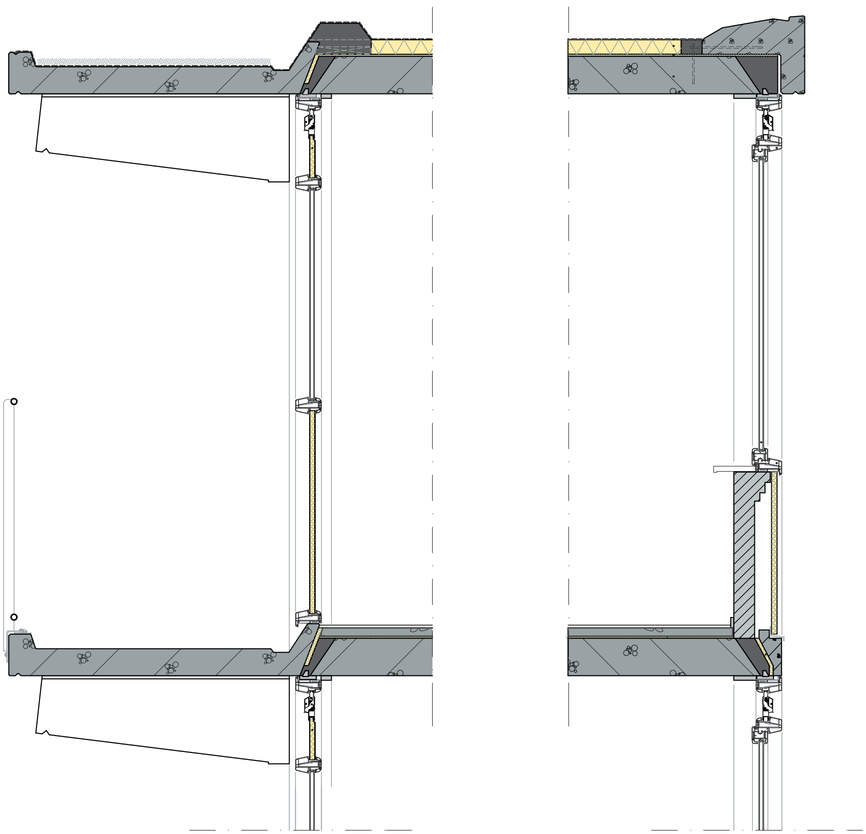


Figure 6.6
Current details of the building construction.

Current problems and refurbishment requirements
Several problems regarding the technical state of the building as well as the social aspect of the neighbourhood were highlighted during site visit and conversation with occupants and housekeeper. On the technical aspects, there are complains about mould growth in the corner connections of their apartments, draft from the facade connections and noise from the neighbours.

These problems are related to the building's physical condition. The thermal transmittance of the building envelope is insufficient and the lack of insulation results in thermal bridges at the corner, slab and balcony connection. In combination to insufficient ventilation, thermal bridges result in mould growth. Moreover, the connection sealing between facade elements and building structure is inappropriate causing drafts and discomfort. Last, but not least, the noise from the neighbours can be explained by the lack of sound insulation between walls, floors and ceilings.

There are some plans to refurbish the building by the housing company, aiming at a life extension of the building at least 25 years. The refurbishment strategy should solve technical problems, as well as improve occupants' comfort and energy consumption. The dwellings will stay in the social rent sector and people will not have to move out of their apartment.

§ 6.3.4 Coevordenstraat complex, The Hague, the Netherlands

General information

The case study buildings are in The Hague, in the area of Morgenstond. The area consists mostly of post war social housing buildings and people of a medium or low income live there. A number of buildings are still in their original condition. The area is within the municipality's planning for upgrade and development. There is a master plan according to which this area will become the "second centre" of The Hague.

Initially, four buildings were built, belonging to the same building complex, located on Coevordenstraat and Melis Stokelaan. The buildings under consideration for the case study are one three-floor building and one four-storey building porch flat buildings. They were designed by E.F Groosman in 1954 according to the industrialised system "AB elementen", which is similar to MUWI system. Nowadays, they belong to VESTIA, a large housing association, and owner of more than 89,000 dwellings in the Netherlands. All the apartments are rented; there is no other owner in the buildings, which is important when a decision on refurbishment has to be made.

The buildings are laid-out mirrored to each other, with their porches entrances on Coevordenstraat and the other on Melis Stokelaan respectively. The livingroom of the apartment is every time adjacent to the front façade, overlooking the street. Each stairwell gives entrance to six or eight flats, in the three and four-storey buildings respectively. The buildings consist of 8 porches each, resulting in a total of 112 dwellings. The orientation of the buildings is shown in Figure 6.7.a. The three-storey building's front façade has S-E orientation and the four-storey building's front façade has N-W orientation. Between the buildings there is a common courtyard, which the residents use as playground and common space.

a

b

c

Figure 6.7
(a) Urban layout of the Coevordenstraat complex.
(b) Front and (c) rear facade of the three-storey building.

Building Construction

The building construction is based on an industrialised system, MUWI, developed by Muijs and De Winter, which was one of the most popular systems in the Netherlands in the post war period (Priemus & Elk, 1971) . The principle of the system is based on the use of lightweight hollow concrete block. The hollow core concrete blocks (500x194x210) were stacked to make canals along the whole height of the wall, which were then filled with concrete. The load bearing walls had to be finished with plastering. For the long facade, prefabricated façade panels were used, with or without masonry parapets. The edge external walls consisted of a 220 MUWI inner leaf, 50mm air cavity and 110mm brick veneer. On top of the wall, a reinforced concrete beam was cast, anchoring the prefab floor beams. At the connection with the facade, one in situ column was cast, cladded with brick veneer. The surface of the concrete in the cavity was treated with bitumen. The floor construction consisted of prefabricated pre-stressed concrete beams with a centre-to-centre distance of 50 to 60cm, filled with hollow core lightweight concrete elements in between. The beams are supported by the load bearing MUWI walls.

The façades of the buildings consist of different elements. The windows are single glazed with wooden frames. The parapet is a cavity wall, with a 110mm brick masonry inner leaf; 25mm air cavity is 2.5 cm and a 40mm prefabricated concrete element outer leaf. The construction of the walls adjacent to balconies is shown in Figure 6.8. a and b. and it is the similar to construction as the edge wall.

Current problems and refurbishment requirements
According to the building envelope existing construction, the thermal resistance of the components is far from adequate, particularly considering current standards. The apartments' energy labels confirm this observation. Most houses score a G in the label scale from A to G, while few have a label F. The flats with the better labelling are the middle flats, since they have less thermal losses.

Moreover, based on discussion with the residents and individual observations, the problems identified were mainly regarding moisture and condensation problems. There is a large amount of condensation on the single glazed windows (Figure 6.8.d). Externally, the façade has whole parts that have serious mould problem. This mainly noticed close to the connections of the façade to the concrete slabs, also shown in Figure 6.8.e.

The interest of the housing company in these buildings is high. As mentioned before, the area is under the plan of the municipality for upgrade and development. This, together with the crisis the housing market is going through, changed the initial plans of the company, which were to demolish the buildings and build new ones. Such a plan was too expensive and time consuming. The intention now is to refurbish the buildings, because it will take much less time and will not cause them to lose the income of the rents. Therefore, they are highly interested in a solution that will upgrade the energy performance, while the residents can remain in the building, during the constructions.

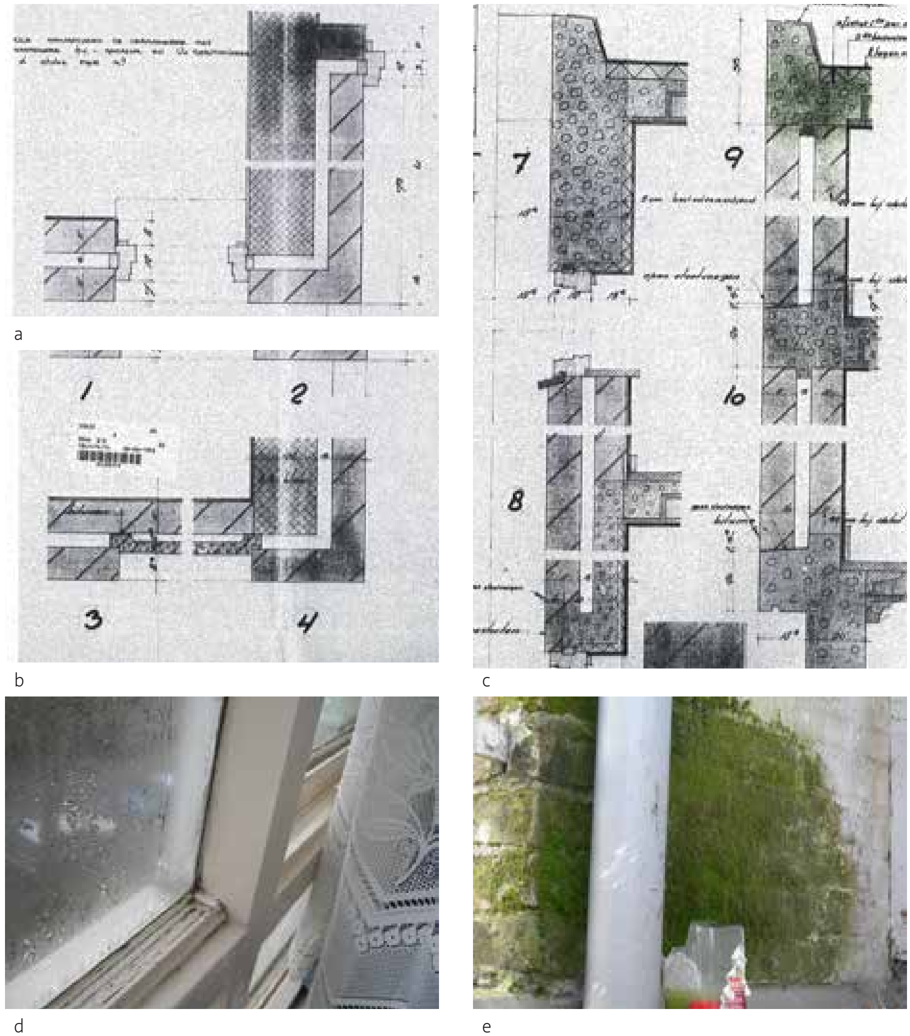


Figure 6.8

Original construction drawings.

(a) ,(b) Horizontal section on external wall.

(c) Vertical section.

(d) The condensation on the windows and (e) mould growth on the front façade close to the connection of the slab.

§ 6.3.5 Overview of case-study buildings

The analysis of each case study has shown that the five case buildings share similarities, such as construction period and problems, but also are different with regard to certain components constructions and, most importantly, the specific requirements that the refurbishment needs to fulfil. The four post-war apartment building complexes investigated resulted in five case studies. Breslauer complex consists of two of the same original condition, but the project requirements differ. They are, hence, investigated as two separate cases.

The first issue that the analysis focuses on is the original construction. It is important to understand the physical characteristics of the building that determine the current energy demand and the possible reduction after the application of the measures, according to toolbox calculations. A variety of constructions was found that can be, nevertheless, associated with the constructions considered in the toolbox calculations, described in Table 2.2, and the quantification building types in Table B.1. It is interesting to notice that out of the five buildings, only one has still the original single glazed windows, while the rest have them replaced with uncoated double glazing panes and PVC frames, already more the 20 years old. The ventilation and heating system are the same in all buildings and they are typical for buildings of that period. They are naturally ventilated with gas boiler and radiators.

The problems identified are also typical of existing building stock. They are mostly related to lack of insulation and thermal bridging, as well as deterioration of components. Apart from the obvious need to improve these aspects, the specifications for the refurbishment differ. In three of the buildings, owned by the same housing association, current occupants are going to be removed and there are changes to the internal layout, intended to result in improved quality and higher rent price of the apartments. In the other two buildings, the residents will remain in the apartments during and after the refurbishment and the works need to cause minimum disturbance.

Table 6.1 summarises the key building characteristics that are important in forming the refurbishment strategies, described subsequently in the chapter. Section 6.4 elaborates on how the refurbishment strategies were developed taking into account the requirements for each building, as well as the information provided by the toolbox approach.

		1	2	3	4	5
Building		Breslauer Complex		Platanen Complex	Suringarflat complex	Coevordenstraat complex
						
Location		Gartenstadt, Krefeld, Germany			Poelenburg, Zaandam, The Netherlands	Morgenstond, Den Haag, The Nether-lands
Date of construction		1967		1957	1963	1954
Owner		Wohnstatte Krefeld			Rochdale	Vestia
No of storeys		4	3	2	5 (groundflr garage)	3 and 4
No of apart-ments	in the building	24	24	16	96	112
	in the complex	144		128	672	186
orientation		E-W (N and S long facades)	N-S (E and W long facades)	N-S (E and W facades)	E-W and N-S	E-W (N and S long facades)
Construction	Structure	Concrete in situ slabs 130mm			Prefabricated con-crete slabs 180mm (and 50mm finis-hing layer)	Prefab pre-stressed concrete beams, hollow core light weight concrete
	Loadbea-ring walls	Internal walls masonry brick walls 240mm		Masonry brick walls, external 240mm and inter-nal 175mm	Prefabricated con-crete elements	Lightweight hollow concrete block, with concrete filling
	External walls (non-load-bearing)	External walls: 24mm lightweight concre-te blocks, brick cladding		n/a	Prefabricated concrete 115mm, finishing concrete 115mm	Cavity wall of two masonry leafs 110mm, cavity of 5cm
	windows	u-PVC Frame, Double-glazing, 25-30 years				Wooden frames, Single glazing
	Balcony	Incised loggias	Continuous can-tilevered concrete slabs	Continuous can-tilevered concrete slabs	Prefabricated con-crete slab, incised loggias	Continuous can-tilevered concrete slabs
	Roof	Timber joists, wooden casing, bitumen roofing membranes / attic floor in-situ concrete 130mm		Timber rafters, clay tiles/ attic floor in-situ concrete 130mm	Concrete 180mm, eternit 10mm, insulation 70mm	Flat roof, prefab concrete slab 140mm, wool cement 30mm, bitumen
	Ground floor	Concrete in situ slabs 130mm			Concrete 180mm, finishing 50mm	Concrete 140mm, finishing 50mm

>>>

		1	2	3	4	5
Building		Breslauer Complex		Platanen Complex	Suringarflat complex	Coevordenstraat complex
Technical installations	Heating	Gas heating with panel radiators			Central gas heating	Gas heating
	Ventilation	Natural	Natural	Natural	Natural	
Current energy label		E, F	E, F	E, F	E, F	F,G
Problems	Energy efficiency	Lack of insulation, thermal bridging, insufficient thermal performance, outdated installations		Lack of insulation, thermal bridging, insufficient thermal performance, outdated installations	Lack of insulation, thermal bridging, insufficient thermal performance, outdated installations	Lack of insulation, thermal bridging, single glazing, insufficient ventilation outdated installations
	Physical problems	mould growth, degradation of elements, noise		Mould growth,	mould growth, air drafts, noise	mould growth, condensation on window panes
	Functional problems	Non handicap-accessible, vacancy		Non handicap-accessible, use of external spaces, small size of dwellings	n/a	n/a
Requirements for refurbishment	Changes appearance	Yes, modernisation of architectural appeal		Yes, but preservation of neighbourhood character	Yes	Yes
	Layout modification	Diverse sizes	Bigger apartments	Bigger apartments, merging of existing	No	No
	Rent of apartment	Moderately higher	Higher	Higher	No change	No change
	Occupants during works	Removed	Removed	Removed	Remain	Remain

Table 6.1
Overview of case-study buildings

§ 6.4 Refurbishment strategies development

After examining the existing condition of each building and determining problems and specific requirements, this section aims at guiding through the refurbishment strategy decision-making. The options that shape the refurbishment strategy were chosen according to the requirements for the refurbished building, in terms of energy upgrade, the new apartments' quality, as well as the designers' preferences. The decisions were also determined by the building's characteristics and orientation. Based on these parameters, the toolbox aided the organisation of the solution by making the different options available and offered information of the energy demand reduction, which supported the decisions.

If we combine all the considerations accounted in the decision-making, a roadmap to building envelope refurbishment is composed. The roadmap indicates at which point are the parameters considered, which options are excluded then and when the toolbox information is adequate to support the decision. This section guides thought the decision-making process for each building, addressing each individual building envelope component, similarly to the toolbox and explaining what the considerations behind each decision were. In this way, the roadmap to the Façade Refurbishment Toolbox is composed.

The decision-making for each component is presented in respective flowcharts. They are organised according to the key points and considerations that occur during the decision-making. Based on the answers to the key questions that depend on the condition of the building projects specifications etc., the toolbox can support in either organising the options, by excluding or favouring options, or it can give a specific number on the potential energy reduction. The final choice of measure results through the process. The charts show the questions and consideration together with the relevant answers and decisions. The relevant sub-sections complement the charts explanations of the measures selection. Moreover, they include where the toolbox can have impact, either in organising the possible choices or giving the figures of the energy reduction. When the final selection needs to be made, the toolbox options are presented, often in a graph with the relevant energy reduction, shown as the percentage of the current energy demand, based on the toolbox calculations. To avoid over-accumulation of information, the flowcharts are presented in Appendix D. Nevertheless, the decisions on retrofitting measures for the first case-study building, the four-storey apartment block of the Breslauer complex, are explained in detail, to demonstrate the key points and considerations.

In order to provide the figures on the energy reduction, each building needs to be associated with the model pre-calculated according to the methodology described in Chapter 5 and summarised in Table 5.25. The corresponding to the case study buildings pre-calculated models are shown in the table below. Based on this correlation the figures on the energy saving are derived and used in the decision-making process for each component.

After explaining the design process for each component separately, the combined solution is evaluated. The integrated solution formed by the decision-making followed is simulated to estimate the total energy reduction. Moreover, the additional potential benefits for the building function and appearance are underlined. Finally, the combinations of measures shaped by the decision-making process shows a compilation of relevant combinations.

	1		2		3		4		5	
Building	Breslauer Complex				Platanen Complex		Suringarflat		Coevordenstraat complex	
	Building characte-ristics	Toolbox model	Building characte-ristics	Toolbox model	Building characte-ristics	Toolbox model	Building characte-ristics	Toolbox model	Building characte-ristics	Toolbox model
Orientation	E and W		N and S		E and W		E-W and N-S		N and S	
WWR	30%	30	50%	60	30%	30	70%	60	60%	60
External walls	Light-weight concrete blocks, brick cladding	M6_30_E M6_30_W	Light-weight concrete blocks, brick cladding	M6_60_N M6_60_S	Masonry brick walls	M1_30_E M1_30_W	Prefa-bricated concrete finishing concrete	M6_60_N M6_60_S M6_60_E M6_60_W	Cavity wall of two masonry leaf cavity of 5cm	M3_60_N M3_60_S
Windows	PVC Frame, Dou-ble-gla-zing, 25-30 years	M6_30_E M6_30_W	PVC Frame, Dou-ble-gla-zing, 25-30 years	M6_60_N M6_60_S	PVC Frame, Dou-ble-gla-zing, 25-30 years	M6_30_E M6_30_W	PVC Frame, Dou-ble-gla-zing, 25-30 years	M6_60_N M6_60_S M6_60_E M6_60_W	Wooden frames, Single glazing	M1_60_N M1_60_S
Balcony	Continuo-us can-tilevered concrete slabs	M1_30_W	Incised loggias	M1_60_S	Continuo-us can-tilevered concrete slabs	M1_30_E M1_30_W	Prefabri-cated con-crete slab, incised loggias	M1_60S M1_60E	Continuo-us can-tilevered concrete slabs	M1_30_N M1_30_S
Roof	Timber rafters bitumen roofing mem-branes / attic floor in-situ concrete	M1_30_EW	Timber rafters bitumen roofing mem-branes / attic floor in-situ concrete	M1_30_NS	Timber rafters, clay tiles/ attic floor in-situ concrete	M1_30_EW	Concrete 180mm, eternit, insulation 70mm	M6_30_NSEW	Flat roof, prefab concrete slab, wool cement 30mm, bitumen	M6_60_NS
Ground floor	Con-crete in situ slabs 130mm	M6_30_EW	Con-crete in situ slabs 130mm	M6_30_NS	Con-crete in situ slabs 130mm	M1_30_EW	Concrete 180mm, finishing 50mm	M6_30_NSEW	Concrete 140mm, finishing 50mm	M6_30_NS

Table 6.2
Association of the case-study buildings to the calculated models, according to Table 5.25.

§ 6.4.1 Breslauer Complex, 4-storey building

The refurbishment strategy of the 4-storey building of the Breslauer Complex needs to solve the technical problems analysed in 6.3.1. Moreover, the housing association that owns the estate has decided to change the internal layout of the apartments, providing more diverse-sized apartments to attract a mixed group of users. Additionally, barrier-free access and noise protection were required. The increase in rent price was expected to be moderate.

The development of the integrated refurbishment strategy addresses the individual building envelope components. The study explains the refurbishment measure selected for each component, taking into account the key points about the building construction, the possibility to modify external appearance, building programme, orientation, level of intervention and energy generation.

Starting with the external wall, the thermal resistance of the envelope needed to be improved (Figure 6.9.a). The percentage of wall/window is about 2/1, making the external wall performance of great significance. Moreover, thermal bridging had to be resolved, to prevent mould growth. The option external insulation finishing system (EIFS) with 20 cm mineral wool is selected to be implemented on the south, east and west facades. The internal insulation option was rejected because the external insulation is more efficient for thermal bridging (Figure 6.9.b). Since there are no requirements to retain the existing external appearance (Figure 6.9.b), the intervention form the outside is preferable. The cavity insulation and complete replacement of the wall were excluded, due to existing structure (Figure 6.9.a). The EIFS was chosen over ventilated façade system, as they have the same effect on the heating demand, but the ventilated façade has higher cost (Figure 6.9.e).

A different option is chosen, though, for the north façade. A second skin façade, comprising a gallery, through which the apartments are accessed, is introduced along the entrance façade. This decision was mainly due to functional benefits. It enables elevator access for all the apartments with the use of only one elevator and it acts as a noise barrier towards the highway, which was one of the projects requirements. In terms of spatial improvements, the space previously used for the staircase can be now integrated into the apartments, giving the possibility for more spacious layouts. The single glazing façade was chosen over the double glazing, as the gallery is a semi-open space and does not require to be integrated into the thermal envelope. Moreover, the decision was supported by the toolbox calculation. It performs as a thermal barrier for this north façade, providing the potential for greater energy savings than the other orientation (Figure 6.9.d).

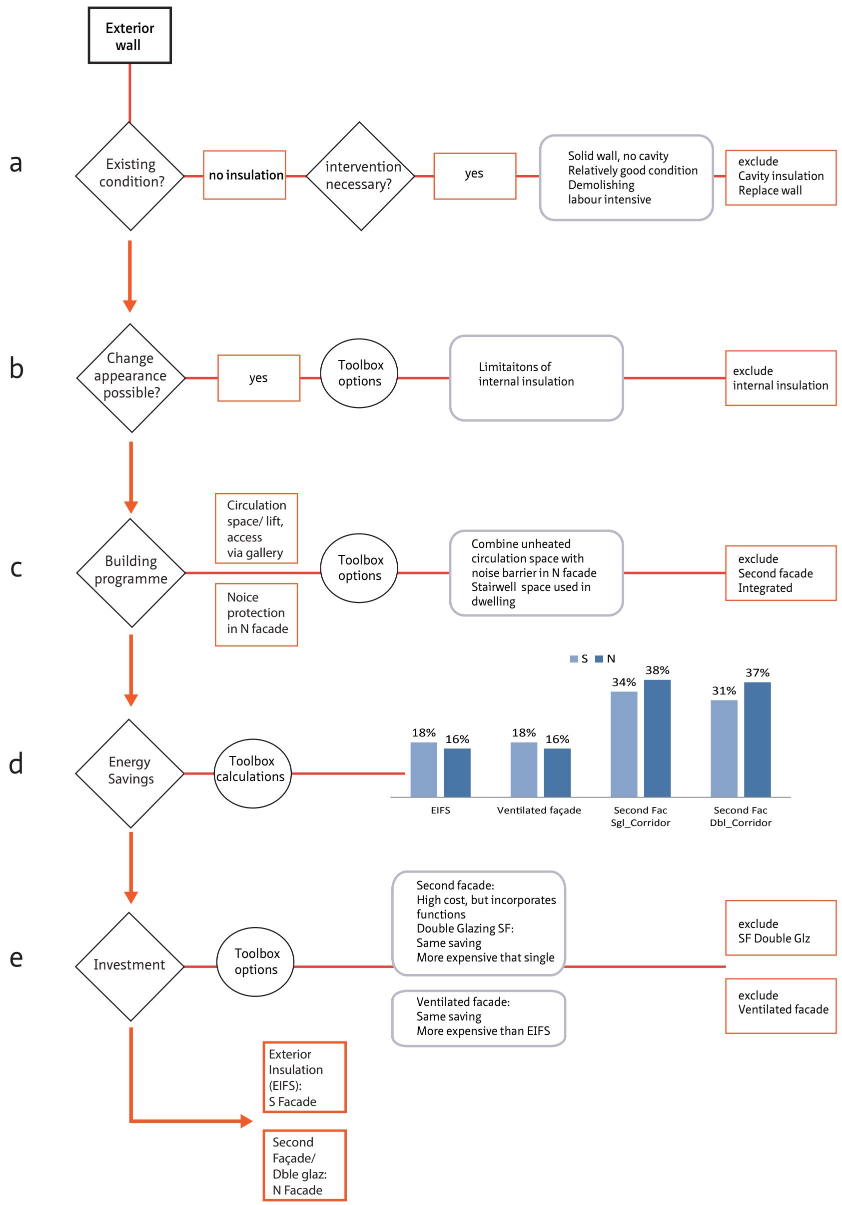


Figure 6.9

Decision path for the external walls of the four-storey apartment block of the Breslauer complex

Currently the balconies, in form of loggias, are located at the south façade. Balconies are problematic areas of the envelope, because of the thermal bridging caused by the continuous slab. To solve this problem, the balconies are integrated into the thermal envelope. Double glazing is used to clad the loggia's open side and insulation is applied on the edge of the slab, to prevent thermal bridging in this way, the thermal bridging problem at the balcony slab is solved and up to 39% of heating energy can be saved, as indicated by the toolbox calculations. The energy savings are greater on the south façade compared to other orientations. Moreover, extra space is added to the apartments, as required by the building programme. The additional space was an important argument of the decision. New, larger, lightweight balconies are constructed on the garden façade, giving a fresh, diverse appearance to the building.

Windows are the next elements to be considered. Even though, the original single windows have been replaced with double-glazing and PVC frames in the 1980's, the performance is still very low for today's standards. Since there is no monumental protection applied, they can easily be replaced with high performance insulating glazing and new frames. However, not all of the existing windows need to me considered. The windows on the north façade may remain, since the glazing layer of the gallery is applied. The windows between the living room and the loggia on the south façade are completely removed, as the loggia becomes part of the living space. For the remaining windows of the south facade, the toolbox calculations can help to decide the glazing type. The option transforming windows to occupy the whole floor-to ceiling height, creating French windows, was not selected, even though the toolbox calculations indicate higher saving in heating energy demand. The reason was mostly the cost in terms of money and time to demolish the existing concrete parapet.

The existing pitched roof is maintained and clad with PV panels and solar collectors, as it already has a favourable orientation to the south. Since the attic is unheated, the slab of the top-floor ceiling is insulated. The insulation of the pitched roof is recommended only when the attic is heated, otherwise there are still heat losses through the top-floor ceiling slab. This has been also proven by the toolbox calculations.

The basement is an unheated space and, as such, allows heat flow through the uninsulated ceiling slab. To prevent these thermal losses, insulation needs to be applied on the slab. The height of the ground floor is limited to apply insulation on top of the slab. For this reason, the basement ceiling is insulated from below with 14 cm of high quality insulation, for example Polyurethane foam. VIP's are not recommended in this case, mainly due to budget reasons.

As far as the technical installations are concerned, similar solutions as with the previous example are proposed, with the exception of the ventilation system. Natural ventilation through the windows has been chosen, due to financial limitations. Special consideration is needed to the openings of the glazed gallery, to prevent overheating in the summer. Openings operated manually or mechanically, are needed primarily on top of the gallery, to allow ventilation. Fans to enhance air movement can also be used. Heating is based on a low temperature system, just as the previous example, because this facilitates the optimal integration of solar or geothermal energy sources.

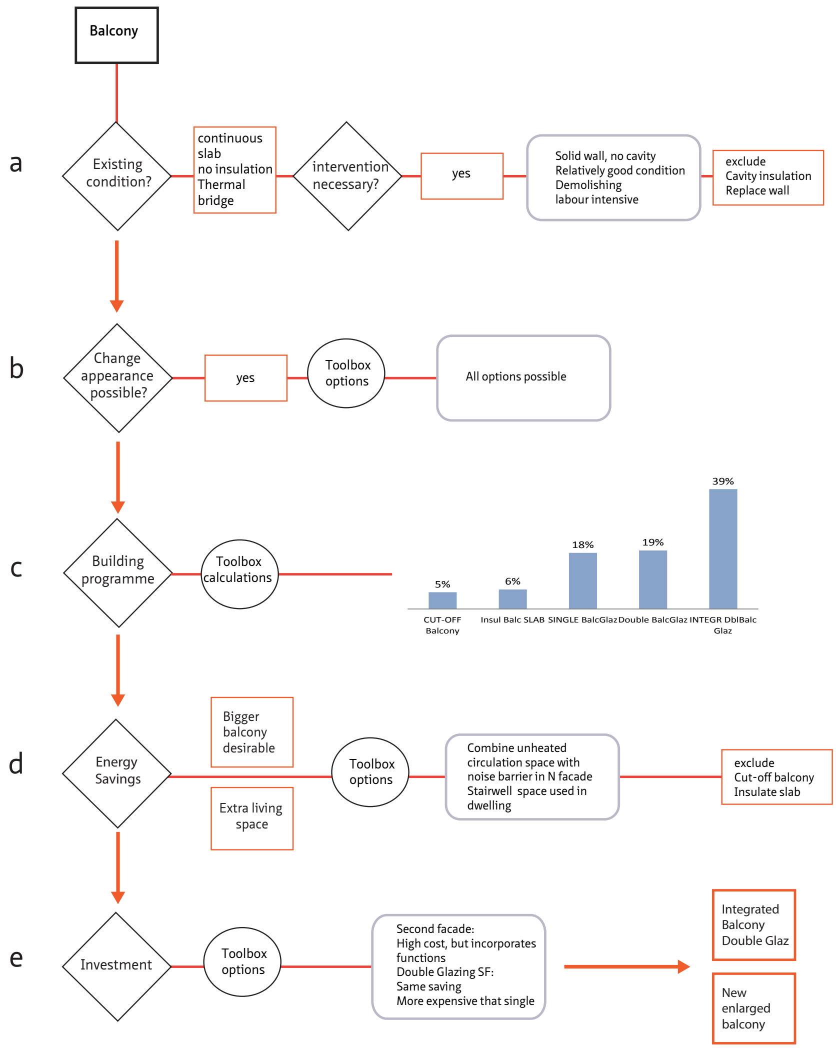


Figure 6.10

Decision path for the balcony of the four-storey apartment block of the Breslauer complex

Evaluation of the solution

Based on the considerations and the decision processes discussed before, the refurbishment strategy is formed as shown in Figure 6.11.b. The proposed strategy has been simulated, to prove the thermal performance of the refurbished buildings. It has resulted in saving of the heating energy need of 80%. The reduction has been achieved by minimising conduction heat losses through the building envelope components, by increasing their thermal resistance and creating a thermal buffer at the north façade.

Further saving in the primary energy can be achieved with retrofitting of technical installations. The design of the technical installations retrofit is not described in detail, as the research focussed on the building envelope. Nevertheless, the installations are an integral part to be considered; that is why they are included in the toolbox and proposed in the strategy. The specific installation design depends on specialised knowledge and calculations of the building's needs, the applicability of options and the investment.

Additionally, refurbishment improves thermal comfort. Required ventilation rates for indoor air quality is achieved trickle ventilation openings in the new windows and mechanical exhaust. Moreover, adequate ventilation, coupled with solving thermal bridging result in eliminating mould growth. Last but not least, overheating risk is reduced to acceptable hours per year, as calculated through dynamic thermal simulation.

Finally, the strategy has spatial benefits for apartment block. Changes in the layout and the gallery access resulted in a higher number and more diverse sizes of apartments. The main input of the façade refurbishment strategy to additional space is the glazing of the balconies and the addition of the gallery. In this way the balcony and the staircase space is added to the apartments. The new layout, together with the renewed appearance of the building, meets the housing company wishes that aim in a diverse population mix amongst the tenants.

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	**Continuous slab, no insulation**	**Pitched roof, timber rafters no insulation/ occupied loft**	Slab on ground, no insulation	**Natural ventilation**	Gas stove
	Lightweight concrete/ hollow brick, no insulation	**Early, double-glazing**	Separate slab no/little insulation	**Pitched roof, timber rafters no insulation/ unheated loft**	**Basement unheated. Concrete slab, no insulation**		**Fossil fuel boiler in each dwelling**
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

a

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	**Natural inlet/ mechanical exhaust**	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	**Insulation under existing floor**	Mechanical inlet/ natural exhaust	**Replace existing boiler per block, high efficiency**
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	**Insulation of top floor slab**		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	**Replace windows (Double pane)**		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			**Photovoltaic**			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	**Integrated balcony**				Geothermy
	Lift addition	Enlarged windows	**New balcony**	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

b

c

d

The "tools" showing (a) the existing condition (b) forming the refurbishment strategy for the four-storey apartment block, highlighted on the FRT matrix of Table 5.8.
Current façade (c) and impression of the glazed gallery of the four-storey apartment block (d)

§ 6.4.2 Breslauer Complex, 3-storey building

The similar process was followed for the second case study building, the four-storey apartment block of the residential complex. However, the specifications for this block, provided by the housing company, were slightly different from the previous one. Along with barrier-free access, the apartments needed to be converted into bigger and more luxurious, to attract a higher socio-economic group of residents.

Starting the decision-making of the refurbishment strategy with the external wall (Figure D.6), the thermal resistance of the envelope needed to be improved. The percentage of wall/window is about 2/1, making the external wall performance of great significance. Moreover, thermal bridging had to be resolved, to prevent mould growth. The option external thermal insulation composite system (ETICS) with 20 cm mineral wool would be implemented in all facades. The internal insulation and the options were rejected because the external insulation is more efficient for thermal bridging. Since there are no requirements to retain the existing external appearance, for monumental or other reasons, the intervention form the outside is preferable. The cavity insulation option does not apply, as there is no cavity in the wall.

Between external insulation and second façade the second was rejected, due to higher costs and lack of space on the street façade. The construction of a second facade is becoming excessively expensive because it cannot be suspended from the existing construction and new foundation would be required. Even though the energy reduction is slightly better for the second façade in the east and west oriented facades, the difference is not so significant to support the choice, especially if it is not be paired with other functional benefits, such as noise protection, access etc.

The ETICS was chosen to ventilated façade system, as they have the same effect on the heating demand, but the ventilated façade has higher cost. The option is not completely rejected, but it is subject to the choice of finishing material and financial analysis to decide on its feasibility.

Regarding the accessibility, the existing staircases are changed, in order for the extra lift to give access to all the levels. One lift is constructed in in each staircase. This was selected over the option of gallery access, due to lack of space and privacy issues.

Windows are the next elements to be considered. Even though, the original single windows have been replaced with double glazing and PVC frames in the 1980's, the performance is still very low for today's standards. Since there is no monumental protection applied, they can easily be replaced with high performance insulating glazing and new frames. The toolbox calculations can help to decide the glazing type. Where possible, the windows are transformed to occupy the whole floor-to ceiling height, providing more natural light and better contact with the outside. Moreover, the toolbox calculations indicate higher saving in heating energy demand for this option, as higher heat gains are ensured (Figure D.7).

Balconies are problematic areas of the envelope, because of the thermal bridging of the continuous slab. To solve this problem, the balconies are integrated into the thermal envelope. Insulating glazed cladding is applied around the balcony. In this way, the thermal bridging problem at the balcony slab is solved and 26% of heating energy can be saved, as indicated by the toolbox calculations. In corner apartments, the savings are even greater. Moreover, extra space is added to the apartments. The additional space was the main argument of the decision, as the building program requires bigger apartments. New, bigger, self-supported balconies are added. In the specific building where located on the west façade, this option is even more favourable, as it gives higher saving in the west orientation compared to the east.

One of the main modifications is the removal of the existing pitched roof and the creation of a green roof and an extra floor on the roof space of each respective staircase (Figure D.9). In this way four spacious maisonette apartments with individual roof gardens are created. The ceiling of the new floor has the possibility to be optimally aligned to the south for the use of thermal solar energy and Photovoltaic panels. The top floor of the maisonette is accessed through an internal staircase.

Finally, the basement ceiling was insulated with 4 cm thick VIP's, placed between concrete slab and top floor. The reason for the VIP insulation was on the one hand the very limited height of the basement that didn't allow the insulation to be placed under the ceiling and on the other the need for as thin insulation layer as possible in order not to use much of the height of the ground floor spaces (Figure D.10).

Regarding the technical installations, new technical building installations are proposed according to the current needs. A mechanical ventilation with air exhaust and heat recovery system is planned, to provide the necessary air quality. The windows can be also operated by the user, which is a parameter for improved comfort (Yao et al., 2009). Magnetic window contacts switch off the ventilation and thus prevent energy losses. The outdated heating system is replaced by a low-temperature surface heating. Currently, each apartment has an individual gas boiler. Instead, a central boiler per block will be sufficient. A central boiler is a better option in regards to possible future energy investments, as it can be replaced with a CHP plant or connected to a community heating system, without many adjustments in the apartments. Finally, solar thermal collectors and photovoltaic panels will be installed on the pitched roof, oriented to the south.

The design of the technical installations retrofit is not described in detail, as the research focussed on the building envelope. Nevertheless, the installations are an integral part to be considered which is why they are included in the toolbox. The choice depends in specialised knowledge and calculations of the building's needs, the applicability of options and the investment.

Evaluation of the solution

Based on the projects requirements and other consideration, described above, the refurbishment strategy for the three-storey apartment block was composed. The "tools" selection, according to the decision-making process for each building envelope component, is shown in Figure 6.12.b. Simulating the performance of the combined measures resulted in 90% reduction to current heating energy demand. Further savings in Primary Energy and CO_2 emissions are accounted if the heating system efficiency upgrade and the PV energy generation are considered.

Moreover, the proposed strategy fulfils the requirements for bigger and better quality apartments. This is achieved by adding the balcony space to the thermal envelope and the relevant changes in the layout. The top apartments in particular have benefit from the additional floor, as well as the roof garden, not only in terms of roof heat losses reduction, but also the extra internal and external space. Since the refurbishment suggest to have big interventions in the interior and the current residents will be remove during construction works, added quality can be the renewal of internal finishing, as well as bathroom and kitchens, that are not, nevertheless, included in the toolbox, as it is not part of the building envelope.

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

a

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	**Insulation under existing floor**	Mechanical inlet/ natural exhaust	**Replace existing boiler per block, high efficiency**
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		**Ventilation system with heat recovery (HR)**	Heat pump
	Timber-frame wall	**Replace windows (Double pane)**		**Green roof**			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			**Photovoltaic**			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	**Integrated balcony**				Geothermy
	Lift addition	**Enlarged windows**	**New balcony**	**Additional floor/ occupied loft**	Additional floor/occupied basement		District/ community heating

b

c

d

The "tools" showing (a) the existing condition (b) forming the refurbishment strategy for the three-storey apartment block, highlighted on the FRT matrix of Table 5.8.
Current façade (c) and impression of the glazed gallery of the three-storey apartment block (d)

§ 6.4.3 Platanen Complex

One of the requirements for these buildings was to upgrade the quality of dwellings. The refurbishment aims at making the dwellings more appealing, in order to attract higher socio-economic group of residents. Therefore, the investment could be high. Apart from increasing the apartments' space, the exterior space, that is currently being neglected, needs to be revisited.

To accommodate these requirements, the strategy focuses on measures that can provide extra space and added value to the apartments. The principal design decision is to convert the two-storey apartment block into row housing, by connecting the ground and first floor apartment. The internal layout is completely changed and internal staircases provide access to upper floors. Moreover, the rear courtyard is divided into individual gardens for each dwelling, accessed through the ground floor.

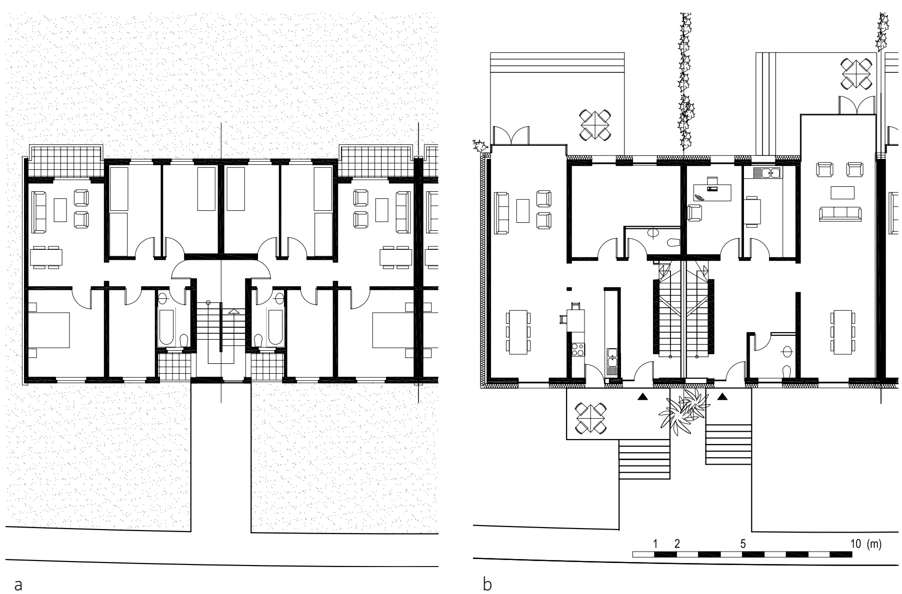


Figure 6.11
Ground floor plan of the Platanen complex dwelling, (a) current and (b) proposed

Roof intervention has the potential of creating extra space. The attic space that is currently unoccupied will be integrated in the dwelling and, hence, become heated. This saves up to 35% of heating energy demand in the floor below (Figure D.11). The roof is replaced, to provide adequate height in the attic space. The new pitch roof construction includes 20cm mineral wool insulation, which reduces the energy consumption by half to the attic with an uninsulated roof. Finally, PV panels are installed, as the investment allows it. The orientation on the roof is east and west, which is not optimal. Nevertheless, they can still produce approximately 130kWh electricity per m2 of PV panel, per year (Solar Campus GmbH, 2012) and improve the overall primary energy consumption.

The balconies provide also opportunities for additional space. They are integrated in the thermal envelope, by cladding then with double glazing and removing the intermediate wall (Figure D.12). In this way the space is enlarged and thermal bridging through balcony slab is prevented.

The windows are replaced with high performing double, argon-filled glazing and aluminium framed windows, as they provide potential for bigger savings, according to toolbox calculations (Figure D.13). Given the changes in the layout and the budget allowances, it is suggested that the window are enlarged to occupy floor-to-ceiling height.

The external wall needs also to be upgraded, to reach current standards of thermal resistance. The wall is insulated externally with 20 cm mineral wool, resulting in 22% reduction on current energy demand (Figure D.14). Since the refurbishment seeks to improve the image of the currently monotonous and dull apartment block and the investment allows is, the option of ventilated façade cladding is applied. This gives the possibility for each dwelling to have different material, according to the users' preferences, creating a diverse appearance of the block.

The apartment features a wooden floor finishing, which creates a cavity of 10 cm over the concrete slab. This space is used for preventing heat flow between ground floor and the unheated basement, by the application of mineral wool in the cavity, without reducing the occupied space height (Figure D.15). The existing floor construction is also advantageous with regard to the technical installations. Low-temperature floor heating can be installed in the cavity.

Evaluation of the solution

The development of the strategy was mostly influenced by the specific requirements of the project, namely, to improve the quality and attractiveness of the apartments. The toolbox supported the process by organising the options availability according to the specifications. The toolbox calculations provided figures for the potential energy reduction, validating the design choices. Figure 6.14.a and b shows the "tools" describing the existing condition and composing the refurbishment strategy.

Project requirements included enhancing the overall attractiveness of the estate for tenants or buyers. The apartments were turned into terrace houses with individual gardens, solving the space limitation and the problematic use of external spaces. Along with improvements of layout and refreshed appearance, reducing primary energy is an additional benefit. Firstly, heating energy demand is 90% less, compared to current demand, due to the upgrade of the building envelope. Moreover, ventilation with heat recovery can be installed, since the interior is redesigned and further reduce the energy need. Finally, the PV panels generate energy and contribute to cover the energy need.

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

a

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

b

c

d

The "tools" showing (a) the existing condition (b) forming the refurbishment strategy for the Platanen complex apartment block, highlighted on the FRT matrix of Table 5.8.
Impression of the refurbished Platanen complex apartment block. (c) Rear and (d) front facade

§ 6.4.4 Suringarflat Complex

The housing company plans to refurbish the building, aiming at a life extension of the building at least 25 years. The refurbishment strategy should solve technical problems, as well as improve occupants' comfort and energy consumption. The dwellings will stay in the social rent sector and people will not have to move out of their apartment.

The process of combining the tools was based on the project specifications and supported by the toolbox. The refurbishment strategy has budgetary limitations, as the company aims to maintain the same rents and the residents would continue to occupy the apartments during construction. This means that the interventions are mostly limited to the building envelope, without many modifications in the interior. The tools that were chosen from the toolbox resulted in a solution with lower level of intervention but still improved efficiency. One of the special characteristics of the building is the L-shaped layout, resulting in two identical buildings with different orientations.

One of the first decisions was to clad the loggias, located on the South and West façade. The loggias are cladded with double glazing to tackle thermal bridges and integrate them to the thermal envelope. Not only does this measure add space to the apartment, but it also provides maximum efficiency, particular for the south façade, as indicated in the toolbox calculations. New, bigger, self-supported balconies are added (Figure D.16).

In this building, the larger percentage of façade consists of façade panel. For this reason, the influence of refurbishment of the window is greater than the previous case studies. The insulation values of the façade panel on the south and east facade were improved by replacing the existing windows with double, argon-filled glazing. The windows were also enlarged, as they would be used to access the balcony (Figure D.17). Moreover, more solar gains are ensured and further reduce the energy demand, as shown by the toolbox calculations. The additional heat gains result in lower heating energy demand in the winter, but might increase overheating risk in summer. For this reason, additional measures, such as shading of the glazed areas should be considered. On the gallery façades, which are the north and west, the façade panel does not need to be replaced. The gallery will be cladded (Figure D.18) and, thus, the existing windows are no longer part of the external envelope.

On the opaque elements of the south and east façade, external insulation is added to improve the prefabricated concrete wall elements. This option was chosen over other options, because it intervenes on the outside of the wall, without affecting too much the interior, which continues to be occupied during refurbishment work. North and west façades are where the circulation gallery is and they are mostly glazed. Instead of replacing the windows the gallery is cladded with single glazing, to create a thermal and noise buffer. Most importantly, it contributes significantly to the reduction of the heating demand. As demonstrated by the toolbox calculations, the addition of a glazing layer on the north façade can reduce the energy demand up to 38% (Figure D.18), without the need of additional insulation on that façade. The integration of the gallery space into the dwelling, even though it has the biggest potential saving (69% in the West façade), is not chosen for several reasons. Additional space is not in the refurbishment objectives and would require disturbance in the interior of the apartments. Besides the galleries are used of circulation and integrating them in the dwellings would suggest modifications that are not within the scope and the investment of the project. The gallery is kept as a corridor to provide access and it is an unheated space. It is clad with single glazing, as it provides a better effect on the energy demand and lower investment than the double glazing.

The existing flat roof will be upgraded with 100mm additional insulation. Since no extra space or apartments are required, the option of additional floor construction was not considered. Moreover, the flat roof insulation was preferred over a green roof, due to budgetary limitation (Figure D.19). Besides, since the roof is not accessible benefits of the green roof to the function of the building are not significant enough to compensate for the extra cost, nor is the energy reduction compared to the flat roof insulation.

The building does not have a basement. However the ground floor is used as garage and storage space and it is unheated. Hence, it is necessary to insulate the ground floor ceiling slab to prevent heat losses from the occupied first floor. The insulation will be applied under the ceiling slab, in order not to interfere with the apartment's interior and reduce the height of the occupied space (Figure D.20).

Evaluation of the solution

The proposed solution has various benefits for the apartment complex. Firstly, a new appearance is acquired by the replaced components and the gallery glazing. Moreover, extra space has been added to the apartment, through the balcony integration. Most importantly, the modifications are possible with minimum disturbance of the residents, since all the measures can be applied on the exterior of the building envelope, without interference with the interior space. In terms of energy, the combined solution has been simulated and it resulted in 69% reduction of the current energy demand. Further improvements on the primary energy use can be achieved by replacing the existing heating system with a higher efficiency one, as well as the installation of PV panels.

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

a

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

b

c

d

Figure 6.12

The "tools" showing (a) the existing condition (b) forming the refurbishment strategy for the Suringarflat complex apartment block, highlighted on the FRT matrix of Table 5.8.
Current façade (c) and impression of the glazed gallery of the Suringarflat complex apartment block (d) (Image source: courtesy of Edwin Tensen).

§ 6.4.5 Coevordenstraat Complex

The intention of the housing association that owns the Coevordenstraat complex is to upgrade the existing building, while the current residents remain in the apartments. This suggests that the strategy should focus on the exterior of the building, without modifications in the internal layout of the dwellings, causing minimum disturbance. Moreover, the expenditure is limited, since no increase in the rent prices is intended.

A special characteristic of the project is that two rear facades where the living room is have different orientation. Even though this may suggest that different measures could be selected, this is not a possibility as it is required the two building to have the same refurbishment strategy.

With regard to the external wall, some of the toolbox options are excluded. Internal insulation, replacement of the existing wall with timber frame wall, causes a lot of disturbance to the interior of the dwelling and, thus, is not considered. Moreover, since the internal layout will not be changes, a second façade that integrates the space into the apartment, is not within the scope of the refurbishment. Considering the energy saving potential (Figure D.21), cavity wall insulation has the lowest, as the existing cavity gives the possibility of only 5cm of insulation. The second façade has the potential of higher savings. However, it is not selected due to budget limitation, especially since it cannot be combined with functional and spatial benefits. Therefore, external insulation is applied is all facades, which has a potential saving 21% and 32% in middle and corner apartments respectively.

The current windows are single glazed with wooden frame and need to be upgrades. Since the appearance of the building can be changed, the window pane upgrade and the secondary glazing are excluded from the choices. The windows will be replaced with double glazing and aluminium window frames.

As mentioned already in the analysis of the buildings, the cold bridging caused by the balcony slabs – which is a continuation of the floor slab – causes serious mould problems. Serious problems are depicted for the front façade balconies. In this case, solutions of isolating the balcony slab from the building can be applied. The balconies could be replaced by new ones, which will be only structurally connected to the buildings. By replacing the heavy concrete balconies with light self-bearing steel structures not only are treated thermal bridges eliminated, but it is also possible for wider balconies, even in different sizes and shapes to be constructed. The new balconies will contribute to the renewed appearance of the building.

The roof also needs to be upgraded to increase the thermal performance. The decision path is similar to the Suringarflat building (Figure D.19). As minimum intervention and investment are sought, the measures of green roof and additional floor are not considered. Additional insulation of 20cm is applied to rood structure, resulting in a U-value of 0.2 W/Km2 and a 23% reduction in the heating energy demand in the top floor apartments.

Finally, the concrete slab between basement and ground floor has to be insulated. The insulation will be placed under the floor slab, to prevent disturbance in the apartments. However, there are currently plans to connect the buildings to geothermic system existing in the area. In this case, the heating systems should be replaced with floor heating and some disturbance is unavoidable. In this case the insulation can be applied in the top of the slab.

Evaluation of the solution

The heating energy reduction is approximately 40%. The thermal comfort of the flats is improved. Based on the calculation, the energy savings are achieved taking into account comfort temperature for heating, while overheating is decreased by 45% to the existing condition and reaches a very good level of 175 hours per year. Through the refurbishment, passive measures are used.

As the building construction is based on an industrialised system, the proposed strategy can be used in other MUWI buildings of a similar height, which constitute a large part of the post-war stock in the Netherlands and are expected to have similar problems and requirements. It provides an early solution to improve their quality and energy performance. Of course the solution needs to be adapted to different surroundings and buildings.

In the specific building the heating will be provided by district geothermal heating plan that exists in the location (ADH, 2014). This is an efficient way to cover the remaining energy need and has low PE factor, further reducing the primary energy demand of the estate.

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

a

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	Balcony cladding - Single glazing	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

b

c

d

The "tools" showing (a) the existing condition (b) forming the refurbishment strategy for the Coevordenstraat complex apartment block, highlighted on the FRT matrix of Table 5.8.
Current façade (c) and impression of the glazed gallery of the Coevordenstraat complex apartment block (d)
(Image source: courtesy of Aikaterini Loukopoulou)

§ 6.5 The Roadmap

After going through the decision-making regarding the building envelope refurbishment of the case-study buildings, some of the considerations were re-occurring. Those aspects are regarded as key decision points and, when combined, they compose a roadmap to decision-making. A roadmap is defined as a plan or strategy intended to achieve a particular goal. Road mapping is used in several disciples as an effective process and for coordinating planning and strategy, as well as communication tool (Lee et al., 2012). In the present approach, the roadmap is used to highlight key considerations in the decision-making process for refurbishment strategies and explain how the toolbox information facilitate the process, either by organising available options or providing specific figures about the energy demand reduction. The goal is the development of integrated refurbishment strategies, while stimulating critical thinking and arguments to support informed decision that take into account the project specifications and energy demand reduction.

The design of strategies for the case-study buildings served to emphasise on the key points that shape the decisions. They are the following, subsequently as they appeared during the study of the building envelope components. The order is indicative, as it is not always linear and clearly separated and it can be iterative, depending on each project and design team. Nevertheless, they are aspects relevant to the choice of retrofitting measures and the toolbox approach information can support this decisions.

A Existing condition

Understanding and evaluating the existing condition of the building is an essential first step. Deciding which components need to be replaced or upgraded derives from this evaluation. The decision depends mainly on their existing condition. Firstly the thermal transmittance of the components has to comply with current standards, not only because they are required by regulations, but also to ensure lower energy demand. Critical connections have to be checked for problems, such as thermal bridging. Apart from the thermal performance of the envelope, the technical problems as a result of the building envelope degradation need to be resolved.

The toolbox does not support the existing condition evaluation, as the focus is on the design phase that comes subsequently. Nevertheless, based on the existing construction some options of the toolbox matrix can be excluded. For example, the measure of cavity insulation is not applicable if there is no cavity wall. Furthermore, identifying the existing construction is necessary in order to associate the building with the approach's pre-calculated models and provide the tools' quantification.

B Changes in the external appearance

An important parameter for the design is whether changes on the external appearance are allowed. Even though a changed, more appealing architectural expression is often a requirement for the refurbished building, in some occasions the change of the appearance of the façade is not allowed or desired. This is mostly due to the monumental status of the building, but it is also possible that the project's specifications require preserving the original character of the building.

If changes in the external appearance are not possible, additional limitations to the design are imposed and some possible refurbishment options are completely excluded and other options need special consideration. Options that are excluded the application of material in the exterior, as external insulation, or construction of second façade. Moreover, changes in the design such as enlarging the windows and balconies, or appendices to the building will not be considered. Figure 6.17.a highlights the toolbox options that can be used without changing the external appearance.

C Building programme

The building programme requirements are a decisive factor. Even though the toolbox focused on the building envelope components and not the internal layout of the dwellings, certain measures can be determined by the programme specifications. The building programme and the considerations that are related to it can vary significantly. They may refer to the size and layout of the dwellings, to changes in the circulation, and to the position of the occupant during and after the construction.

If bigger dwellings are required, for example, measures that add space are more favourable, as shown in Figure 6.17.b. Such measures are the cladding of the balcony, second façade, new constructions on top or adjacent to the existing building, the introduction of circulation spaces outside the volume of the existing building etc. On the other hand, if the occupants are planned to stay in the apartments during the refurbishment works, the upgrade should happen on the outside and measures such as internal insulation, replacement of exterior walls and relocation of circulation areas, which interfere heavily with the interior and the layout of the dwelling, are excluded.

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	**Cavity insulation**	**Upgrade windows**	**Insulate balcony slab**	Pitched roof, no insulation/ unheated loft	**Insulation on top of ground/ first floor slab**	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	**Secondary glazing single**	Cut off balcony	**Pitch roof insulation**	**Insulation under existing floor**	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	**Secondary glazing double**	Balcony cladding - Single glazing	**Insulation of top floor slab**		Mechanical ventilation	CHP installation
	Ventilated façade		Balcony cladding - Double glazing	**Flat roof**		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	**Shading adjustable**					Biomass boiler
RES	BIPV's			Photovoltaic			Solar collectors
spatial interventions	Additional space/ Second façade integrated	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	Additional floor/ occupied loft	Additional floor/occupied basement		District/ community heating

a

	Building envelope					Building Systems	
	Exterior wall	Window	Balcony	Roof	Ground floor	Ventilation	Heat source
Existing construction	Masonry/ cavity wall no insulation	Single glazing	Continuous slab, no insulation	Pitched roof, timber rafters no insulation/ occupied loft	Slab on ground, no insulation	Natural ventilation	Gas stove
	Lightweight concrete/ hollow brick, no insulation	Early, double-glazing	Separate slab no/little insulation	Pitched roof, timber rafters no insulation/ unheated loft	Basement unheated. Concrete slab, no insulation		Fossil fuel boiler in each dwelling
	Little/outdated insulation			Concrete slab, no/little/ outdated insulation	Little/outdated insulation	Trickle ventilation	Fossil fuel boiler per block
Retrofitting measures	Cavity insulation	Upgrade windows	Insulate balcony slab	Pitched roof, no insulation/ unheated loft	Insulation on top of ground/ first floor slab	Natural inlet/ mechanical exhaust	Replace existing boiler in each dwelling, high efficiency
	Internal insulation	Secondary glazing single	Cut off balcony	Pitch roof insulation	Insulation under existing floor	Mechanical inlet/ natural exhaust	Replace existing boiler per block, high efficiency
	Exterior Insulation and Finishing Systems (EIFS)	Secondary glazing double	**Balcony cladding - Single glazing**	Insulation of top floor slab		Mechanical ventilation	CHP installation
	Ventilated façade		**Balcony cladding - Double glazing**	Flat roof		Ventilation system with heat recovery (HR)	Heat pump
	Timber-frame wall	Replace windows (Double pane)		Green roof			
	Second Façade/ Single glazing	Replace windows (Triple pane)					
	Second Façade/ Double glazing	Shading adjustable					Biomass boiler
RES	**BIPV's**			Photovoltaic			Solar collectors
spatial interventions	**Additional space/ Second façade integrated**	Shading fixed	Integrated balcony				Geothermy
	Lift addition	Enlarged windows	New balcony	**Additional floor/ occupied loft**	**Additional floor/occupied basement**		District/ community heating

b

The "tools" that are possible if the building appearance is not to be changed (a) and the "tools" that are favourable if additional space is required (b). The respective measures are highlighted on the FRT matrix of Table 5.8.

D Energy savings

Energy savings is an important consideration and it is the basis of the toolbox approach, which aims at supporting the design process by integrating the energy performance of refurbishment into decision-making. Moreover, the orientation of the component to be refurbished determines the effect the measure will have on the energy need reduction. After the previous decisions have been supported by the toolbox mostly in terms of the options organisations, the toolbox calculations can assist the choice between the individual component possibilities by indicating how effective the measure is for the specific orientation, compared with other measures or the differently oriented façades. Therefore, in the specific approach, the parameter of orientation refers to the data on the energy saving potential.

E Level of investment

The level of intervention depends on the project's budget and ambition. When a higher budget is available, more advanced and possibly expensive options can be selected. The toolbox does not provide cost estimations, as the cost depends on each project size, location, strategy details etc. It is not possible to provide in a generic way, as the toolbox information are organised. Nevertheless, it acknowledges the determining role of the measure cost and gives an indicative categorisation by organising the measures in the matrix from low to high intervention. Moreover, the toolbox supports the evaluation of the measure. Since the potential energy demand reduction is calculated, it facilitates estimating the payback of the investment.

F Energy generation

The energy generation-mainly with the application of solar collectors and photovoltaic cells- is an additional possibility, next to the building envelope energy upgrade. The energy generation has a positive effect on the energy consumption and it can be a requirement in order to obtain an environmental or energy certificate. Its importance increases, as nZEB will be required. Nevertheless, it is not included in the toolbox calculation, as it does not constitute a building envelope upgrade, but rather an upgrade on the overall energy performance of the building. During the design process, firstly measures to minimise the energy demand must be selected (reference needed), according to the process presented by the roadmap. The energy generation will be an addition to these measures that will further reduce the primary energy consumption. It refers to the second step in the Trias Energetica, as discussed in section 3.3. The decision depends essential and the budget and ambition of the project.

Figure 6.18 shows the refurbishment toolbox roadmap in the form of a flowchart. The flowchart consists of questions, regarding the key points, and answers and decisions about those key points. Moreover, it includes questions and considerations regarding the key points. The toolbox information have input on that considerations, depending to the respective answers. The process presented in the flowchart, must be applied for each component separately, as demonstrated in the case studies.

Even though the process is not necessary linear, nor do the considerations always appear in this order, the order and the questions are indicative for the process. Assessing the existing condition and the need to upgrade comes first. Then, specifications of the project, such as the external appearance, dwelling quality, residents etc. come into the scope. The points of investment and energy savings are often interchangeable in order. The decision on a specific measure can be based on the project budget and ambition and then check its efficiency or a measure can be selected on the grounds of high energy savings and its feasibility will be then decided according to the investment.

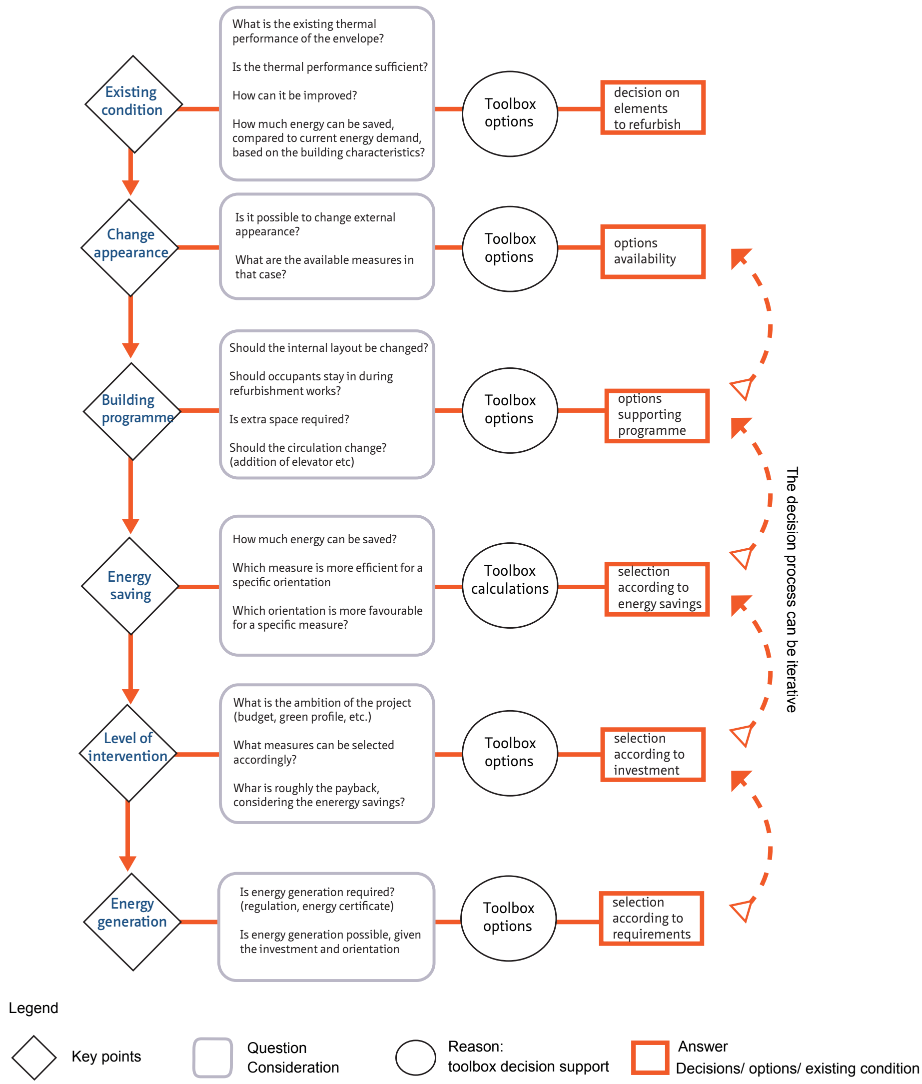


Figure 6.13

The Roadmap to Façade Refurbishment Toolbox.

§ 6.6 Conclusion

This chapter created a roadmap to the refurbishment toolbox. Four case-study buildings were studied and five refurbishment strategies were proposed, according to each project's requirements. Table 6.3compares the combined solutions for the case studies by indicating the selected toolx on the FRT matrix.It also gives information about the energy reduction on the heating demand of each separete measure and the total solution.

The process was supported by the toolbox database, as the different options were available and the possible effect on the heating energy need was indicated. However, during the design process of the refurbishment strategy, the energy reduction cannot always be the only decisive factor. Some of the options had already to be excluded, due to other parameters, such as the monumental status, extra space required, the budget etc.

The key points identified through this process were considerations regarding the existing building condition, the possibility to change the appearance, the building programme, the energy savings, the level of investment and the options for energy generation. Those issues were addressed in each building envelope component separately. In reality, the process is not necessarily linear, as some decisions affect other components as well. However, the roadmap, as well as the toolbox, highlights the components to be considered in an integrated refurbishment, which is why they present the possible decisions for the individual component.

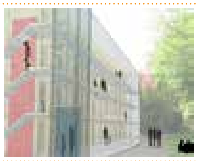
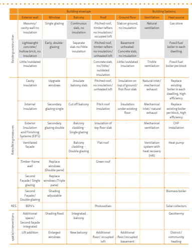
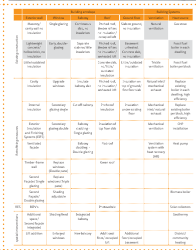
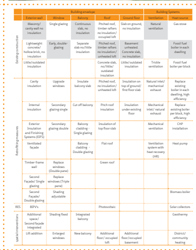
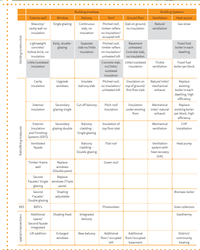
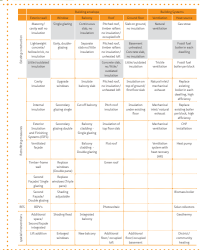
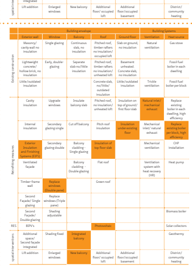
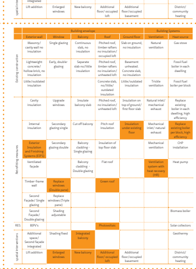
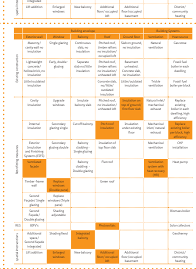
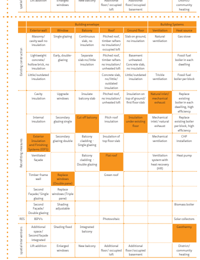
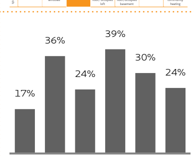
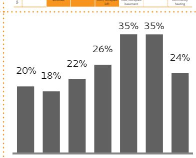
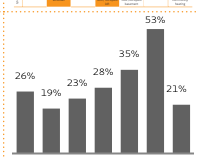
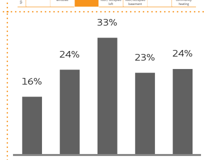
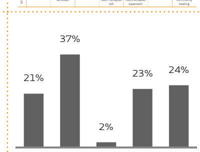
	1	2	3	4	5
	Breslauer complex		Platanen complex	Suringarflat complex	Coevordenstr complex
Current					
Refurbished					
Toolbox matrix current condition					
Toolbox matrix solution					
Selected options energy reduction					
Combined solution energy reduction	90% reduction to current heating energy demand	80% reduction to current heating energy demand	90% reduction to current heating energy demand	69% reduction to current heating energy demand	40% reduction to current heating energy demand

Table 6.3

Overview of case studies solution.

The FRT matrices show the tools "footprint" of existing and refurbished building, based on the measures in Table 5.8.

Relevant combinations and general recommendations

Even in cases with budgetary limitations, measures for all components are proposed, constituting an integrated refurbishment strategy. The toolbox measures, organised per building envelope component, need to be combined to compose the integrated solutions. If we look at the matrix, there are several combinations of measures. However not all combinations are relevant. For example, if a second façade is applied, the wall and windows behind it do not necessary need to be retrofitted, like in the case of Breslauer Complex (Figure D.3). The measures combinations that were demonstrated in the solutions are relevant not only for the case-study buildings, but also for a large amount of buildings with similar specifications, and can be used as examples.

A general recommendation to identify relevant combinations is that heat losses must be prevented through all components. As heat transfers when there is a temperature difference, every component between spaces with different temperature must be insulated. Temperature differences exist between interior and exterior space, but also between heated and unheated spaces. Such spaces are storage basements, unoccupied attics, stairwells etc. However, unheated spaces are possible to reach comfort temperature due to high solar and internal heat gains. This happens for example in glazed balconies and second facades and they function as thermal buffer. The heat flow then between interior and thermal buffer spaces is reduced. As proven by the toolbox calculations, such measures can result in a significant energy demand reduction, without additional insulating of walls and windows.

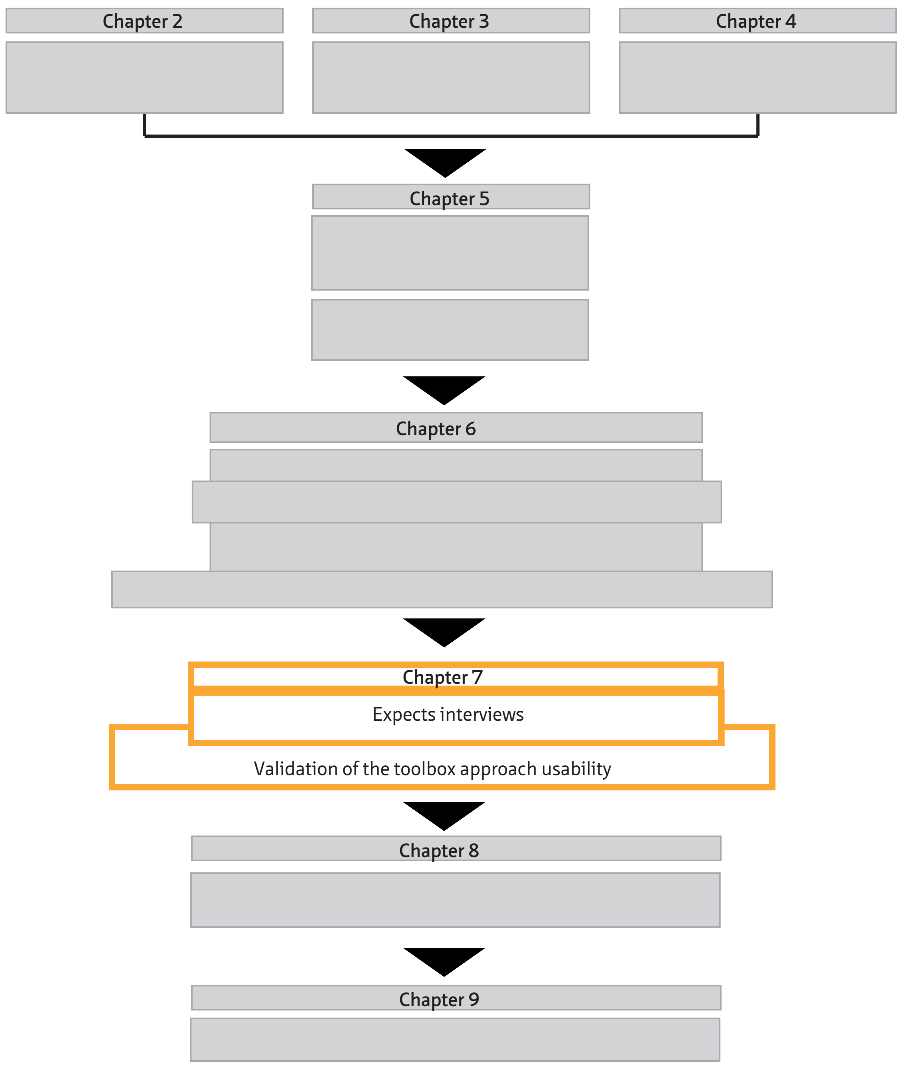
Throughout the decision-making process certain observations were made, regarding measures applicability. These can serve as recommendations for future projects, without, of course, excluding other solutions that fit each project. Starting with the external wall, the options of internal insulation and cavity insulation are in general not preferable, if change of the external appearance is possible. The internal insulation uses up occupied space and causes a lot of disturbance to the interior. The cavity insulation is an easily applied measure, but most likely does not offer adequate thermal resistance, due to the limited depth of the existing cavity. A second façade is particularly favourable if combined with functional and special benefits, for example circulation space.

Replacing the window was the preferred solution is all cases. Often it can be combined with removing the existing parapet to enlarge the window area. The window then can also be used as a balcony door to a new balcony. With regard to the balcony, in most cases glazing of the balcony was selected. In terms of energy demand reduction, it offers considerably better performance, as it reduced heat flow form all the components and not only the thermal bridge. If the balcony is integrated in the dwelling, there might be the need to construct new balconies.

The roof gives several possibilities for modification and extra space for the dwellings. The structural integrity needs to be considered, particularly is an additional construction is placed on top of the existing, increasing the loads. Finally, regarding the ground floor, the main consideration is whether the basement is heated or not and whether there is enough height available for the insulation addition. Given that in most case it is preferable, not to reduce the height of the dwelling and avoid modifications for stairs etc., it is preferable to apply the insulation under the slab.

With the completion of Chapters 5 and 6, the research question is answered. Integrating the energy upgrade potential of residential façade refurbishment strategies into the design can be supported by applying the proposed approach.

Chapter 7 provides a validation of the approach. Since it is a decision support instrument aiming at facilitating the design process of refurbishment projects, it can be validated by the designers and other refurbishment stakeholders. Finally, Chapter 8 explains how to associate each project to the generic toolbox calculations, in order to provide the potential energy reduction of the different measures, which is then used to support the design process, as demonstrated in the current chapter.


Chapter 2
Chapter 3
Chapter 4
Chapter 5
Chapter 6
Chapter 7
Expects interviews
Validation of the toolbox approach usability
Chapter 8
Chapter 9

7 Toolbox approach validation

The previous chapters developed and answered the research question on how integrating the energy upgrade into the early stages of the design process can be possible. The result is the toolbox approach, supported by the roadmap development. The next step is validating the approach. As it is intended to be used by designers and stakeholders of refurbishment practice, the validation comes as feedback of this target group. The feedback is provided in the form of qualitative data on the usability of the approach, collected during interviews with designers and refurbishment experts. Moreover, recommendations on improving the approach are suggested. The first part of this chapter explains the interview type and the methodology used. The second part summarises the interview findings and draw conclusions on the validation.

§ 7.1 Introduction

An important step in the research methodology is the approach validation. Since the approach aims at supporting the design of refurbishment strategies, it should be validated by building industry professionals, which are likely to use the Façade Refurbishment Toolbox. The professionals involved in the decision-making of refurbishment projects include primarily architects, but also housing association and constructors that are responsible for the estates and their refurbishment. Therefore, experts from these disciplines can give feedback on how the approach can be helpful in the design process.

Research interviews are a prominent data collection strategy for both qualitative and quantitative research (Bryman, 2012). Interview is an important source of information in case studies, in which the respondents are asked for their opinion and insights (Yin, 1994). In the context of the current research, the case study is the application of the toolbox approach in real-life situation, which would be the design and decision-making of a refurbishment project.

There are different types of interviews. Bryman (2012) categorise them according to their qualitative or quantitative perspective in data collection, type of questions etc. Although the distinction between interview styles may be blurred in practice, particularly between semi-structured and unstructured styles, it is useful to be aware of the range of interview types available (Broom, 2005).

Interviews focusing on qualitative research can be semi-structured or in-depth. In this case the researcher has an interview schedule with a list of themes and potential questions to ask the interviewee. This interview style is flexible, allowing for an open dialogue that can extend beyond the parameters set by the interview schedule. Similarly, unstructured interview style, where a brief topic guide allows considerable freedom, aims at qualitative data. The interview becomes then a conversation rather than a more structured question-answer session. On the other hand, structured interview style is appropriate for quantitative data. A structured or standardised interview involves the researcher asking each interviewee the exact same questions. Questions will generally offer the interviewee a fixed range of answers (typical of survey research), followed by a statistical analysis of the results.

In the case of the toolbox approach validation, the information sought is of qualitative nature, as they refer to the design process and the usability of the approach. They refer to the quality of the toolbox approach, which cannot be expressed in quantified numbers. To this end, the interview type to be applied is semi-structured. The respondents are presented with the approach and they are requested to give feedback on its usability and suggest improvements, which could be incorporated into the toolbox approach or future research.

Chapter 7 elaborates on the validation process through experts' interviews. Firstly the interviews methodology is developed. It explains the topics on which feedback is required, in order to validate the toolbox approach, as well as the selection of respondents and the interviews process. The second part consists of the interviews results and the conclusions that can be drawn out of the feedback regarding the usability of the toolbox approach.

§ 7.2 Validation Methodology

Qualitative interviews offer means to explore attributes and characteristics of a research subject. Within the scope of the current research, the subject is the developed approach and the qualitative interviews aim at validating it as a design support instrument. The answers will be summarised as validation results in the current chapter giving overall conclusions on the relevance and usability of the information. There can be also recommendation for improvements or suggestions for further research. This section elaborates on the topics that need to be discussed and validated, the different respondents groups and the process to execute the interviews.

§ 7.2.1 Interview topics

The interview aimed at validating the toolbox approach as a support instrument for refurbishment strategies decision-making. The approach targets the early stages of the design process, when architects and stakeholders look for information to help in the design direction (Attia et al., 2012). Therefore, the important aspects to validate the toolbox were related to the design process, the usability of the toolbox information and the relevance of the roadmap key points.

The design process of refurbishment strategies is complex, with a lot of restrictions and parties involved. The first part of the interview aimed at clarifying this process, particularly as far as energy upgrade is concerned. The objective was to underline to what extend the potential energy upgrade shapes the refurbishment strategy, at which point during the process specialised advice is sought, and what type of information may support the process. In this way, the background of the toolbox data application was set.

The second part referred to feedback on the usefulness and usability of the toolbox, which is the main purpose of the validation. Firstly it is important the approach and the information to comprehensible by the respondent and get recommendations how it can be improved. The toolbox information is interesting for the design process when applied in a specific building, so that specific numbers on energy reduction potential are available and comparable for different measures. Thus, the respondents were provided with these data and were asked to use them in a current refurbishment design project. The question then was if and how the toolbox database helped in organising possible options and taking decision. Finally, the respective data were considered for an older project, in order to reverse engineer it. The respondents evaluated if the decisions taken would be facilitated by the toolbox information and if any of the strategy would be different.

The toolbox information is organized and highlighted by the roadmap. Feedback was required on the relevance of the roadmap key points in reflecting considerations during the design process. Finally, the case studies presented in Chapter 6 aimed at demonstrating the process. The validation should include feedback on the clarity and usefulness of the examples, in order to motivate designers to use the information in future refurbishment projects.

§ 7.2.2 Choice of interview partners

The selection of interviewees was based on their potential to use the Façade Refurbishment toolbox. The decisions the approach aims at supporting are taken not only by architects, but also stakeholders such as housing companies or maintenance constructors. Therefore, the validation should not be limited to architects but include other parties and experts that influence decisions about the building stock. Apart from professionals in the building industry, feedback was also provided by architecture students. Even though the feedback of the professionals is different, due to more extended experience, the input of students can show the relevance of the toolbox for educational purposes. Table 7.1 shows an overview of the different respondents groups and the number of respondents in each group.

Respondents group	Number of respondents	Influence on design decisions
Architectural students	10	Design development. Strategy concept. Combination of different parameters of function and performance
Architect/designers	6	
House owner/consumer	2	Initiator of refurbishment. Formulation of specification. Definitions of solution feasibility. Evaluation of final solution benefits for the user.
Housing company	4	Initiator of refurbishment. Formulation of specification. Definitions of solution feasibility. Evaluation of added value of solution for the estate
Refurbishment contractor	2	Design execution. Definitions of solution feasibility
Energy consultant	1	Evaluation of energy performance. Influence on design development

Table 7.1
Respondent groups interviewed

Building industry experts

The experts that can validate the research are primarily architects, as the approach is intended as a design process support tool. The main selection criterion for the architects is that they have refurbishment projects in their portfolio. The architects can apply the data provided by the toolbox on a specific project they are designing and give feedback on whether the information can help them.

Apart from designers, there is a second group of experts that can have feedback on the approach. This group is multi-disciplinary and the respondents were selected on the basis of their experience on refurbishment decision-making. This group will be referred to as stakeholders. Freeman (2010) defines as stakeholders all group and individuals that can affect, or be affected, by the accomplishment of organisational purpose. They can be attributed to categories such as owners, financial institutions, clients/users, employees, competitors, suppliers and others.

Within the scope of the present thesis, the organisational purpose is the refurbished, well-performing buildings and the stakeholders are individuals and companies that take refurbishment related decisions. The decisions that are relevant with the research approach are connected with the design and, hence, the stakeholders are selected according to the influence they can have on the design aspects of refurbishment. They include housing companies that are often the refurbishment initiator and shape the specification, together with maintenance and renovation constructors and climate consultant on refurbishment strategies. These experts are often part of the design team and can give feedback on whether the toolbox information can give arguments on the measures selection. Table C.14, Appendix C gives the overview of the interviewed experts.

Students' design studio

The Graduation Laboratory of the RMIT (Research & Education of Modification, Intervention and Transformation) department is part of Master Programmes in the Faculty of Architecture and the Built Environment of the Technical University of Delft. The objective of the graduation project is a complex transformation brief, which combines all aspects of the RMIT levels of scale and areas of expertise (Quist & Spoormans, 2012). This design studio that focuses on upgrading existing building provides the opportunity to validate the toolbox approach as part of education process for architects.

Two different groups of students can be used in the validation methodology. Both groups, consisting of 5 to 6 students each, are currently in the stage of designing refurbishment strategies for residential buildings from the 30's and the post-war period in Amsterdam and Rotterdam. The difference between the two groups lies on the phase of design they were at the time of the interviews. The first one was close to finalise their design, while the second one was at the early phase of concept design. Therefore, the input of the information in different design phases can be considered. The students are included in the designers group in the table above.

§ 7.2.3 Interviews process

Even though the exact process is different for each respondents group, according to their experience and expertise, the main idea is similar. The first step is to get the interviewee acquainted with the approach. Both the toolbox and roadmap are explained. Following that, depending on the respondent's field and experience, data on specific projects can be provided, so that the respondents have the opportunity to use the information in their design process. The second step in the interview is the feedback to validate the approach, on the topics explained in section 7.2.1. It is possible for a time period to intervene between the first and the second step, so that the information can be processed into the design. The collection of questions to be asked to the respondents, also referred to as interview schedule, is presented in Appendix A. As the interview is semi-structured, it is flexible and variations may occur in the questions and procedure, depending on each respondent's field and expertise.

Architectural students

The first group of students got acquainted with the research approach through a lecture on refurbishment, which took place on the 12-11-2013. At that point the students were at the process of developing refurbishment strategies for different residential buildings. They were provided with the data derived from the toolbox calculation for each specific building and they were consulted on how this information can be considered. They were contacted again after the design completion, when they gave feedback on how the toolbox information was able to help them.

The second student group was presented with the approach on 10-01-2014, when they were at the early stages of their project initial design. The feedback was given three weeks later, after the concept design was completed and before proceeding with the final, detailed design.

Architects

The architects as designers have the possibility to apply the approach on a project and evaluate the usability of the information. The first step was to present them with the approach, demonstrate the input it may have and explain how it can be applied further in buildings. Following that, they were asked about the project information that is necessary to associate the building with the pre-calculated models and they were provided with the respective overview of measures potential energy reduction. This process was followed both for a current and past project. The second meeting was scheduled few weeks after the first, so that they have some time to consider the information. They were asked for feedback on how the information supported their design in the current project, as well as reverse engineering of the past project.

Stakeholders

Refurbishment stakeholders included housing associations, homeowners and energy consultants. The qualitative evaluation topics were the same as in the other groups. However due to their role in the design team they do not participate in the design process, but rather to some of the decision-making. Therefore, they were not required to apply the information of a specific design, but rather consider if, based on their experience, this type of information can support their decision and argumentation within the project team. In the case of stakeholders, the two steps of the validation, explaining the approach and the feedback, is possible to occur in one meeting.

§ 7.3 Validation results

The interviews provided qualitative data on the toolbox approach usability by architects and stakeholders. As they are the target group of the approach that aims at supporting their decision-making, the validation will be their opinion on whether and how the information was able to help them. Given the qualitative nature of the validating information, the interview had a semi-structured schedule and in many cases it became a more general discussion on refurbishment and The validation results, presented in this section, is the summary of the topics discussed during the interviews, with regard to the issues of section 7.2.1, which are the design and decision-making process of the respondents, the usage of the toolbox information and the relevance of the roadmap.

Design process

The first set of questions was regarding the parameters and requirements typically considered when dealing with existing residential buildings refurbishment, as well as the design process and decision-making. This part was useful to define the role of the different stakeholders and set the framework of the possible toolbox impact.

Looking at the design process the different stakeholders are involved in different stages. With reference to the phases in refurbishment projects presented in Figure 5.1, the pre-design phase begins with the owner of the dwelling, housing association or private, deciding that the dwelling needs to be refurbished and setting some of the requirements. At this stage often architects are involved, to evaluate the potential and contribute to the requirements development. Energy consultants and structural engineers can also have a role in this stage. Architects main involvement is in the design phase, with the participation of other consultants and the owner, which has to make decisions of the design direction. The role and decisions of the other parties in the design team, including the owner, come as a reaction to architects ideas. The role of architects diminishes in the execution and after refurbishment phase.

Architects' considerations during the design process, which are related with the project specifications but also their own ambitions and ideas, included the improvement and update of the building function and appearance, ranging from upgrading the building entrance, bathroom and kitchens to more radical changes in the internal layout, barrier-free access, change of circulation areas for optimal space use and the introduction of parking spaces. The flexibility of the solution to be adjustable to occupants' needs and variations in design was also a consideration. The building existing value and how to preserve and improve was the main consideration of the students, as it is one of the objectives of the graduation studio.

The stakeholders group has various considerations, depending on the role of each of the respondents. Housing associations are interested in upgrading the building, from the perspective of a business model were the financial benefits of the improvement, such as if the rent price can be raised, to compensate for the investment cost. Homeowners and refurbishment constructors have reported that they aim at quality and affordable living conditions. Long and short life-cycle of the refurbished components is also considered as it is related with refurbishment and maintenance cycles.

The energy performance was reported in most cases as being part of the requirements. According to an agreement of housing companies in the Netherlands, by 2020 the dwellings owned by the corporations should have an average energy label B, with more than 80% of the dwellings having a label higher than C (AEDES, 2012). Therefore, upgrading the energy label by minimum two scales during refurbishment is a requirement. In most cases the architects, but also the students, are based on this minimum requirement, with regard to energy performance. High energy performance, beyond the two label scale steps, is not very often required by housing companies, who are seeking to reach the needed performance with minimum cost. The split-incentives were mentioned by the housing associations as barrier to high investment for energy savings. Private owners are sometimes more concerned about high energy savings and other sustainability aspects, as reported by both architects and the interviewed owners. The cost can be a preventive factor in this case, as well, but can be more easily overcome depending on the owner's ambition and the balance with the financial benefits of the energy savings.

Nevertheless, in the design phase (Phase 2 in Figure 5.1), the energy performance becomes less influential. Architects and students reported that the design decisions are mostly determined by other parameters of the design objectives. The energy upgrade comes as an additional task to be applied during the final design (Phase 3 in Figure 5.1), in collaboration with the energy consultant who calculates the energy performance and gives relevant specifications, for example regarding insulation thickness and type of glazing. However, architects in some cases try to consider the energy upgrade earlier in the design development, mostly based on their experience. In the case of the students, unless energy upgrade is a starting point for their concept, the energy upgrade comes to the very end, when detailing of the technical solutions is required, without in most cases proving the achieved performance.

The energy upgrade is considered in the stakeholders' decisions in the difference phases. The different scenarios are from the beginning evaluated in terms of energy performance as it is directly related with financial benefits. Efforts toward more integrated design teams that include difference specialist working together, rather than successively, and base their decision on performance assessments were reported by housing associations and constructors. Architects are often part of that team.

Final decision of what strategy to follow and which measures to execute is always taken by the estate owner, both in case of housing associations and individual homeowners. This is understandable since they are responsible for the investment and the available funds. The costs have to be balances against the benefits, in terms of energy saving, housing quality and the possible changes in the rent price.

Toolbox approach information of energy

The second part of the interview focused on the Façade Refurbishment Toolbox and aimed at identifying its applicability by the different respondents groups. The approach was in general perceived as comprehensible. However, the respondents noted that a moderate amount of effort was required in order to understand all the information provided. Both architects and students found the data useful for their design process. Different degrees of looking at it were perceived by the respondents, varying from a general overview, without looking at the numbers, to interest in the specific amount of energy to be saved. The impact of the approach in organising the measures availability and provide in an easy way information of energy reduction was in general perceived as positive, to support a more energy-conscious design and develop awareness for possibilities.

The amount of information given by the tool overviews was considered satisfactory, for the early stages of the design. It was able to give a general, but clear idea of the effect of different measures. The energy saving percentages helped to categorise the measures, as well as quantify the measure effectiveness. In few occasions, the students required additional information, comparing different orientation and different apartment positions.

The respondents believed that the data can be more useful at the early stages of the design process. This became particularly clear in the two students groups, which used the approach in different stages of their design. The group of students at the beginning of the concept design found that the information was influential to the concept and directed the design towards measures with higher energy savings. On the other hand, the students that was close to finalise the design found the information interesting, but did not influence their design, as most of the decisions were already made. They still used the information, nevertheless, to argue about the decisions and their added value.

A similar observation was regarding the past projects, for which the architects had to the energy saving information provided by the approach. When decisions have already been made, they would not change them on the ground of higher energy reduction. However, they could still be used to support their decision and validate their ideas

One of the questions was to suggest what type information, complementary or incorporated in the toolbox, can be useful to support the decisions. The cost of the measures and payback time in relation with the savings was regarded as the most valuable information to help the decision. Amongst other, the effect of the lower energy demand on building system installation and the influence of retrofitting measures on the buildings function were highlighted. Moreover, the energy reduction of the total strategy was suggested as extra information to facilitate the design, since the toolbox approach compares individual retrofitting measures and not their combinations. Finally, the energy savings suggested by the approach could be associated to energy label, as this is the main indicator used by the design team and users.

All respondents agreed that the information the approach provided can be useful arguments within the design team in various levels. Firstly, they can be used to communicate and validate a design decision. For example, architects can present the information to their clients, who are the estates owners and responsible for the budget, to argue the selection of a more expensive measure that provides higher savings. Moreover, it can be used in the discussion between architects and energy and building system consultants to form initial scenarios, but also when the performance of the total strategy need to be calibrated and evaluated. Nevertheless, the respondents believed that the approach is better suited for discussion within a design team of building industry professionals, rather than the communication with the end-users. The measures are detailed, while the level of savings is still indicative, which is difficult to be accepted by non-specialised audience.

The Roadmap

The roadmap to the toolbox information was the last part of the validation discussion. The roadmap evaluation concluded that the key points are relevant and reflect the consideration of architects during the design. However both architects and students highlighted that the process is not linear and many iterations are possible.

Regarding the importance of each point, the change of the appearance and the building programme were signified as the ones that mostly influence the design decision. The energy saving was also important particularly in the cases when the energy upgrade was a starting point of the concept. Finally, the level of intervention, related to the project budget, was considered as the most decisive factor, particularly by stakeholders. The integration of energy generation technologies was the least important consideration in the design phase.

Additional key points and considerations that affect the decisions and are not included in the approach roadmap were suggested to be the urban layout, the buildings appearance and architectural value, as well as integration in the surroundings. Moreover, scenarios regarding refurbishment life-span, ease, speed, and feasibility of construction are considerations that determine the measure selection and its execution. Finally, housing companies that mostly deal with the occupants suggested that appeal and effect of a measure to the users and their behaviour is an important consideration.

§ 7.4 Conclusions

This chapter presented the Façade Refurbishment Toolbox approach validation process and results. The approach was validated by building industry professionals, who are expected to use it in their decision-making. The information sought was of qualitative nature, as they refer to the design process and the usability of the approach. Therefore, semi-structured interviews were used as a mean of qualitative data collection. The first part of the interview got the respondents acquainted with the approach, while in the second phase, they were asked on their opinion regarding refurbishment design process and the impact of the toolbox information and the roadmap.

The main categories of respondents are designers and stakeholders, divided in different groups, as shown in Table 7.1. Since the approach focuses on the design phase, architects were an important respondent group to provide feedback. Additionally architectural students working on refurbishment projects were part of the designers' category. Aside from designers, refurbishment decisions are influenced by other building industry parties, referred to as stakeholders. The respondents were selected on the basis of their experience on refurbishment decision-making. They include housing companies that are often the refurbishment initiator and shape the specification, together with maintenance and renovation constructors and climate consultant.

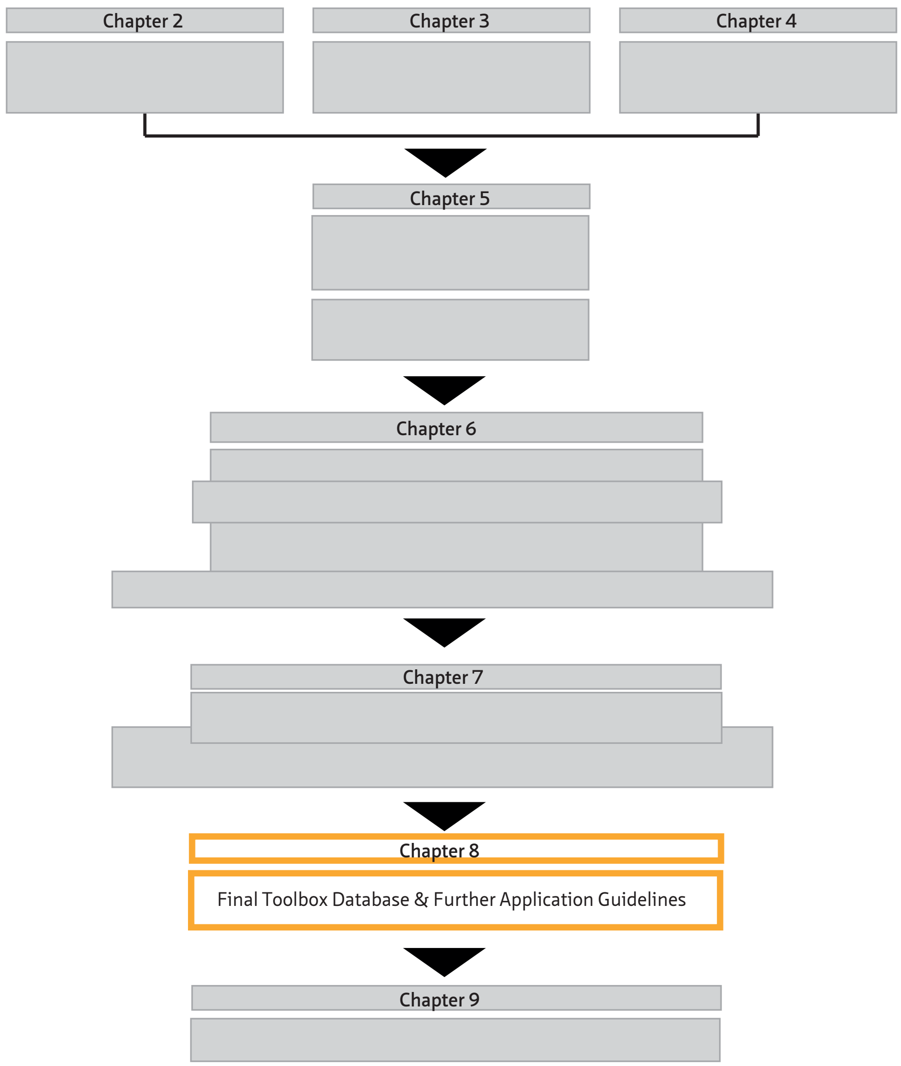
The interviews resulted that energy upgrade is typically part of the project requirements. However in most cases it does not influence the concept development and comes as an additional parameter to be incorporated in the final design. Efforts toward reversing this process are taking place, particularly from the stakeholders' point of view. Multi-disciplinary teams, often, but not always, with the participation of architects, aim at making refurbishment decisions based on the solution performance. Stakeholders appear to be more aware than architects of the need to integrate the energy performance in their decisions. The reason is the direct relation of energy savings and cost, which is the most decisive factor for stakeholders. Housing companies and refurbishment consultants are already using tools to get early indicators of performance, while architects mostly rely on their experience and general knowledge. In this context, the approach focus on architects is justified.

With regard to design choices, the students were more influenced by the information than the professional architects. This can be explained by the students' lack of experience that renders them more open to different design process. Particularly, the second group of students, which was at the beginning of the concept development, was the respondent group mostly influenced by the information. This observation suggests that the toolbox approach has the potential to contribute to architects education and raise awareness on potential energy savings.

In general, the participants believed that the toolbox information is useful to provide an overview of possibilities and arguments within the design team. Even if the decision is not on the measure with the higher energy savings, it is beneficial that it triggers the discussion on why an efficient measure is not selected. On the other hand, it can direct the design towards high-saving options. Most importantly, the information can be valuable when negotiating possible options with clients.

The investment cost came up several times during the interviews, as the main factor to determine the decisions taken by the client. Even though the approach does not provide specific numbers for the cost of a measure, it addresses its importance as a parameter in the matrix organisation. Measures that are more intervening and are, hence, expected to be more expensive are placed after the less intervening measures. Calculating the expense of a measure it is not possible within the scope of the approach as it depends on the specific project, in terms of scale, location, detailing of the solution etc. Nevertheless, when a specific project is considered and the expenses are known, the toolbox information can easily give an indicative pay-back time, based on the calculated energy savings.

Finally, the key points composing the roadmap were considered relevant by the respondents. The importance of each point, however, varied in each case. Moreover, the process of considering the points is not linear but iterative and often the decisions are influenced by each other. Provided that result, the roadmap is composed in the form of key points list, highlighting the toolbox influence, as shown in Figure 6.18, rather than a flowchart form that suggest some prioritisation.


Chapter 2
Chapter 3
Chapter 4
Chapter 5
Chapter 6
Chapter 7
Chapter 8
Final Toolbox Database & Further Application Guidelines
Chapter 9

8 Façade Refurbishment Toolbox application

The previous chapters developed the background and gave an answer to the research question. The result was the Façade Refurbishment Toolbox approach, systematically organising retrofitting measures and quantifying them in terms of energy demand reduction. Moreover, key points of the refurbishment design process where the impact of the toolbox information is possible are organised in a roadmap. The present chapter explains how the toolbox information can be used in future refurbishment projects. The steps to obtain the toolbox measure energy reduction overview for a specific building are explained, together with examples of potential energy reduction for different buildings.

§ 8.1 Introduction

Introduction

After the need to support the design, the objective of the Façade Refurbishment Toolbox approach is its application in future refurbishment, to support the design process decision-making. The support can be provided in terms of the measures organisation by the toolbox matrix, as well as the roadmap. Moreover, one of the main outcomes of the approach development is the numerical output regarding the saving in energy demand, expressed as a percentage of reduction to the energy demand, before and after the application of measures. The numerical output is also referred to as toolbox data, as it comprises the quantification of the refurbishment tools.

The previous chapters have presented how the different measures were systematically organised and quantified and demonstrated how the information can be used to design the refurbishment strategy in five case study buildings. To know the energy savings in the case studies, each building was associated with the pre-calculated building types, developed in Chapter 5.

For the applicability of the approach in future refurbishment projects, the present chapter sets off to present the process of providing the numbers of energy demand reduction for each specific building, considered to be refurbished. The data can be used to support the decision-making.

§ 8.2 Method to acquire the toolbox data for a building

Based on the methodology developed in Chapter 5, the energy savings after each measure application differs in each building, depending on the existing construction, orientation, WWR and dwelling to neighbouring dwellings. This section explains the steps to be taken in order to associate any given building to the pre-calculated models. This process can be applied in case of a specific building to obtain the data on the energy reduction after each measure application. To illustrate the process, one of the case study buildings of Chapter 6, namely the four-storey building of the Breslauer complex, is used as an example. Each step is explained on the type of data that are used as input or output and subsequently the respective date of the example building are filled, to demonstrate the process.

A Identify existing building and construction information matrix

Identifying and understanding the existing building is essential for the development of any refurbishment strategy. Furthermore, it is a necessary step for the Façade Refurbishment Toolbox usability. The characteristics of the existing building that need to identify are related to the building envelope components construction, the building type, the orientation of the façades that are considered for retrofitting and the window wall ratio. Those are the characteristics used to create the model building types variations in section 5.6.1.

To organise the existing building information that will be then used in step B, the matrix shown in Table 8.1 should be filled in. The table in this case is already filled in with the information regarding the example building of the Breslauer complex.

B Associate each component with the pre-calculated model

The association of existing construction and pre-calculated model is given in Table 5.25, page 257, which presents a range of construction types, thermal transmittance coefficient U-value and window-wall ratio (WWR). According to the characteristics of the considered building, identified in Step A, the percentage of reduction of the building can be determined with reference to the pre-calculated models. If the existing construction does not match exactly the construction possibilities given in Table 5.25, which is of course not exhaustive, the building can be associated to the most relevant construction, based for example on the U-value. Table 8.1 shows the existing construction and other building characteristics of the example building and the reference models highlighted.

Construction year/period	Building type	Orientation	WWR
1960s	Apartment block	N and S façades	50%
Component	**construction**	**Component U-value (W/m2K)**	**Building type Model**
External wall	24mm lightweight concrete blocks, brick cladding	1.2	M6_60_N M6_60_S
Window	PVC Frame, Double-glazing, 25-30 years	3.0	M6_60_N M6_60_S
Balcony	Incised loggias	1.9	M1_60_S
Roof	Timber joists, wooden casing, bitumen roofing membranes / attic floor in-situ concrete 130mm	2.9	M1_30_NS
Basement	Concrete in situ slabs 130mm	1.9	M6_30_NS

Table 8.1
Building and construction information matrix, filled in for the example building of the Breslauer complex, according to Table 5.25, page 257

C Identify relevance of typical apartment, building block or dwelling

The quantification of the measures uses as reference the typical apartment. The typical apartment is a better indication for retrofitting measures effect. Typical is the type of apartment where a measure has more effect, because it is then an appropriate reference to identify and isolate the measure quality and its energy savings are then more important for the total savings of the block. In apartment buildings, typical in most cases is a middle apartment, in a middle floor, which is also repeated more times in the block. Type T2 is then the typical, with regard to measures for the external wall, window and balcony. For roof and ground floor retrofitting measures, typical are considered the top (T3) and ground (T1) apartment respectively (Figure 8.1.a).

The need for information of typical or other types of dwellings depends on how the information will be used and varies in every design process. For example it is possible that the typical apartment is more appropriate for architects to appreciate the differences between measures. On the other hand, housing associations may be interested in the whole block reduction, to make a business model. In the case of single family and raw houses, the whole house reduction is more relevant when all floors consist one dwelling (Figure 8.1.b).

Based on the apartment types presented in Figure 5.3 and the energy demand reduction simulated in apartments with different position, the energy savings in a whole building or in different buildings types can be calculated according to the average demand in kWh/m2.yr. To calculate the average, it is necessary to know how many apartment of each type are there in any apartment block. This depends on the number of floors and apartment per floor. In the case of a middle terrace house, the reduction would be the average of types T1, T2 and T3, while for the cornet terrace house, the average of types T4, T5 and T6. Figure 8.1.c and Table 8.2 show the apartment types for the example building of the Breslauer complex. Nevertheless, for the design purposes, as described in Chapter 6, the typical apartment impact was used.

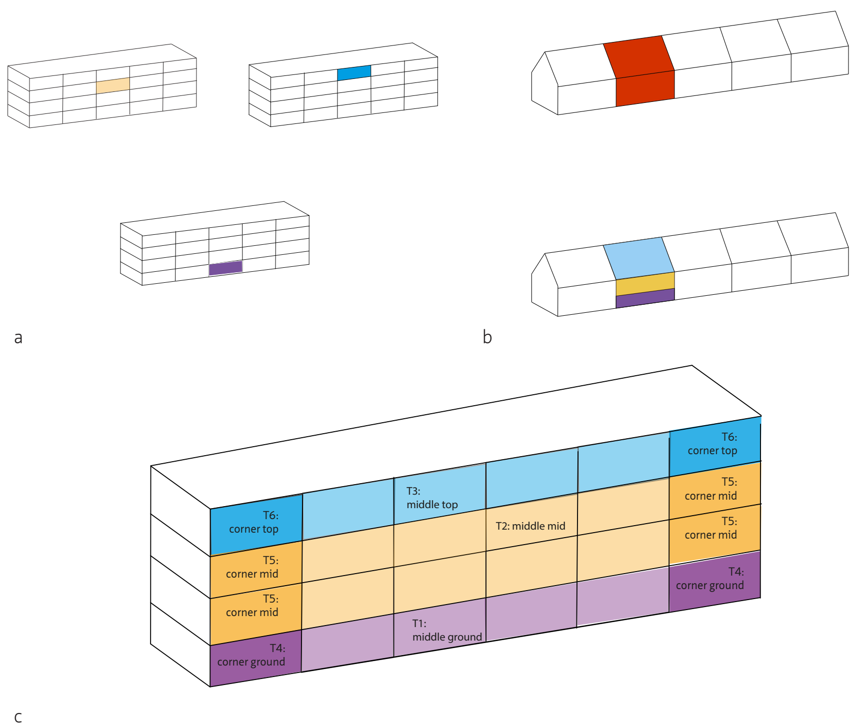


Figure 8.1

(a) The typical apartments types that are used as reference of the energy reduction for the respective component.
(b) The whole terrace house energy reduction is the average of the different apartment types.
(c) Apartment types for the example building of the Breslauer complex

Floors	Apart-ment/floor	T1: G_MID	T2: Mid_MID	T3: Top_MID	T4: G_CORN	T5: Mid_CORN	T6: Top_CORN
4	6	4	8	4	2	4	2

Table 8.2

Number of floors, apartments per floor and apartment types in the example building. They can be used to estimate the average energy demand reduction for the whole apartment building

	Referred table	N	S
External wall measures			
External insulation	Table C.7	16%	18%
Cavity Insul		12%	13%
Internal Insulation		15%	16%
Second Fac Sgl		39%	34%
Second Fac Sgl_Corridor		38%	34%
Second Fac Dbl		34%	27%
Second Fac Dbl_Corridor		37%	31%
Second Fac Dbl Integr		63%	43%
Windows			
Upgrade	Table C.12	8%	7%
Replace Dbl LoE		28%	24%
Replace Dbl LoE ARGON		30%	28%
Replace Tpl LoE AIR		25%	18%
Replace Tpl LoE ARG		42%	23%
Second Glaz Sgl		25%	19%
Second Glaz Dbl		31%	20%
Shading fixed		15%	2%
Shading adjust		18%	14%
Balcony			
CUT-OFF Balcony	Table C.15	n/a	5%
Insul Balc SLAB		n/a	6%
SINGLE BalcGlaz		n/a	18%
Double BalcGlaz		n/a	19%
INTEGR DblBalc Glaz		n/a	39%
Roof			
pitched roof	Table C.17	10%	13%
Top Slab insul		28%	33%
Flat Roof insul		35%	39%
Green Roof		23%	29%
Additional roof		28%	32%
Ground floor			
ON slab insul	Table C.21	22%	26%
UNDER Slab insul		23%	26%
Additional Grfloor		21%	23%

Table 8.3

Components' retrofitting measures and respective energy demand reduction for the example building of the Breslauer, obtained with reference to the toolbox data of pre-calculated models in Appendix C

D Retrofitting measures overview

Following the steps described above to refer to energy demand reduction for the specific building types, Table 8.3 can be composed. The data on energy demand reduction for each building type can be found in Appendix C. In this way an overview similar to Figure 8.2 presenting retrofitting measures for each component and the respective energy demand reduction can be creating for the building under consideration for refurbishment. As found in the toolbox approach validation in Chapter 7, the level of information provided by this overview is adequate to be used in the design process. More detailed information, for example comparing the reduction for different orientations, can be provided based on the tables of Appendix C.

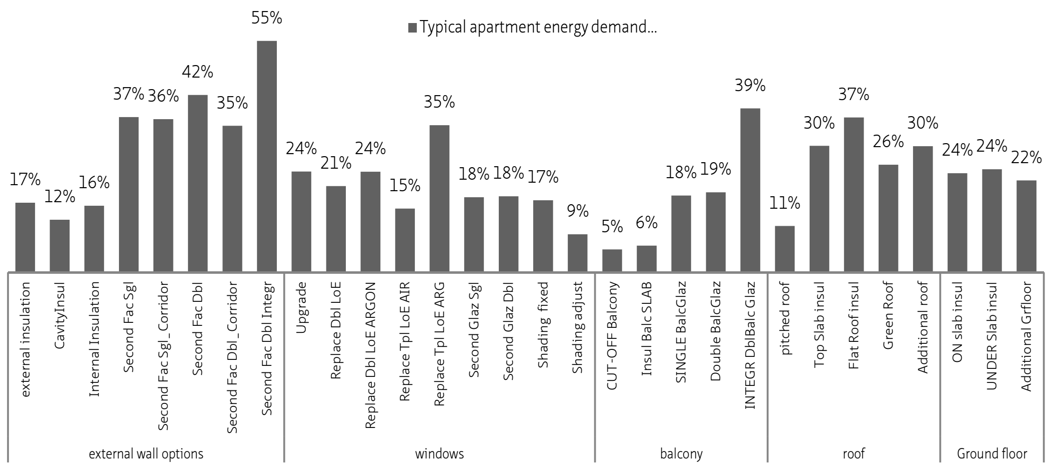


Figure 8.2
Overview of heating demand reduction after the application of retrofitting measures in the respective components. The values refer to typical apartment and they are average for different building types, WWRs and orientation.

§ 8.3 Examples of specific buildings data

This section presents some examples of measures overviews, generated by the FRT approach and the process described in Section 8.2. The examples of reduction overviews were developed for specific buildings, as part of the approach validation methodology. The architects and students interviewed were asked to provide information of a specific refurbishment design project, in order to provide the toolbox data for each case. As a result, the retrofitting measures impact was investigated for a variety of building types and comparison between the different buildings can be made.

Same building type- different reduction potential

The reduction potential depends on the existing performance of the building. A worse performing building can result in greater energy reduction when refurbished than a building with better initial performance. This is because the worse building had higher energy demand before the application of the retrofitting measures.

a

b

Figure 8.3

The apartment building with the masonry wall and single window (a) and cavity wall and double window

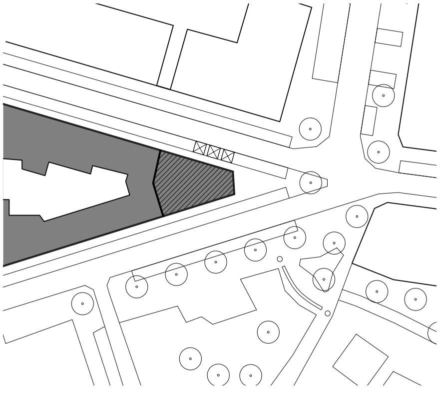
The dependence of the energy reduction to the construction can be illustrated by the two post war apartment building shown in Figure 8.3.The first building façade consists of solid brick masonry wall and single glazing windows, while the second of cavity wall with lightweight masonry construction in the inner leaf and brock cladding. Both buildings consist of concrete floors and timber pitched roof. The WWR is similar and both have east and west oriented facades. Based on the existing construction and following the Steps A-D described in the previous section, the tools reduction overviews were generated for the buildings. The overviews are compared in Figure 8.4. It shows that even though the buildings are of the same type and period and share similar characteristics, the energy reduction potential of the different measures is different, due to differences in façade construction. This observation confirms the suggestion that each building is specific and has to be separately investigated, while the refurbishment strategy has to address its specific needs.

Figure 8.4

Comparison of measures energy reduction percentage for two buildings of the same type, but different construction

Typical apartment –dwelling- whole buildings

As explained in Step C of the method to get the toolbox information for a specific building, the quantification of the measures can refer to the typical apartment or to the whole building. The type of information that is more relevant to the process depends on the building's type, occupancy and ownership, as well as the decision-making party. The example building show in Figure 8.5 is used to demonstrate the differences in energy demand reduction between the typical apartment and the whole dwelling.



a

b

Figure 8.5

The example four-storey dwelling, located at the end of a terrace houses array

The building is a four-storey dwelling, located at the end of a terrace houses array. The dwelling is occupied by the same owner and it is considered for refurbishment as a whole. Based on steps A-D described before, the overview of Figure 8.6. To estimate the reduction for the whole dwellings, the average of corner apartment types T4, two times T5, and T6 were considered, as the dwelling is at the edge of the terrace array and has two middle floors.

Comparing the energy reduction between typical apartment and the four-storey dwelling in Figure 8.6, the conclusion is that the typical apartment has higher energy savings. The reason is that in the typical middle apartment the effect of the measure is greater as it has less heat losses than other types (figures B.1, B.2 and B.3). Moreover, measures that affect only one apartment type, such as roof retrofitting that affects only the top apartment (Type T3 and T6), have result in lower savings if we consider the whole dwelling or apartment block, including the floors that the measure does not influence. In any case the specific reduction that is relevant to compare and select retrofitting measures depends on each project and type of information should be decided in Step C.

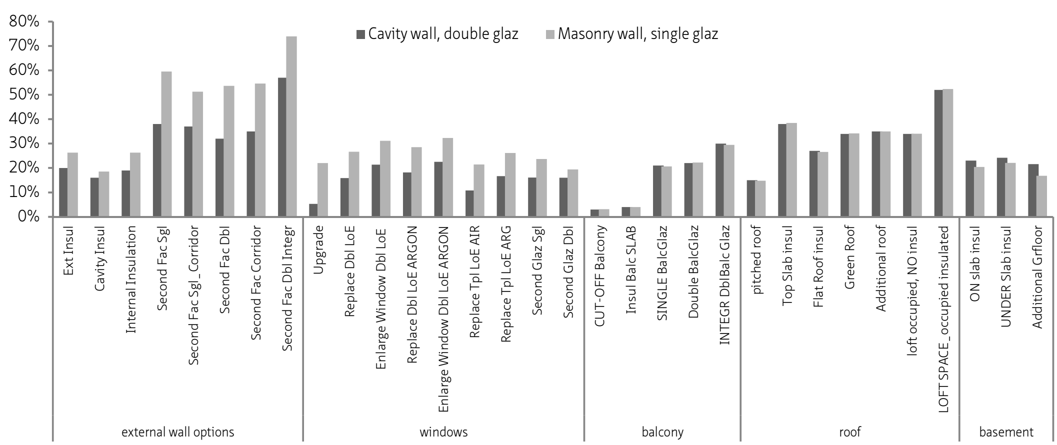


Figure 8.6

Comparison of measures energy reduction percentage for the whole terrace house and the typical apartment.

Different orientations

The calculation has shown that the precise percentage of energy reduction is affected by the orientation and the impact of the same measure is different in each orientation. The differences are bigger in measures for façade than roof and floor, particularly in those that have transparent components and are, thus, more affected by solar gains. Even though the tools overviews provided by the approach refer each time to a specific building for the given orientation, comparing the effect for different orientations is sometimes relevant for the design process.

a b

Figure 8.7
Floor plan and façade of the apartment complex. The layout results in various orientations of the dwellings

In the example building shown in Figure 8.7, the V-shaped layout of the floor plan results in façades with different orientation in the same complex. Figure 8.8 compares the effect of each wall, window and balcony retrofitting measure for different orientation. The balcony options show only east and north orientation, because only those façade comprise balconies. During the design process, the effect on different orientations can result in different decision for retrofitting of each façade.

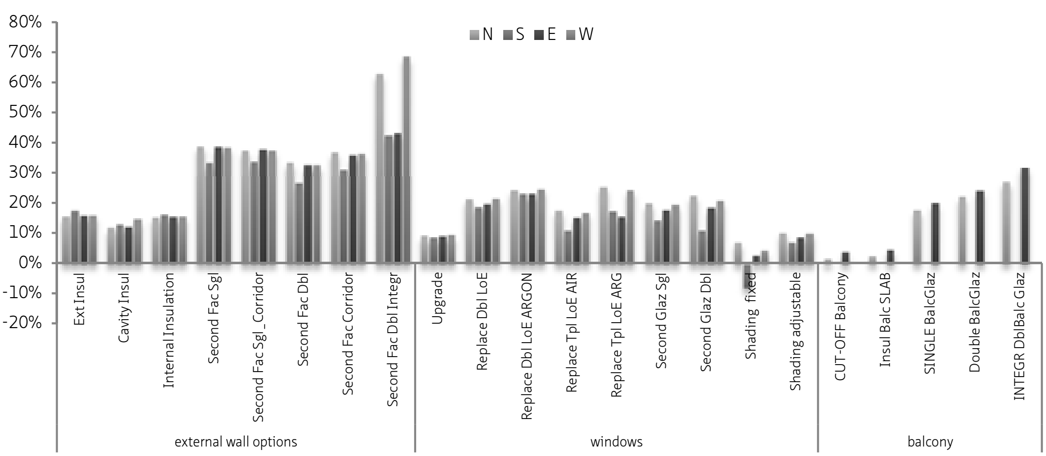


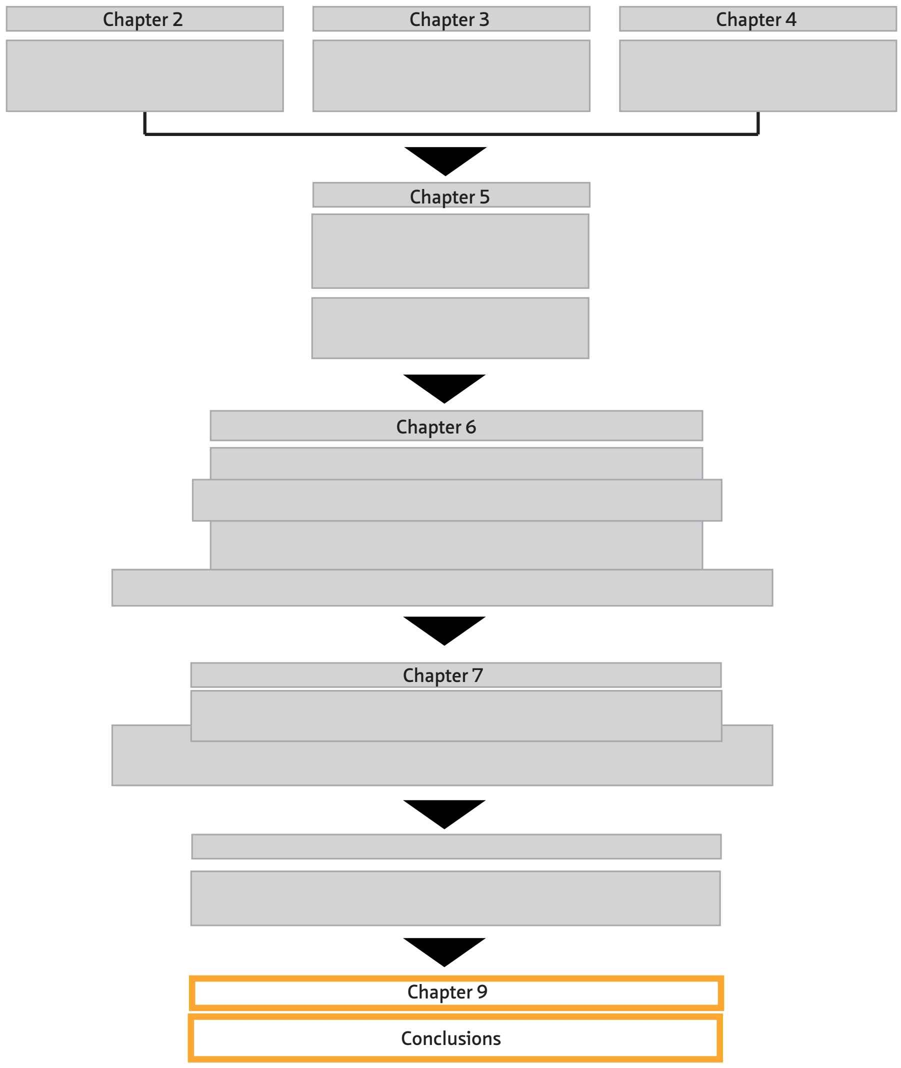
Figure 8.8
Overview of heating demand reduction after the application of retrofitting measures in the respective components. The values refer to typical apartment and they are average for different building types, WWRs and orientation.

§ 8.4 Conclusion

The Façade Refurbishment Toolbox supports the design process by organising refurbishment measures and quantifies them, so that they can be comparable. The previous chapters explained the different measures systematically organised them and highlighted the design process and when the toolbox information can be used. The quantification of the measures is based on simulation of different building types before and after the application of a measure. The result is the percentage of reduction on the energy demand.

Based on the pre-calculated models, the approach can provide percentages of energy demand reduction after the application of various measures regarding each specific building. The steps to follow to obtain those data were explained in the present chapter. First, the existing construction, together with WWR and the façades orientation need to be identified. According to this information, the building can be associated with the pre-calculated model, based on Table 5.25. Moreover, it needs to be determined whether it is relevant to look at the typical apartment or the whole building. In most cases, particularly in apartment building, the savings of the typical apartment are a better indication to consider in the decision-making, as the effect of the measure is greater than in other types. Nevertheless, depending on the building type and the objectives of the design team, the whole building consumption may be also relevant. Finally, based on the previous steps, the energy demand reduction for each component retrofitting measures can be found in Appendix C, composing the measures overview, as shown for example in Figure 8.2. The approach validation in Chapter 7 showed that this type of overview is considered as useful lever of information during the early design phase. More detailed information is also provided in the tables of Appendix C, such as energy demand reduction in different orientations and WWRs.

Different buildings have different reduction potential. The parameters to be considered are the construction, the building types and orientation. The comparison of buildings that differ in those characteristics has shown that first understanding of the existing building is important, but also that there are different levels of information that can be interesting for the decision-making. The toolbox can provide a range of information, but the objectives of the design and the type of information it needs have also to be defined early in the process.


Chapter 2
Chapter 3
Chapter 4
Chapter 5
Chapter 6
Chapter 7
Chapter 9
Conclusions

9 Conclusions

§ 9.1 Introduction

This study has demonstrated how refurbishment of the aging residential buildings can upgrade their energy performance, and has presented an approach to integrate the upgrade potential into the design process. The starting point of the research was the need to refurbish the existing housing stock, in order to reduce its energy demand, which accounts for over one fourth of the energy consumption in the EU (Eurostat, 2013a). This is a necessary step to reach the ambitious energy and decarbonisation targets for 2020 and 2050, suggesting an eventual reduction of up to 90% in CO_2 emissions (EuropeanCommission, 2007, 2010, 2011).

In this context, both rate and depth of refurbishment need to grow (BPIE, 2011a), increasing not only the number of buildings to be renovated each year, but also the amount of energy savings in renovated buildings. To achieve that, not only is it necessary to find politics and incentives, but also to enable the building industry to design and construct effective refurbishment strategies. The present thesis concluded with an approach to enable informed and energy-efficiency conscious decisions at the early stage of refurbishment strategies design.

Chapter 9 presents the thesis conclusions. Firstly the research question and sub-questions are revisited and discussed. The research questions outline the thesis chapters. Therefore the conclusions summarise the main findings of each chapter. The first three chapters comprised the theoretical background that shape the research question, discussion of the residential building stock, energy performance and refurbishment practice. Chapters 5 and 6 developed the core of the approach. Finally, Chapters 7 and 8 are concerned with its further applicability, regarding the approach validation and usability. The last part of the conclusions consists of a general discussion together with recommendation for future applicability of the approach and research to further develop it.

§ 9.2 Research questions

How can the energy upgrade potential of residential façade refurbishment strategies be integrated in the early design phase, in order to support decision-making?

The answer to the research question is given by the Façade Refurbishment Toolbox approach. It consists of three different types of information that can support the decision-making of residential façade refurbishment strategies. Firstly, the building envelope components that need to be addressed in an integrated refurbishment strategy are identified and different retrofitting measures for each one are proposed, composing the façade refurbishment toolbox. Secondly, the measures are quantified in terms of energy upgrade potential, expressed by the simulated energy demand reduction after the measure is applied. Finally, a roadmap consisting of key decision aspects in the refurbishment strategy development indicates when the toolbox information can be used.

As a result, the toolbox calculations provide an indication of the potential energy demand reduction at the early stages of the design and give the possibility to compare different measures when decisions need to be made. Additionally the toolbox matrix and the roadmap help organising the available options and highlight key considerations during the process that the toolbox information can have an impact on. All the information can support the decision-making within the refurbishment strategy design team. The approach primarily targets the architect, who has to generate the design development, but users, owners and other stakeholders can also use the information.

The main research question can be broken down into sub-questions regarding energy upgrade, residential façades typical construction, refurbishment strategies, design phases and decision-making support. The background and the development of the approach were based on elaborating these terms, as addressed in the research sub-questions, which are answered below.

1 What is the condition and construction of existing residential building stock?

Knowing and understanding the building which is considered for refurbishment is always the starting point of the strategy development. Therefore, the first question for the thesis to answer was about the existing building stock. To set the context of refurbishment, the building stock was analysed on three levels: past, present, future, which correspond to the original construction, current condition and future prospects (Zijlstra, 2009).

The original construction is very important to understand how the building performs and how it should be retrofitted. To this end, typical constructions of residential buildings in Europe were categorised, according to external wall construction as a starting point, as the thesis focuses on the building envelope (Table 2.2). Most importantly, identifying typical construction was a necessary step to the approach development and the retrofitting measures quantification. The age of the building is a good indication for its physical characteristics. However, due to parallel use of different construction principles in the same time period, the classification of constructions cannot be strictly chronological. The categories identified were timber-frame construction, masonry walls, cavity walls, lightweight masonry, prefabricated concrete panels and lightweight façade panels. Each one presents a range of variations, as they developed through time, but still share a common principle.

Regarding the current condition, it can be concluded that the building stock is subject to various damages and failures that refurbishment has to address. Next to the expected physical problems as components approach the end of their service life, energy efficiency, which is the focus of this thesis, is a big issue, since a large part of the stock performs far below today's standards. Measures to solve physical failures and upgrade energy efficiency should coexist, as it is also more efficient from a financial point of view.

Given the necessity to upgrade the building stock performance, in terms of both energy and damages, refurbishment is the future of the building stock. Even though refurbishment or replacement, by demolition and new construction, is a common point of discussion in real estate management, extending the life of an existing building is a better solution from the environmental point of view and should be the first consideration. Building process and materials are both energy intensive, resulting in new homes using four to eight times more resources than an equivalent refurbishment (Itard & Klunder, 2007), while demolition also consumes energy and produces waste volume. Nevertheless, demolition is necessary, but should be considered as the last resort. Buildings that suffer non-repairable problems, require extensive, cost-intensive non-energy related measures, or are located in areas where supply exceeds demand are not successful candidates for refurbishment and are likely to be removed. Still, there is a big share of the stock that can and should be refurbished.

2 What is the role of building stock refurbishment in the context of sustainable development?

Even though technical, financial and social aspects related to the residential buildings function and condition are often the main motivations to refurbish, when looking at the bigger picture, the energy demand of the building stock and its potential reduction is connected with sustainability. One of those key issues of sustainability addressed by the WCED is energy (UNESCO, 2003), as energy use is the main responsible factor for GHG and hence climate change (Eurostat, 2010). The building sector is the biggest energy user in the EU, accounting for approximately 40% and, hence, a reduction in buildings' energy demand can contribute considerably to the alleviation of the climate change and compliance with decarbonisation targets. The interest in the building sector that has been taken by legislative parties and the EU in particular, comes to confirm its importance. Together the Energy Efficiency Directive (Directive, 2012/27/EU) and the EPBD (DIRECTIVE, 2002/91/EU, 2010/31/EU) provide a framework for Member States to drive the reduction of energy use in buildings. In this context and given the slow renewal rate and the current poor condition of the stock, refurbishment of the existing buildings is a necessary action.

Even though there are various sustainability and other motivations to refurbish existing residential building, prevailing renovation rates, averaged in the EU, are as low as 1% and renovation depths are mostly minor (BPIE, 2011a). To reach the energy and carbon reduction goals, both rate and depth of refurbishment must increase (Ad-Hoc, 2012). To improve energy savings, both technological and behavioural options are necessary (Barrett et al., 2008). The thesis approach focuses on integrating technological improvements into existing buildings retrofits.

3 What are the design principles to improve the energy performance of existing buildings?

To improve the energy demand of an existing building, three steps are possible, according to the Trias Energetica concept (Koebel et al., 2010): firstly, preventing the use of energy; then, using sustainable, renewable energy sources as widely as possible; finally, if there still remains an energy demand, using fossil fuels as efficiently as possible. Within the Trias Energetica concept, there are two courses of action to be taken during refurbishment. Passive measures are based on principles exploiting the design and properties of the building envelope to minimise or maximise heat loss and heat gain respectively, thus reducing the energy demand. The objective is to avoid heat flow, which is achieved with high thermal resistance and air-tightness of the building envelope, using solar heat gains in the winter and avoiding overheating by blocking or removing heat gains. In addition to passive ones, active measures are used, including systems for conditioning the building, producing and distributing the energy needed to achieve occupants' comfort.

The thesis focuses on passive measures of building envelope retrofitting, which is the first step to reduce the energy demand. In existing buildings the implementation of these principles poses some additional challenges, as many of the parameters that determine the performance, such as construction properties, openings size and orientation already exist and cannot always be modified. These challenges make energy conscious design decisions even more important.

4 What strategies and retrofitting measures are applied in current refurbishment practice?

Refurbishment is already an acknowledged issue in the building industry. The total turnover of major repairs, renovation, adaptation and redevelopment has been growing over the last two decades, recently accounting for more than that of new construction (Flourentzou et al., 2001; Genre, 1996; Thomsen, 2010). The building industry, including architects, constructors, material manufacturers etc., is already busy upgrading existing buildings. Besides the building industry, institutions, such as the BPIE (Building Performance Institute Europe), and regulatory bodies, such as the European Commission, have been researching the potential of refurbishment to upgrade the energy efficiency of the building stock and the resulting savings in CO_2 emissions, reporting possible savings up to 90% by 2050. To achieve those savings, deep renovation with energy savings between 60% and 90% is necessary, while superficial renovations, on the other hand, significantly increase the risk to miss the climate targets and huge absolute savings to remain untapped (Hermelink & Müller, 2011). A deep renovation typically adopts a holistic approach, viewing the renovation as a package of measures working together.

In this context, the toolbox approach proposed that the refurbishment strategy should integrate all components of the building envelope, where heat losses occur, which comprise the thermal envelope. The thermal envelope does not always coincide with the building envelope, as it depends on the spaces design and function, determining the components adjacent to spaces with temperature difference. The key components are the external walls, windows, balcony, roof and ground floor. Therefore, the toolbox matrix organises refurbishment measures according to those components. Selecting measures to upgrade each component results in integrated refurbishment of the thermal envelope, which is the recommended strategy to reach the required savings in energy.

The solution for each component includes three levels of decisions that are interconnected with each other: refurbishment strategies, material and component retrofitting measures. The strategies, named after the type of intervention, are "replace", "add-in", "wrap-it", "add-on" and "cover-it". They were determined based on examples in current refurbishment practice. Each category presents several variations in the type of intervention, which has, however, the same principles in common, determining also the result in the building performance. Combinations of strategies might be encountered.

The second decision level is the materials that are used in the construction. The materials discussed in the thesis are the ones mostly relevant to energy upgrade and particularly passive design principles. They can be categorised as insulation, glazing, window frames, sealants and cladding/ finishing. Those materials are used in the building envelope components' retrofitting measures. Every measure detailing includes several materials categories. For example, when replacing the window decisions on the glazing and frame material need to be made, together with the sealant for the wall fixing, the position of the frame in relation to the wall insulation and cladding etc. On the other hand, the same measure, e.g. wall insulation, can be applied with different insulation material and the choice varies in each specific case, based on the material properties, price, ease of application, or even environmental consideration. For this reason, the retrofitting measure is the third decision level.

5 When are decisions made during the design process of refurbishment strategies and how can they be supported?

Refurbishment is a necessary action to improve the condition of the residential building stock, together with the living conditions of the population, while considerably reducing the current energy demand and the respective CO_2 emissions. To create and realise successful refurbishment strategies, effective design is necessary. The refurbishment project process can be divided in five phases, as shown in Figure 5.1. The pre-design phase (Phase 1) is when the requirements are defined, usually by the building owner in consultation with the architect and other experts. The design has two phases: the concept and the final design. During the concept design (Phase 2), possible scenarios are identified and evaluated in order to select the scenario to be further developed in the final design phase (Phase 3). The next two phases refer to the design execution and the final refurbished building.

The interest of the present thesis lies on the first three phases, as they are more influential for the energy upgrade. More than 80% of the building performance, both in terms of energy savings, generation and cost, is set during this stage (Ad-Hoc, 2012). The early design phases are very important, as decisions taken during this stage can determine the success or failure of the design. The design decisions made earlier can have bigger impact with lower cost and effort.

Given that refurbishment is already extensively researched, as well as practiced, it is understandable that tools to support the process already exist. Nevertheless, an analysis of several tools has identified problem in the level of performance feedback in relation to a specific design phase (Riether & Butler, 2008). The ideas-generation phase is iterative and comparative. Most existing tools do not emulate this process and focus on post-design evaluation. Moreover, only 1% of these tools targets architects during the early design phases, while architects consider these tools non-user-friendly and are reluctant to integrate them into the early design phase of high performing buildings (Attia et al., 2012).

To improve the design process, the Façade Refurbishment Toolbox was developed focusing on the architect. Refurbishment is addressed as a design issue that varies in every case. The proposed approach aimed at supporting the decision-making and enabling the development of refurbishment strategies in different cases and for different specifications, without limiting or dictating designers' choices. Taking into account the freedom of the designer, an effective rating must not punish design components, or judge whether one system is better than another, but assess the quality in each case. The design process can be supported and improved by enabling the designers of refurbishment project to know at the early stages of the design, the impact their choices will have.

6 How can the different measures be organised and quantified?

Since the goal of an integrated refurbishment is improving all components of the building envelope where heat loss occurs, the different retrofitting measures are organised according to the component they address. Apart from organising the retrofitting measures, information to evaluate and compare them is needed. To this end the measures are quantified, according to energy saving, in comparison with the existing building energy demand, prior to the application of the measure. To quantify this effect, dynamic simulation is used.

The measures are quantified in terms of heating energy demand. This is the energy needed to balance the heat losses in order to maintain the required temperature. As a large part of heat losses are through the building envelope components, the retrofitting measures reduce these losses and, hence, the energy demand. The energy need is supplied by the heating system, which converts and distributes the delivered energy. The primary energy demand, which is essential to appreciate the environmental impact, is the delivered energy multiplied by primary energy factor (PEF). Replacing the existing system with one of higher efficiency will result in additional savings in delivered and primary energy demand than the savings in heating energy demand already suggested by the toolbox calculation. To estimate the savings in primary energy, however, it is then necessary to consider the fuel type or the energy mix, with the respective PE factor, as well as the system efficiency. This information is specific for each building and it cannot be generalised in the toolbox data.

Uncertainties are bound to manifest when predicting future energy consumption, as it involves predicting future user's behaviour. The actual operation can differ significantly from the simulated, resulting in different actual energy demand than predicted (Haas et al., 1998; Hens et al., 2010). For this reason, it is very difficult to calculate a specific, reliable number for the real energy demand. Expressing the improvements on building performance as a percentage of reduction in the current energy demand has the advantage of tackling the uncertainties of the simulation, assuming that the usage patterns will not change significantly. Even though this may not always be the case, the comparison of the demand before and after, expressed in a percentage, is still indicative of the improvement that can be applied in different buildings with similar characteristics. Most importantly, it gives an assessment and comparison for the different measures quality.

The assumptions used as input in the calculations were based on European standards, such as EN15251 (2007). They were regarding ventilation, heating and cooling user thermal comfort criteria, as well as values for internal gains and occupancy. Based on the inputs, the building thermal performance was simulated on an hourly basis, throughout the year and gave results on the energy demand of the modelled building and the internal temperature. The toolbox quantification aimed at results that can be comparable, the simulation settings were kept as much as possible fixed when simulating different measures. This means that the performance of each measure can be further optimised, if a high-resolution simulation, to predict more detailed performance, was required. This was, however, beyond the scope of the approach.

Considering the above issues, it becomes clear that the quantification aimed at giving an indication of the possible reduction, which can serve to give an understanding to the quality and potential of measure application. Moreover it can be used for a rough payback calculation, as it can be easily converted into expenditure savings when considering the current energy bill. Nevertheless, it needs to be accepted that the numbers are an indication of the energy reduction.

The methodology followed to quantify the retrofitting measures included simulation of existing building types variations. Subsequently, the effect of each measure on energy reduction was assessed by simulating the energy demand after the measure application. The numerical output of the toolbox quantification is presented in overviews, such as the ones of Figure 5.19 and Figure C.1, and is included in tables in Appendix C. Based on the process described in Chapter 8, the information can be used to estimate the potential savings in specific buildings that are considered for refurbishment, in order to support the strategy design process.

7 What are the key points during the design to consider the energy saving potential?

An important outcome of the calculations is that every building is different, resulting in different energy saving potential. Apart from the existing building's condition and possible energy savings, every refurbishment project is different as far as specifications are concerned. Those parameters determine the decisions that shape the refurbishment strategy. As part of the toolbox approach objective to support the design process, the key considerations and the influence of the toolbox is highlighted.

The key points, as they appear during five case study buildings refurbishment strategy development are the building existing condition, the possibility to change the external appearance, the building programme, the energy savings, the investment level and the generation of energy. Those key points cover a wide range of considerations, depending on each project. The sequence of the key points is not linear and it is often iterative, as decisions and considerations influence each other.

The Façade Refurbishment Toolbox supports this process, by means of options organisation. It does not provide ready-made solutions, as the architects and the design team in general have to translate the specifications into design decisions. The toolbox approach supports these decisions by offering the possibility to organise and compare retrofitting measures according to the key considerations.

8 What type of information do refurbishment stakeholders find useful to support the decision-making?

The final part of the approach development is its validation. Building industry experts, designers and stakeholders were interviewed to give feedback on the qualitative assessment of the approach usability. The respondents were selected on the basis of their experience in refurbishment decision-making. Apart from designers, who are the main target of the approach, housing association and renovation constructors were included as validating parties.

Investment and financial business plans, balancing the cost with benefits, was reported as the most influential for the decision of retrofitting measures, particularly from the point of view of the owners. The cost of the measures and payback time in relation with the savings was therefore regarded as the most valuable information to support the decision. The direct relation of energy savings and living cost results in the stakeholders being more aware of the need to integrate the energy performance in their decisions, than architects. Housing companies and refurbishment consultants are already using tools to get early indicators of performance, while architects mostly rely on their experience and general knowledge. In this context, the approach's focus on architects was justified.

Both designers and stakeholders have found the energy saving potential and the level of information provided by the approach useful information, not only during their own decision-making, but also in their argumentation within the project team and the client. The approach provided a general, but clear idea of the effect of different measure, by quantifying measure impact on energy demand. The integration of measures' cost was recommended as further development of the toolbox. Additional consideration that influence the decisions, particularly form the architects perspective, included the improvement of the building's function and appearance, the flexibility of the solution to be adjustable to occupants needs and the preservation of the existing value of the building. These considerations can be addressed by the key points composing the roadmap. The toolbox information can support the decision, integrating the energy savings to the project specifications.

§ 9.3 Recommendations for further development

The present thesis proposed the Façade Refurbishment Toolbox as an approach to integrate the energy upgrade potential into the early design decision-making process. Ensuring future usability of the approach depends on more parameters, such as accessibility of the information, willingness of the practitioners, user interface etc. The information already provided by the approach has the potential facilitate designers to make informed and energy-conscious decisions, as found during the validation interviews. However, further development of the approach, incorporating additional information and aspects, would support the decision-making process and extend the approach usability even further.

First of all, the research had set certain boundary conditions for the approach development. Expanding the approach beyond these boundaries would enlarge its applicability. Particularly, the approach focuses on one climatic zone, the north-west European climate, aiming at limiting the parameters that influence the energy consumption and the toolbox complexity. The concept behind the approach can support refurbishment decision-making in other climatic zones, but in order to be applicable additional research is needed. The toolbox matrix could be modified to include measures that are common in other countries and most importantly the numerical output of the tools quantification would be different. To this end, additional simulations need to be executed, including weather data of the climate under consideration as inputs.

Moreover, space heating demand was used as the indicator for building energy performance, as it accounts for the largest percentage of energy consumption in buildings. Nevertheless, other loads, such as water heating and lighting, are responsible for energy consumption as well. A further development of the toolbox would be to evaluate and estimate the effect of retrofitting measures on the total energy demand of the dwelling. This can be further improved by quantifying the primary energy savings for the different heating and ventilation sources, which are already included in the toolbox matrix. However, these calculations require detailed information of building systems, which is beyond the scope of the present thesis, which focuses on the building envelope.

Currently, the Façade Refurbishment Toolbox provides information of separate retrofitting measures for each building envelope component and estimates their impact on energy demand reduction, in order to enable comparing the possibilities and facilitating the decision. Nevertheless, the refurbishment strategy has to combine measures for all components and offer an integrated solution. Chapter 6 has demonstrated relevant measures combination applied on the case studies. Further development of the approach can elaborate on the measures combinations and, most importantly, extend the quantification to the integrated strategies.

The investment for the refurbishment has been reported as a decisive factor in literature studies and during the approach validation. Therefore, the cost and payback time of a measure is information that can support the refurbishment decision-making process. The toolbox information about energy savings is the first step to estimate the investment payback. Even though the cost of a measure is difficult to be assessed in a generic way, as the approach assesses energy savings, further research should try to address the range of the investment and the relation to energy savings.

Finally, further development of the Façade Refurbishment Toolbox should incorporate the toolbox information in a user-friendly, easily accessible interface. The steps described in Chapter 8, together with the pre-calculated data on energy reduction found in Appendix C should be integrated into the interface, thus automating the tools overview generation, once the respective information of each building is filled in. The decision can be further supported by the addition of information of each strategy, measure and material, such as discussed in Chapter 4, along with visualisation and detailing of measure. Such information can be more appealing to and helpful for architects.

§ 9.4 General discussion

Besides the separate conclusion on the sub-questions the research set off to answer, the main outcome of the research is the Façade Refurbishment Toolbox information. The information has two aspects, the organisation of available measures and their quantification and comparison. First the systematic compilation of retrofitting measures, organised in a matrix, can support recognising the available options, support the choice of some or reject others, according to the different parameters and key considerations. Furthermore, the approach has calculated the energy reduction related to each measure application, quantifying them according to their efficiency.

The objective of the Façade Refurbishment Toolbox is to support designers and other refurbishment stakeholders to integrate the energy upgrade potential into the early phase of the refurbishment strategy development. Therefore, further applicability of the approach was a starting point when answering the research question. Not only the approach development, but also its validation was generated by investigating and applying building envelope retrofitting measures in different buildings. In this way the applicability of the approach in future refurbishment projects was demonstrated.

Furthermore, the Façade Refurbishment Toolbox is valuable for architects' education. The architecture students that implemented the approach on their design project were influenced by the potential energy reduction. The earlier in the design process they were provided with the information, the more they were swayed towards measures with higher energy savings. Even if the most efficient measure was not always chosen, the potential energy saving was used along with other considerations as additional arguments to support their design decisions.

The approach objective is neither to generate ready-made solutions nor to suggest one that is optimal from the energy point of view alone. Given the wide range of combination of measures and the parameters that vary in every project, the approach aims at incorporating energy savings as a factor that facilitates and supports the design. In this way, architects can get used to take the energy performance, together with the numerical output of the toolbox information, into account in their decision-making process.

Residential building refurbishment is not only about the technical aspects, but most importantly about the people that use and enjoy the dwellings. The refurbished building has to be an attractive solution, so that they are willing to undertake the effort and expense to upgrade their existing dwelling. The role of the architect to increase both rate and depth of renovation is thus important. Architects, in collaboration with the rest of the stakeholders, have the potential to design refurbishment strategies that improve the energy performance, while at the same time result in a more agreeable living environment, in terms of comfort, functionality and aesthetical value. To this end, the toolbox approach focuses on supporting the architects and the design process. It provides design solutions that go beyond general guidelines and enables informed and responsible design decisions, resulting in better and more effective refurbishment strategies.

Designing is deciding. Knowledge and information can lead to better understanding of a decision consequence and, therefore, result in better design solutions. Different buildings have different energy saving potential. They also have different specifications, performance requirements and design ambitions. All these parameters result in different refurbishment strategies. The aim of the proposed approach is not to replace the design process and generate a solution, but to support the process by providing information to lead to responsible and knowledgeable decisions. In this way refurbishment strategies can be designed that take into account the building improvement, occupants comfort and efficient energy use, contributing to the greater goals of society's decarbonisation and sustainable development.

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Definitions

The terms' definitions are presented in alphabetical order and the chapter where encountered is mentioned. The specific terms have been used in several places throughout the thesis. The chapter mentioned is where they are encountered first, or where the importance of the meaning is more relevant.

Approach, also often referred to as "the toolbox approach" and "Façade Refurbishment Toolbox (FRT)": the method developed in this thesis to answer the research question. It includes they systematic organisation of refurbishment measures, the quantification of their impact on energy demand reduction, the development of a roadmap to indicate when the information can be useful during the design process and guidelines on how the specific options quantification for each building can be provided, based on pre-calculated models (introduced in Chapter 5).

Building envelope: The space enclosing components. The building envelope does not necessarily coincide with the load-bearing structure. In the discussion and the title of the thesis, the terms of building envelope and façade are used interchangeably.

Integrated refurbishment: The refurbishment strategy that integrates all the different building components, comprising the thermal envelope. (Chapter 2, section 2.5.2, Chapter 4, section 4.1 , Chapter 5)

Key points: Consideration, parameters, aspects that take into account the building condition, project requirements etc. (Chapter 6)

Materials: The physical elements or substances of which something is composed. Building materials determine the qualities and performance of the building. In the context of the thesis, the materials are used to realise the respective retrofitting measures. (Chapter 4)

Models or building types: the simulated building, set up to resemble a real situation, with regard to geometrical characteristics, construction, location, etc. In the thesis methodology to quantify retrofitting measures, theoretical models of existing buildings are set up that vary in the characteristics of the building envelope construction. Thereby, each model is referred to as a set of parameters and used to further determine the energy reduction potential, based on these specific characteristics. (Chapter 5)

Performance: The manner of the efficiency with which something reacts or fulfils its intended purpose. In the building context, performance can refer to various aspects, such as technical, functional, social, aesthetical, etc. Within the scope of the thesis, performance refers mostly to the energy use of the building and its energy efficiency as a system, in the sense of minimal losses in the use of energy. Moreover, the building performance often refers to comfort of the occupants, as the intended purpose of the building's function.

Refurbishment strategy: The total intervention in the building, including upgrade, replacement, or addition of components. (Chapter 4)

Retrofitting measure: The task of upgrading or replacing existing components or the construction of new. In this thesis, the retrofitting measures are organised according to the component they address (Chapter 4).

Thermal envelope: The components where heat losses occur. They are the enclosing elements between a conditioned space and an unconditioned or exterior space. The thermal envelope does not necessarily coincide with the building envelope

List of abbreviation

ACH	Air change per hour
BIPV	Building integrated Photovoltaic
BPIE	Building Performance Institute Europe
BPS	Building Performance Simulation
DHW	Domestic Hot Water
DSF	Double Skin Façade
EIFS	Exterior Insulation and Finishing Systems
EPBD	European Directive on the Energy Performance of Buildings
EPC	Energy Performance Certificate
EU	European Union
FRT	Façade Refurbishment Toolbox
HVAC	Heating Ventilation Air Conditioning
Low-E	Low Emissivity coating
nZEB	Nearly Zero-Energy Building
PV	Photovoltaic
RES	Renewable energy sources
SF	Second Façade
uPVC	Unplasticized polyvinyl chloride
U-value	Thermal transmittance coefficient
WCED	World Commission on Environment and Development
WWII	World War II
WWR	Window-wall ratio

Appendix A Construction types for building envelope components

Appendix A presents the typical construction of the building envelope components. The information are based on literature review of several sources (Andeweg et al., 2007; Giebeler, 2009; Loga et al., 2005; TABULA, 2010). According to this information, the construction techniques classification of Table 2.2 was developed, as well as the existing building types models used in Chapter 5, shown in Table B.1.

The time period assigned to each construction is indicative, based on the periods described in Table 2.1. The periods can vary in different countries, relating to construction tradition and legislative standards introduction. Moreover, several types and technologies co-existed in the same periods.

The thermal transmittance coefficient U-value indicated in the tables is typical for the respective construction, obtained from Loga et al. (2005). More precise values depend on the specific construction.

Construction type	Sub-categories	Description	Time period	U-values (W/m^2K)
Massive construction (masonry, concrete)	Loadbearing masonry	Masonry of solid brick or stone, 250-400mm	<1950	2.0-1.7
	Cavity wall	Two leaves of masonry with intervening air cavity	1920-1950	1.5
	Cavity wall	Two leaves with intervening air cavity. Inner leaf with lightweight masonry units. Sometimes insulation in cavity 30-150mm	1950-today	1.1-0.5
	Lightweight concrete blocks,	Lightweight masonry units, often cladded with additional layer	1950-1975	1.4
	Perforated bricks	Perforated brick masonry	1950-today	1-0.8
	Precast concrete panels	Prefabricated concrete panels, sometimes with insulation 50mm	1950-1975	1.1-0.9
Lightweight construction	Wooden frame	Timber-frame structure with brick or watt-le-and-daub filling	<1920	2
	Timber frame panels	Timber-frame structure with insulation infill, boxed in cardboard/plasterboard	1950-today	1.1-0.5 (varying insulation thickness)
	Façade panels, aluminium frame panels	Sandwich panels consisting of plasterboard and insulation 6mm	1950-today	

Table A.1
External wall construction types classification

Glazing type	Sub-categories	Time period	U-values (W/ m^2K
Single glazing, g=0.87 (Ug=5.8)	Wooden frame,	<1975	5
Double glazing panes, g=0.75 (Ug=2.8)	Aluminium frame without thermal break	1975-1990	4.3
	Aluminium with thermal break	1990-Today	3.2
	Plastic frame	1975-Today	3
	Wooden Window, box-windows	<1990	2.7
Double glazing, insulation g=0.75 (Ug=1.1)	Improved plastic or aluminium frame (Uf=2 W/m2K)	>1990	1.9
	Wooden frame	>1990	1.6
Triple insulation glazing g=0.6 (Ug=0.7)	Improved Wooden frame (Uf=1.5 W/m2K)	>1990	1.2
	Passivhaus windows Uf=0.8 W/m2K	>1990	0.9

Table A.2

Window construction types classification

Construction	Sub-categories (layers under roof finishing, eg. ceramic tiles)	Description	Time period	U-values (W/ m^2K)
Wood construction (esp.pitched roofs)	Wooden beam ceiling	Plaster, wood-wool boards, rafters, sheeting, Counter battens, roof covering	<1975	0.8
	Prefabricated or timber ceiling with insulation	Plaster, plaster background, timber joists, floorboards	1975-1990	0.6
	Plaster-covered, no insulation in cavity	Plaster, wood-wool boards, rafters, sheeting, Counter battens, roof covering	<1950	2.6
	Wood fibre plates, plastered		1920-1975	1.4
	50-160 mm insulation between rafters		>1950	1.0-0.3
Massive construction (esp. Flat roofs)	Reinforced concrete slab	Plaster, 130-160mm reinforced concrete slab, screed	1920-1975	2.1
	Hollow-core slab	Steel or concrete frame, precast, pre-stressed slab, screed		
	Concrete slab with insulation on top	Plaster, 130-160mm reinforced concrete slab, 20-40mm insulation, screed	1950-1975	1.3
		Plaster, 180mm reinforced concrete slab, 60-80 mm insulation, bitumen, gravel	1975-1990	0.5

Table A.3

Roof or top floor ceiling construction types classification

Construction	Sub-categories	Time period	U-values (W/ m2K)
Wood construction	Wooden beams construction	<1920	1.0
	Timber slab with secondary floor construction and gravel	<1975	0.8
Massive construction	Stone base on the ground	<1920	2.9
	Stone vault construction	<1948	1.2
	Reinforced concrete slab	1950-1975	1.5
	Hollow-core slab		
	Concrete slab with 2-4-5cm insulation on top	>1975	1.0-0.6

Table A.4

Ground floor construction types classification

Appendix B Existing buildings' simulation

external wall	U-values (W/m²K)	Window	U-values (W/m²K)	Roof	U-values (W/m²K)	Ground floor	U-values (W/m²K)	Balcony	U-values (W/m²K)
Masonry of solid brick or stone, 250-400mm	1.7	Single glazing, g=0.87	6.2	Pitched roof, Timber rafters, no insulation in cavity	2.5	Rein-forced concrete slab	2	Rein-forced concrete slab	2
Two leaves of masonry with air cavity (30-50mm)									
Cavity. Inner leaf with lightweight masonry units	1.0	Double glazing, g=0.75	3.2	Flat roof, plaster, 130-160mm reinforced concrete slab, 20-40mm insulation, screed	0.8				
Perforated brick masonry									
Prefabricated concrete panels, insulation 50mm									

Table B.1

Original construction variations groups

Apartment Types	Position	Floor
T1	Mid	G
T2	Mid	Mid
T3	Mid	Top
T4	Corner	G
T5	Corner	Mid
T6	Corner	Top

Table B.2

Apartment types, according to position in the building

	construction	apartment type	WWR	orientation	total nr of models
models variation	M1	T1	30%	North South West East	
	M2	T2			
	M3	T3			
	M4	T4	60%		
	M5	T5			
	M6	T6			
nr	6	6	2	4	288

Table B.3

Model variation and total number of existing building models to be simulated

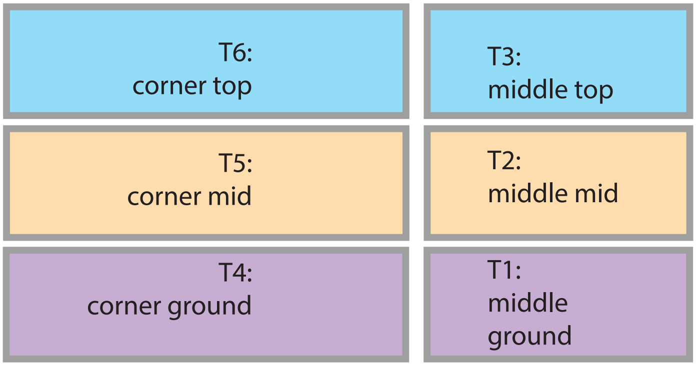

Figure B.1
Apartment types in the building, according to their position

Position of the apartment

Table B.4 presents which apartment types are compared and how percentages regarding the difference in energy demand are calculated. Percentages of all building types are presented in Table B.5 till Table B.7. The percentages in Figure B.1, Figure B.2, Figure B.3, are the averages of all building types, based on the average heating demand of all orientations apartment.

	Mid to corner		Top to middle	Ground to middle
ground	(T4-T1)/T4	corner	(T6-T5)/T6	(T4-T5)/T4
middle	(T5-T2)/T5	middle	(T3-T2)/T3	(T1-T2)/T1
top	(T6-T3)/T6			

Table B.4
Comparison of apartment with regard to position

WWR	floor	M1	M2	M3	M4	M5	M6
30%	ground	26%	28%	21%	22%	21%	22%
	middle	28%	33%	26%	28%	26%	27%
	top	6%	9%	4%	7%	9%	10%
60%	ground	25%	28%	21%	22%	21%	22%
	middle	30%	33%	25%	27%	26%	28%
	top	4%	9%	2%	6%	7%	10%

Table B.5
The percentages of difference in heating demand of the middle to corner apartments

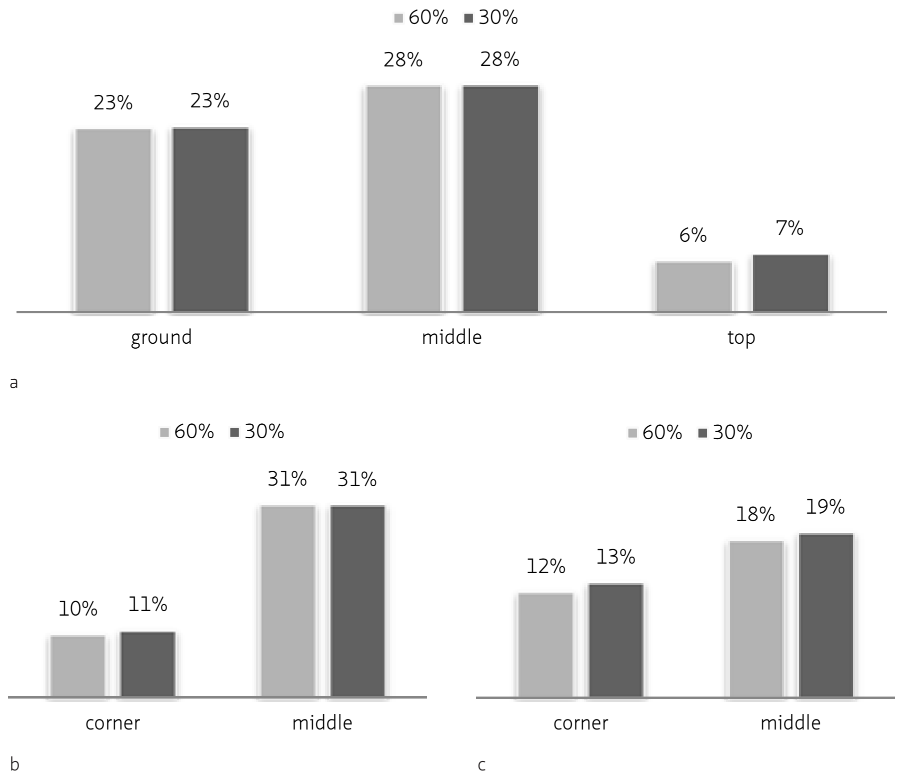

Figure B.2
(a) Percentage of heating demand of the corner to middle apartments, with regard to their vertical position. Average for all building types
(b) Average percentage of heating demand of top to middle apartments, with regard to their horizontal position
(c) Average percentage of heating demand of ground to middle apartments, with regard to their horizontal position

WWR	horizontal position	M1	M2	M3	M4	M5	M6
30%	corner	14%	13%	17%	19%	2%	5%
	middle	34%	36%	36%	37%	21%	22%
60%	corner	9%	14%	14%	20%	1%	4%
	middle	33%	37%	35%	38%	20%	23%

Table B.6
The percentage of lower heating demand of middle to top apartments

WWR	horizontal position	M1	M2	M3	M4	M5	M6
30%	corner	15%	12%	13%	14%	14%	17%
	middle	17%	19%	18%	20%	19%	22%
60%	corner	10%	11%	12%	14%	13%	14%
	middle	16%	18%	17%	20%	18%	21%

Table B.7
The percentage of lower heating demand of middle to ground apartments

Window-to-wall ratio

Horizontal	floor	M1	M2	M3	M4	M5	M6
Middle	ground	-1%	5%	-3%	3%	-3%	3%
	middle	-2%	5%	-4%	2%	-4%	2%
	top	-1%	3%	-3%	2%	-4%	2%
Corner	ground	1%	5%	-2%	3%	-2%	3%
	middle	-4%	4%	-4%	3%	-4%	0%
	top	1%	3%	-1%	2%	-2%	2%

Table B.8
The percentages of differences in heating demand of apartments with 30% to apartments with 60% WWR

Construction

External wall

			M1 to M3	
Apartment type	Floor	Position	WWR 30%	WWR 60%
T1	ground	MIDDLE	9%	7%
T2	middle	MIDDLE	10%	8%
T3	top	MIDDLE	8%	6%
T4	ground	CORNER	14%	12%
T5	middle	CORNER	13%	13%
T6	top	CORNER	9%	8%

Table B.9
The percentage of lower heating demand of building with lightweight block wall (M3) to masonry wall (M1)

Window

			M1 to M2	
Apartment type	Floor	Position	WWR 30%	WWR 60%
T1	ground	MIDDLE	10%	16%
T2	middle	MIDDLE	12%	18%
T3	top	MIDDLE	9%	13%
T4	ground	CORNER	8%	12%
T5	middle	CORNER	6%	13%
T6	top	CORNER	7%	9%

Table B.10
The percentage of lower heating demand building with double (M2) to single glazing (M1)

Roof

			M4 to M6	
Apartment type	Floor	Position	WWR 30%	WWR 60%
T1	ground	MIDDLE	0%	0%
T2	middle	MIDDLE	2%	1%
T3	top	MIDDLE	21%	21%
T4	ground	CORNER	0%	0%
T5	middle	CORNER	3%	1%
T6	top	CORNER	18%	17%

Table B.11
The percentage of difference in heating demand between building with pitched (M4) and flat roof (M6)

Orientation

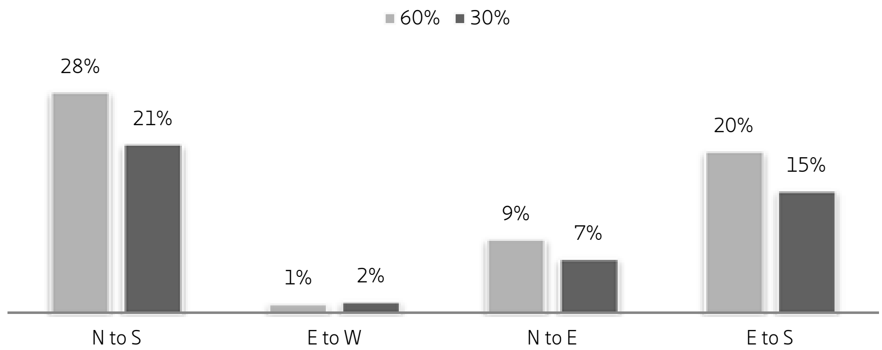

Figure B.3
Orientation comparison, average of all building types

WWR	Orientations compared	M1	M2	M3	M4	M5	M6
30%	N to S	20%	20%	21%	20%	22%	23%
	E to W	4%	2%	1%	1%	1%	1%
	N to E	6%	6%	7%	7%	8%	7%
	E to S	15%	14%	15%	15%	16%	17%
60%	N to S	26%	26%	27%	27%	29%	29%
	E to W	2%	2%	1%	1%	1%	1%
	N to E	9%	8%	9%	9%	10%	10%
	E to S	19%	19%	20%	20%	21%	21%

Table B.12
The percentage of difference in heating demand between different orientation

Appendix C Toolbox options simulation results

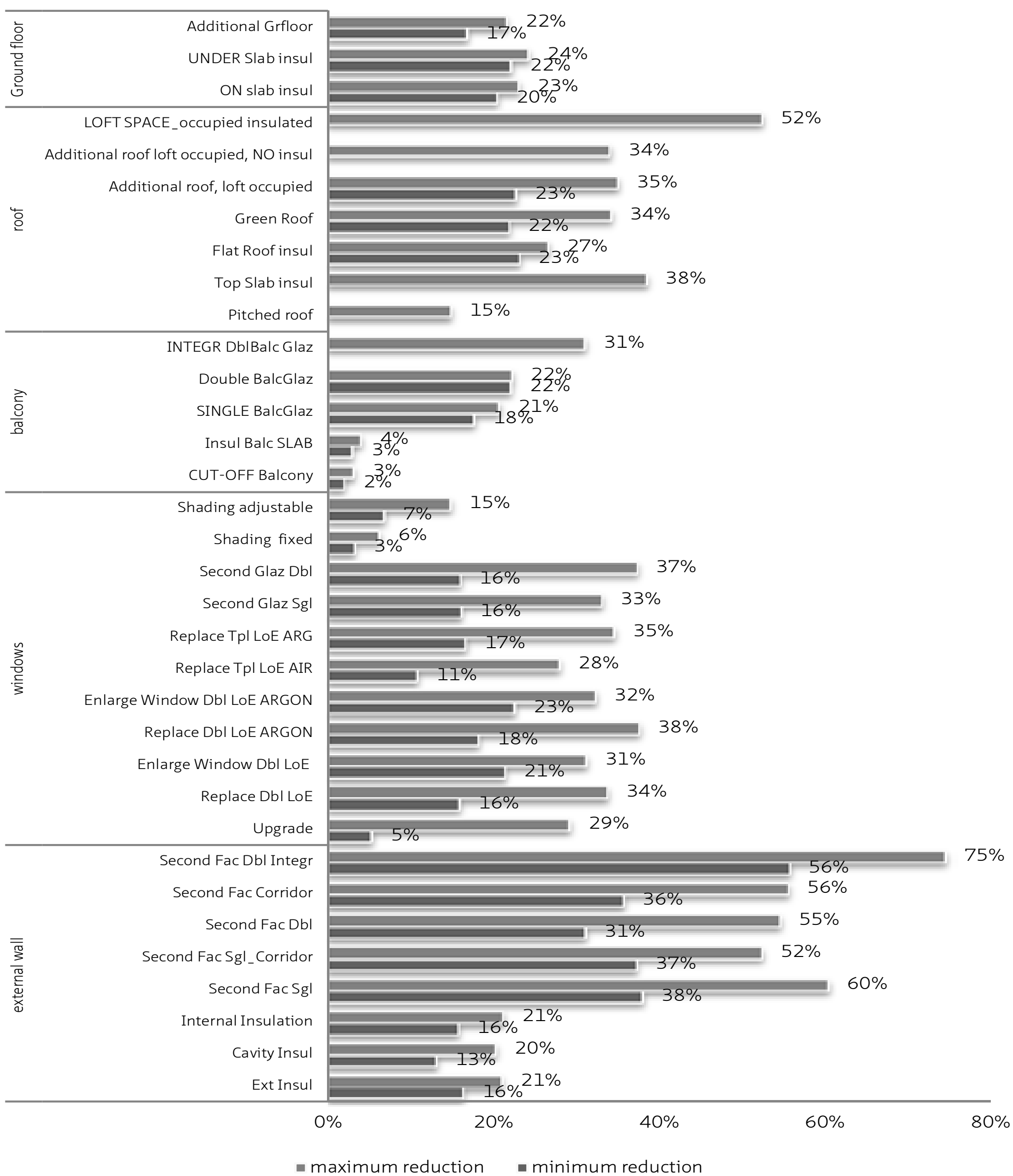

Figure C.1

Overview of maximum and minimum heating energy demand reduction for each retrofitting measure, average for all orientation

External wall

	Measure	Calculated option	Simulated material	U-value (W/m2K)
Existing construction	Masonry/ cavity wall no insulation	Masonry wall	Masonry of solid brick or stone, 320mm	1.7
	Lightweight concrete/hollow brick, no insulation	Lightweight concrete blocks	Lightweight masonry units (0.25m), cladded brick layer (0.1m).	1.1
	Cavity wall or pre-fab panels with little/outdated insulation			
Retrofitting measure	Cavity insulation	Cavity Insul	Existing wall-inner leaf Polyurethan foam insulation 0.05m Existing wall-outer leaf	0.38
	Internal insulation	Internal Insul	Plasterboard Rockwool insulation 0.2m Existing wall	0.2
	Exterior Insulation and Finishing Systems (EIFS)	Ext Insul	Existing wall Rockwool insulation 0.2m Plaster	0.2
	Ventilated façade			0.2
	Timber-frame wall			0.2
	Second Façade/ Single glazing	Second Faç Sgl Cavity	Cladding with single glazing, 0.60m away from the existing wall. Aluminium frame structure. Thermal buffer, unheated zone.	4.3
		Second Faç Sgl Corridor	Single glazing, 3mm LowE coating, 1.5m away from the existing wall. Aluminium frame structure. Thermal buffer, unheated zone.	
	Second Façade/ Double glazing	Second Faç Dbl Cavity	Double glazing, 3/13mm LowE coating, 0.6 m away from the existing wall. Aluminium frame structure. Thermal buffer, unheated zone.	2
		Second Façade Dbl glazing Corridor	Double glazing, 3/13mm LowE coating, 1.5 m away from the existing wall. Aluminium frame structure. Thermal buffer, unheated zone.	
spatial interventions	Additional space/ Second façade integrated	Second Facade Dbl glazing Integrated Cavity 150cm	Double glazing, 3/13mm LowE coating, 1.5 m away from the existing wall. Aluminium frame structure. Existing wall removed. Merged with heated zone.	2
	Lift addition per porch	Second Façade (details depending on specific design of the solution)		n/a
	Lift addition per block (access through gallery)			n/a

Table C.1
Overview of simulated existing construction and retrofitting measures for external walls

Building type model	Apartment type	WWR		overheating	
M1	T2	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overhe-ating
Existing building (Masonry)	N	275	*0%*	29,00	0%
	S	209	*0%*	79,00	1%
	E	250	*0%*	81.00	1%
	W	253	*0%*	93,00	1%
Cavity Insul	N	224	*18%*	32	0%
	S	170	*19%*	80	1%
	E	204	*19%*	82	1%
	W	206	*18%*	98	1%
Internal Insul	N	203	*26%*	38	0%
	S	153	*27%*	82	1%
	E	184	*26%*	87	1%
	W	187	*26%*	103	1%
Ext Insul	N	203	*26%*	25	0%
	S	154	*27%*	68	1%
	E	184	*26%*	71	1%
	W	187	*26%*	89	1%
Second Fac Sgl cavity	N	119	*57%*	49	1%
	S	77	*63%*	89	1%
	E	100	*60%*	91	1%
	W	103	*59%*	92	1%
Second Fac Sgl Corridor	N	140	*49%*	35	0%
	S	97	*54%*	67	1%
	E	120	*52%*	69	1%
	W	124	*51%*	65	1%
Second Fac Dbl cavity	N	132	*52%*	43	0%
	S	90	*57%*	84	1%
	E	115	*54%*	82	1%
	W	117	*54%*	91	1%
Second Fac Dbl Corridor	N	129	*53%*	21	0%
	S	90	*57%*	82	1%
	E	113	*55%*	83	1%
	W	115	*54%*	97	1%
Second Fac Dbl Integr	N	59	*78%*	49	1%
	S	59	*72%*	199	2%
	E	89	*64%*	162	2%
	W	50	*80%*	141	2%

Table C.2
Overview of wall options for model M1 typical middle apartment, for all orientation, WWR 30%

Building type model	Apartment type	WWR		overheating	
M1	T2	60%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overhe-ating
Existing building (Masonry)	N	289	*0%*	59	1%
	S	200	*0%*	158	2%
	E	259	*0%*	153	2%
	W	260	*0%*	168	2%
Cavity Insul	N	224	*22%*	32	0%
	S	170	*15%*	80	1%
	E	204	*21%*	82	1%
	W	206	*21%*	98	1%
Internal Insul	N	230	*20%*	68	1%
	S	156	*22%*	192	2%
	E	201	*22%*	176	2%
	W	207	*20%*	199	2%
Ext Insul	N	203	*30%*	25	0%
	S	154	*23%*	68	1%
	E	184	*29%*	71	1%
	W	187	*28%*	89	1%
Second Fac Sgl cavity	N	119	*59%*	49	1%
	S	77	*61%*	89	1%
	E	100	*61%*	91	1%
	W	103	*60%*	92	1%
Second Fac Sgl Corridor	N	140	*52%*	35	0%
	S	97	*52%*	67	1%
	E	120	*54%*	69	1%
	W	124	*52%*	65	1%
Second Fac Dbl cavity	N	132	*54%*	43	0%
	S	90	*55%*	84	1%
	E	115	*56%*	82	1%
	W	117	*55%*	91	1%
Second Fac Dbl Corridor	N	129	*55%*	21	0%
	S	90	*55%*	82	1%
	E	113	*56%*	83	1%
	W	115	*56%*	97	1%
Second Fac Dbl Integr	N	59	*79%*	49	1%
	S	59	*71%*	199	2%
	E	89	*66%*	162	2%
	W	50	*81%*	141	2%

Table C.3

Overview of wall options for model M1 typical middle apartment, for all orientation, WWR 60%

Building type model	Apartment type	WWR		overheating	
M3	T2	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing building (Masonry)	N	249	*0%*	35	0%
	S	188	*0%*	81	1%
	E	226	*0%*	83	1%
	W	228	*0%*	98	1%
Cavity Insul	N	224	*10%*	32	0%
	S	170	*10%*	80	1%
	E	204	*10%*	82	1%
	W	206	*10%*	98	1%
Internal Insul	N	203	*18%*	38	0%
	S	153	*19%*	82	1%
	E	184	*19%*	87	1%
	W	187	*18%*	103	1%
Ext Insul	N	203	*18%*	25	0%
	S	154	*18%*	68	1%
	E	184	*19%*	71	1%
	W	187	*18%*	89	1%
Second Fac Sgl cavity	N	119	*52%*	49	1%
	S	77	*59%*	89	1%
	E	100	*56%*	91	1%
	W	103	*55%*	92	1%
Second Fac Sgl Corridor	N	140	*44%*	35	0%
	S	97	*49%*	67	1%
	E	120	*47%*	69	1%
	W	124	*46%*	65	1%
Second Fac Dbl cavity	N	132	*47%*	43	0%
	S	90	*52%*	84	1%
	E	115	*49%*	82	1%
	W	117	*49%*	91	1%
Second Fac Dbl Corridor	N	129	*48%*	21	0%
	S	90	*52%*	82	1%
	E	113	*50%*	83	1%
	W	115	*50%*	97	1%
Second Fac Dbl Integr	N	59	*76%*	49	1%
	S	59	*69%*	199	2%
	E	89	*61%*	162	2%
	W	50	*78%*	141	2%

Table C.4

Overview of wall options for model M3 typical middle apartment, for all orientation, WWR 30%

Building type model	Apartment type	WWR		overheating	
M3	T2	60%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overhe-ating
Existing building (Masonry)	N	268	0%	62	1%
	S	184	0%	170	2%
	E	235	0%	166	2%
	W	241	0%	185	2%
Cavity Insul	N	224	16%	32	0%
	S	170	8%	80	1%
	E	204	13%	82	1%
	W	206	14%	98	1%
Internal Insul	N	230	14%	68	1%
	S	156	15%	192	2%
	E	201	14%	176	2%
	W	207	14%	199	2%
Ext Insul	N	203	24%	25	0%
	S	154	17%	68	1%
	E	184	22%	71	1%
	W	187	23%	89	1%
Second Fac Sgl cavity	N	119	56%	49	1%
	S	77	58%	89	1%
	E	100	57%	91	1%
	W	103	57%	92	1%
Second Fac Sgl Corridor	N	140	48%	35	0%
	S	97	48%	67	1%
	E	120	49%	69	1%
	W	124	49%	65	1%
Second Fac Dbl cavity	N	132	51%	43	0%
	S	90	51%	84	1%
	E	115	51%	82	1%
	W	117	52%	91	1%
Second Fac Dbl Corridor	N	129	52%	21	0%
	S	90	51%	82	1%
	E	113	52%	83	1%
	W	115	52%	97	1%
Second Fac Dbl Integr	N	59	78%	49	1%
	S	59	68%	199	2%
	E	89	62%	162	2%
	W	50	79%	141	2%

Table C.5

Overview of wall options for model M3 typical middle apartment, for all orientation, WWR 60%

Building type model	Apartment type	WWR		overheating	
M6	T2	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing building (Lightweight concrete blocks)	N	213	0%	31.00	0%
	S	161	0%	79,00	1%
	E	194	0%	82,00	1%
	W	196	0%	95,00	1%
Cavity Insul	N	180	16%	28	0%
	S	136	16%	73	1%
	E	163	16%	75	1%
	W	165	16%	87	1%
Internal Insul	N	171	20%	35	0%
	S	131	19%	78	1%
	E	156	20%	85	1%
	W	158	19%	96	1%
Ext Insul	N	171	20%	25	0%
	S	129	20%	66	1%
	E	155	20%	74	1%
	W	157	20%	86	1%
Second Fac Sgl cavity	N	132	39%	26	0%
	S	97	34%	57	1%
	E	116	39%	59	1%
	W	118	39%	64	1%
Second Fac Sgl Corridor	N	134	38%	29	0%
	S	96	34%	61	1%
	E	117	38%	62	1%
	W	120	38%	57	1%
Second Fac Dbl cavity	N	143	34%	25	0%
	S	107	27%	55	1%
	E	127	33%	66	1%
	W	130	33%	55	1%
Second Fac Dbl Corridor	N	136	37%	21	0%
	S	100	31%	75	1%
	E	121	36%	74	1%
	W	123	37%	55	1%
Second Fac Dbl Integr	N	80	63%	53	1%
	S	83	48%	195	2%
	E	107	45%	164	2%
	W	60	69%	142	2%

Table C.6
Overview of wall options for model M6 typical middle apartment, for all orientation, WWR 30%

Building type model	Apartment type	WWR		overheating	
M6	T2	60%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing building (Lightweight concrete blocks)	N	216	0%	60	1%
	S	146	0%	155	2%
	E	190	0%	154	2%
	W	194	0%	174	2%
Cavity Insul	N	190	12%	57	1%
	S	127	13%	162	2%
	E	166	12%	161	2%
	W	165	15%	87	1%
Internal Insul	N	183	15%	64	1%
	S	122	16%	177	2%
	E	160	16%	171	2%
	W	163	16%	194	2%
Ext Insul	N	182	16%	54	1%
	S	120	18%	161	2%
	E	159	16%	162	2%
	W	162	16%	169	2%
Second Fac Sgl cavity	N	132	39%	26	0%
	S	97	34%	57	1%
	E	116	39%	59	1%
	W	118	39%	64	1%
Second Fac Sgl Corridor	N	134	38%	29	0%
	S	96	34%	61	1%
	E	117	38%	62	1%
	W	120	38%	57	1%
Second Fac Dbl cavity	N	143	34%	25	0%
	S	107	27%	55	1%
	E	127	33%	66	1%
	W	130	33%	55	1%
Second Fac Dbl Corridor	N	136	37%	21	0%
	S	100	31%	75	1%
	E	121	36%	74	1%
	W	123	37%	55	1%
Second Fac Dbl Integr	N	80	63%	53	1%
	S	83	43%	195	2%
	E	107	44%	164	2%
	W	60	69%	142	2%

Table C.7

Overview of wall options for model M6 typical middle apartment, for all orientation, WWR 60%

Window

	Measure	Calculated option	Simulated material	U-value (W/^{m}2K)
Existing construction	Single glazing	Single glazing (M1)	Single Clear, 3mm, g=0.85	6.2
	Early, double-glazing	Double glazing (M6)	Double Clear 3mm/6mm Air, g=0.7	3.3
Retrofitting measures	Upgrade window pane with Dbl LoE glazing	Upgrade	Double Low-E 3mm/13mm Air, g=0.6 Wooden frame	2
	Secondary single glazing	Second Glaz Sgl	Existing glazing Cavity 300mm Single Low-E 3mm, g=0.75	4.3
	Secondary double glazing	Second Glaz Dbl	Existing glazing Cavity 300mm Double Low-E 3mm/13mm Air, g=0.59	1.79
	Replace windows with double glazing	Replace Dbl LoE	Double Low-E 3mm/13mm Air (coating inner pane), g-0.68	1.78
		Replace Dbl LoE ARGON	Double Low-E 3mm/13mm Argon (coating inner pane), g=0.68	1.51
	Replace windows triple glazing	Replace Tpl LoE AIR	Triple Low-E 3mm/6mm Air (coating in two panes), g=0.47	0.99
		Replace Tpl LoE ARG	Triple Low-E 3mm/13mm Argon (coating in two panes), g=0.47	0.78
	Shading fixed	Shading fixed	Steel overhang 50cm	n/a
	Shading adjustable	Shading adjustable	Venetian Blinds with high reflectivity slats	n/a
Spatial interventions	Enlarged windows	Enlarge Window Dbl LoE	Double Low-E 3mm/13mm Air (coating inner pane), g-0.68	1.78
		Enlarge Window Dbl LoE, Argon	Double Low-E 3mm/13mm Argon (coating inner pane), g=0.68	1.51

Table C.8

Overview of simulated existing construction and retrofitting measures for windows

Building type model	Apartment type	WWR		overheating	
M1	T2	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing window (Singe glazing pane, wooden frame)	N	275	*0%*	29	0%
	S	209	*0%*	79	1%
	E	250	*0%*	81	1%
	W	253	*0%*	93	1%
Upgrade	N	210	*24%*	27	0%
	S	167	*20%*	66	1%
	E	193	*23%*	69	1%
	W	194	*23%*	75	1%
Replace Dbl LoE	N	199	*28%*	27	0%
	S	159	*24%*	74	1%
	E	181	*28%*	77	1%
	W	186	*26%*	73	1%
Replace Dbl LoE ARGON	N	194	*30%*	36	0%
	S	154	*26%*	74	1%
	E	176	*30%*	79	1%
	W	181	*28%*	82	1%
Replace Tpl LoE AIR	N	207	*25%*	23	0%
	S	169	*19%*	51	1%
	E	182	*27%*	52	1%
	W	193	*24%*	67	1%
Replace Tpl LoE ARG	N	195	*29%*	21	0%
	S	163	*22%*	43	0%
	E	182	*27%*	52	1%
	W	183	*28%*	52	1%
Second Glaz Sgl	N	208	*24%*	23	0%
	S	163	*22%*	51	1%
	E	190	*24%*	60	1%
	W	192	*24%*	68	1%
Second Glaz Dbl	N	208	*24%*	23	0%
	S	170	*19%*	37	0%
	E	207	*17%*	47	1%
	W	195	*23%*	56	1%
Shading fixed	N	244	*11%*	26	0%
	S	206	*2%*	54	1%
	E	228	*9%*	62	1%
	W	229	*9%*	66	1%

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Building type model	Apartment type	WWR		overheating	
M1	T2	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Shading adjustable	N	236	*14%*	28	0%
	S	186	*11%*	76	1%
	E	216	*14%*	81	1%
	W	219	*13%*	61	1%
Enlarge Window Dbl LoE	N	190	*31%*	43	0%
	S	159	*24%*	74	1%
	E	170	*32%*	120	1%
	W	171	*32%*	141	2%
Enlarge Window Dbl LoE, Argon	N	183	*33%*	36	0%
	S	127	*39%*	74	1%
	E	155	*38%*	79	1%
	W	165	*35%*	82	1%

Table C.9

Overview of window options for model M1 typical middle apartment, for all orientation, WWR 30%

Building type model	Apartment type	WWR		overheating	
M1	T2	60%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing window (Singe glazing pane, wooden frame)	N	289	*0%*	59	1%
	S	200	*0%*	158	2%
	E	259	*0%*	153	2%
	W	260	*0%*	168	2%
Upgrade	N	201	*30%*	47	1%
	S	144	*28%*	130	1%
	E	180	*31%*	128	1%
	W	182	*30%*	147	2%
Replace Dbl LoE	N	190	*34%*	43	0%
	S	159	*21%*	74	1%
	E	170	*34%*	120	1%
	W	171	*34%*	141	2%
Replace Dbl LoE ARGON	N	183	*37%*	36	0%
	S	127	*37%*	74	1%
	E	155	*40%*	79	1%
	W	165	*37%*	82	1%

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Building type model	Apartment type	WWR		overheating	
M1	T2	60%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Replace Tpl LoE AIR	N	198	*32%*	38	0%
	S	148	*26%*	91	1%
	E	179	*31%*	95	1%
	W	180	*31%*	116	1%
Replace Tpl LoE ARG	N	181	*37%*	28	0%
	S	140	*30%*	78	1%
	E	165	*36%*	78	1%
	W	166	*36%*	93	1%
Second Glaz Sgl	N	208	*28%*	23	0%
	S	119	*40%*	114	1%
	E	152	*41%*	124	1%
	W	195	*25%*	56	1%
Second Glaz Dbl	N	171	*41%*	29	0%
	S	130	*35%*	74	1%
	E	157	*39%*	80	1%
	W	156	*40%*	103	1%
Shading fixed	N	257	*11%*	45	1%
	S	205	*-2%*	79	1%
	E	235	*9%*	90	1%
	W	238	*8%*	103	1%
Shading adjustable	N	244	*16%*	49	1%
	S	176	*12%*	141	2%
	E	217	*16%*	151	2%
	W	222	*15%*	85	1%

Table C.10

Overview of window options for model M1 typical middle apartment, for all orientation, WWR 60%

Building type model	Apartment type	WWR		overheating	
M6	T2	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing window (Singe glazing pane, wooden frame)	N	213	*0%*	31	0%
	S	161	*0%*	79	1%
	E	194	*0%*	82	1%
	W	196	*0%*	95	1%
Upgrade	N	200	*6%*	29	0%
	S	152	*5%*	74	1%
	E	182	*6%*	75	1%
	W	183	*6%*	87	1%
Replace Dbl LoE	N	177	*17%*	27	0%
	S	139	*14%*	74	1%
	E	163	*16%*	73	1%
	W	163	*17%*	73	1%
Replace Dbl LoE ARGON	N	173	*19%*	27	0%
	S	134	*16%*	74	1%
	E	159	*18%*	77	1%
	W	159	*19%*	90	1%
Replace Tpl LoE AIR	N	182	*14%*	26	0%
	S	147	*9%*	63	1%
	E	169	*13%*	66	1%
	W	169	*14%*	73	1%
Replace Tpl LoE ARG	N	171	*20%*	23	0%
	S	141	*13%*	50	1%
	E	160	*18%*	57	1%
	W	160	*18%*	64	1%
Second Glaz Sgl	N	176	*18%*	23	0%
	S	140	*13%*	51	1%
	E	162	*16%*	64	1%
	W	163	*17%*	68	1%
Second Glaz Dbl	N	171	*20%*	20	0%
	S	143	*11%*	39	0%
	E	154	*21%*	74	1%
	W	161	*18%*	58	1%
Shading fixed	N	197	*8%*	27	0%
	S	166	*-3%*	55	1%
	E	185	*5%*	63	1%
	W	185	*5%*	68	1%

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Building type model	Apartment type	WWR		overheating	
M6	T2	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Shading adjustable	N	193	*9%*	28	0%
	S	150	*7%*	76	1%
	E	177	*9%*	83	1%
	W	178	*9%*	64	1%
Enlarge Window Dbl LoE	N	170	*20%*	55	1%
	S	118	*26%*	155	2%
	E	152	*22%*	149	2%
	W	152	*22%*	175	2%
Enlarge Window Dbl LoE, Argon	N	163	*23%*	56	1%
	S	112	*30%*	166	2%
	E	146	*25%*	157	2%
	W	146	*26%*	187	2%

Table C.11

Overview of window options for model M6 typical middle apartment, for all orientation, WWR 30%

Building type model	Apartment type	WWR		overheating	
M6	T2	60%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing window (Singe glazing pane, wooden frame)	N	216	*0%*	60	1%
	S	146	*0%*	155	2%
	E	190	*0%*	154	2%
	W	194	*0%*	174	2%
Upgrade	N	196	*10%*	57	1%
	S	133	*9%*	149	2%
	E	172	*9%*	145	2%
	W	175	*10%*	164	2%
Replace Dbl LoE	N	170	*22%*	55	1%
	S	118	*19%*	155	2%
	E	152	*20%*	149	2%
	W	152	*22%*	175	2%
Replace Dbl LoE ARGON	N	163	*25%*	56	1%
	S	112	*23%*	166	2%
	E	146	*23%*	157	2%
	W	146	*25%*	187	2%

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Building type model	Apartment type	WWR		overheating	
M6	T2	60%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Replace Tpl LoE AIR	N	178	***18%***	42	0%
	S	130	***11%***	111	1%
	E	161	***15%***	111	1%
	W	161	***17%***	132	2%
Replace Tpl LoE ARG	N	161	***26%***	33	0%
	S	121	***18%***	85	1%
	E	160	***16%***	57	1%
	W	146	***25%***	109	1%
Second Glaz Sgl	N	173	***20%***	39	0%
	S	125	***15%***	81	1%
	E	156	***18%***	91	1%
	W	156	***20%***	115	1%
Second Glaz Dbl	N	167	***23%***	29	0%
	S	130	***11%***	70	1%
	E	154	***19%***	74	1%
	W	153	***21%***	91	1%
Shading fixed	N	201	***7%***	49	1%
	S	158	***-8%***	79	1%
	E	184	***3%***	92	1%
	W	185	***5%***	107	1%
Shading adjustable	N	194	***10%***	49	1%
	S	136	***7%***	141	2%
	E	173	***9%***	155	2%
	W	174	***10%***	86	1%

Table C.12

Overview of window options for model M6 typical middle apartment, for all orientation, WWR 60%

Balcony

	Measure	Calculated option	Simulated material	U-value (W/^{m}2K)
Existing construction	Continuous slab, no insulation	Concrete slab	Concrete slab projected as cantilever, simulated as a substructure on the external wall, at the balcony edge	1.96
	Separate slab no/little insulation			
Retrofitting measures	Insulate balcony slab	Insul Balc SLAB	Concrete substructure Insulation Material	0.2
	Cut off balcony	CUT-OFF Balcony	Subsurface removed	0.2
	Balcony cladding single glazing	SINGLE BalcGlaz	Single Low-E 3mm, g=0.75. Aluminium frame structure. Thermal buffer, unheated zone.	4,3
	Balcony cladding double glazing	Double BalcGlaz	Double Low-E 3mm/13mm Air (coating inner pane), g-0.68. Aluminium frame structure. Thermal buffer, unheated zone.	1.78
Spatial interventions	Balcony space integrated	INTEGR DblBalc Glaz	Double Low-E 3mm/13mm Air (coating inner pane), g-0.68. Aluminium frame structure. Existing wall removed. Merged with heated zone.	1.78
	New balcony	n/a	n/a	n/a

Table C.13
Overview of simulated existing construction and retrofitting measures for balcony

Building type model	Apartment type	WWR		overheating	
M1	T2	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing baclony (concrete slab)	N	275	*0%*	29	0%
	S	209	*0%*	79	1%
	E	245	*0%*	81	1%
	W	253	*0%*	93	1%
CUT-OFF Balcony	N	269	*2%*	31	0%
	S	198	*6%*	94	1%
	E	243	*3%*	91	1%
	W	246	*3%*	113	1%
Insul Balc SLAB	N	267	*3%*	30	0%
	S	196	*6%*	93	1%
	E	241	*4%*	90	1%
	W	243	*4%*	113	1%
SINGLE BalcGlaz	N	218	*21%*	14	0%
	S	167	*20%*	87	1%
	E	197	*21%*	69	1%
	W	200	*21%*	86	1%
Double BalcGlaz	N	217	*21%*	11	0%
	S	168	*20%*	82	1%
	E	197	*21%*	65	1%
	W	186	*26%*	73	1%
INTEGR DblBalc Glaz	N	211	*23%*	34	0%
	S	122	*42%*	184	2%
	E	177	*29%*	145	2%
	W	186	*26%*	164	2%

Table C.14

Overview of balcony options for model M1 typical middle apartment, for all orientation, WWR 30%

Building type model	Apartment type	WWR		overheating	
M1	T2	60%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing baclony (concrete slab)	N	289	*0%*	59	1%
	S	200	*0%*	158	2%
	E	259	*0%*	153	2%
	W	260	*0%*	168	2%
CUT-OFF Balcony	N	284	*2%*	60	1%
	S	189	*5%*	210	2%
	E	249	*4%*	175	2%
	W	253	*3%*	208	2%
Insul Balc SLAB	N	282	*3%*	60	1%
	S	187	*6%*	210	2%
	E	246	*5%*	175	2%
	W	251	*3%*	208	2%
SINGLE BalcGlaz	N	238	*18%*	43	0%
	S	163	*18%*	214	2%
	E	207	*20%*	168	2%
	W	214	*18%*	196	2%
Double BalcGlaz	N	225	*22%*	39	0%
	S	162	*19%*	236	3%
	E	196	*24%*	159	2%
	W	203	*22%*	186	2%
INTEGR DblBalc Glaz	N	211	*27%*	57	1%
	S	122	*39%*	233	3%
	E	177	*32%*	182	2%
	W	186	*28%*	208	2%

Table C.15

Overview of balcony options for model M1 typical middle apartment, for all orientation, WWR 60%

Roof

	Measure	Calculated option	Simulated material	U-value (W/^{m}2K)
Existing construction	Pitched roof, timber rafters no insulation	Pitched roof (M1)	Pitched roof, Timber rafters, no insulation in cavity	2.50
	Concrete slab, no insulation	Flat roof (M6)	Flat roof, plaster, 130-160mm reinforced concrete slab, 20-40mm insulation , screed	1.96
	little/outdated insulation			0.80
Retrofitting measures	Pitch roof insulation	Pitched roof insulation	Plasterboard Rockwool insulation 0.2m between timber rafters Hard board, bitumen membrane	0.2
		LOFT SPACE_ occupied insulated		
	Insulation of top floor slab	Top Slab insul	Existing concrete slab Rockwool insulation 0.2m	0.2
	Flat roof	Flat Roof insul	Existing concrete slab XPS Insulation 0.2m Waterproofing Fibreboard, asphalt	0.15
	Green roof	Green Roof	Existing concrete slab Waterproofing XPS Insulation 0.2m Thick plastic sheet Gravel, Soil	0.2
RES	Photovoltaic	n/a		n/a
Spatial interventions	Additional floor	Additional roof loft occupied	Plasterboard Rockwool insulation 0.2m between timber rafters Hard board, bitumen membrane	0.2
		Additional roof loft occupied, NO insul	Plasterboard Timber rafters Hard board, bitumen membrane	2.4

Table C.16
Overview of simulated existing construction and retrofitting measures for roof

Building type model	Apartment type	WWR		overheating	
M1	T3	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing roof (pitched roof, timber construction)	N	404	*0%*	29	0%
	S	330	*0%*	79	1%
	E	381	*0%*	81	1%
	W	381	*0%*	93	1%
Pitched roof insulation	N	348	*14%*	26	0%
	S	274	*17%*	65	1%
	E	323	*15%*	66	1%
	W	323	*15%*	72	1%
Top Slab insul	N	254	*37%*	48	1%
	S	198	*40%*	87	1%
	E	233	*39%*	90	1%
	W	236	*38%*	107	1%
Flat Roof insul	N	299	*26%*	47	1%
	S	245	*26%*	88	1%
	E	271	*29%*	89	1%
	W	284	*26%*	88	1%
Green Roof	N	268	*34%*	32	0%
	S	207	*37%*	81	1%
	E	245	*36%*	81	1%
	W	247	*35%*	97	1%
Additional roof loft occupied	N	265	*34%*	39	0%
	S	210	*37%*	76	1%
	E	244	*36%*	76	1%
	W	248	*35%*	86	1%
Additional roof loft occupied, NO insul	N	286	*29%*	57	1%
	S	228	*31%*	85	1%
	E	264	*31%*	80	1%
	W	268	*30%*	92	1%
LOFT SPACE_occupied insulated	N	121	*53%*	124	1%
	S	121	*52%*	124	1%
	E	123	*52%*	119	1%
	W	123	*52%*	125	1%

Table C.17

Overview of roof options for model M1 typical top apartment, for all orientation, WWR 30%

Building type model	Apartment type	WWR		overheating	
M6	T3	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing roof (pitched roof, timber construction)	N	269	*0%*	66	1%
	S	215	*0%*	115	1%
	E	250	*0%*	112	1%
	W	251	*0%*	129	1%
Flat Roof insul	N	210	*22%*	38	0%
	S	162	*24%*	81	1%
	E	192	*23%*	85	1%
	W	193	*23%*	101	1%
Green Roof	N	209	*22%*	30	0%
	S	162	*25%*	79	1%
	E	191	*23%*	78	1%
	W	193	*23%*	96	1%
Additional roof loft occupied	N	207	*23%*	40	0%
	S	164	*24%*	73	1%
	E	191	*24%*	75	1%
	W	193	*23%*	84	1%

Table C.18

Overview of roof options for model M6 typical top apartment, for all orientation, WWR 30%

Ground floor

	Measure	Calculated option	Simulated material	U-value (W/m2K)
Existing construction	Slab on ground, no insulation	Concrete slab first floor	Concrete slab between first floor and unhea-ted basement	1.96
	Basement unheated. Concrete slab, no insulation			
	little/outdated insulation			
Retrofitting measures	Insulation on top of ground/first floor slab	ON slab insul	Floor covering Rockwool insulation 0.2m Existing floor slab	0.2
	Insulation under existing floor	UNDER Slab insul	Existing floor slab Rockwool insulation 0.2m	0.2
Spatial interventions	Additional floor-occupied base-ment	Additional Grfloor	Basement space heated	n/a

Table C.19
Overview of simulated existing construction and retrofitting measures for ground floor

Building type model	Apartment type	WWR		overheating	
M1	T1	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overhe-ating
Existing building (concrete slab first floor, masonry wall)	N	333	*0%*	9	0%
	S	254	*0%*	27	0%
	E	303	*0%*	35	0%
	W	304	*0%*	37	0%
ON slab insul	N	264	*21%*	50	1%
	S	198	*22%*	104	1%
	E	238	*21%*	102	1%
	W	242	*20%*	119	1%

>>>

Building type model	Apartment type	WWR		overheating	
M1	T1	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
UNDER Slab insul	N	261	*22%*	27	0%
	S	194	*23%*	82	1%
	E	236	*22%*	82	1%
	W	238	*22%*	100	1%
Additional Grfloor	N	275	*17%*	29	0%
	S	209	*18%*	79	1%
	E	250	*17%*	81	1%
	W	253	*17%*	93	1%

Table C.20

Overview of ground floor options for model M1 typical ground apartment, for all orientation, opening proportion 30%

Building type model	Apartment type	WWR		overheating	
M6	T1	30%			
Description	orientation	heating Demand per year kWh/m²	% of reduction to current	hours overheating (T>25oC)	% of time overheating
Existing building (concrete slab first floor, masonry wall)	N	271	*0%*	6	0%
	S	207	*0%*	26	0%
	E	246	*0%*	31	0%
	W	248	*0%*	36	0%
ON slab insul	N	211	*22%*	43	0%
	S	155	*26%*	90	1%
	E	191	*23%*	98	1%
	W	193	*22%*	118	1%
UNDER Slab insul	N	208	*23%*	27	0%
	S	154	*26%*	77	1%
	E	187	*24%*	77	1%
	W	190	*24%*	98	1%
Additional Grfloor	N	213	*21%*	31	0%
	S	161	*23%*	79	1%
	E	194	*21%*	82	1%
	W	196	*21%*	95	1%

Table C.21

Overview of ground floor options for model M6 typical ground apartment, for all orientation, opening proportion 30%

Appendix D

Decision path for case-study components' retrofitting- the toolbox roadmap

Breslauer Complex, 4-storey building

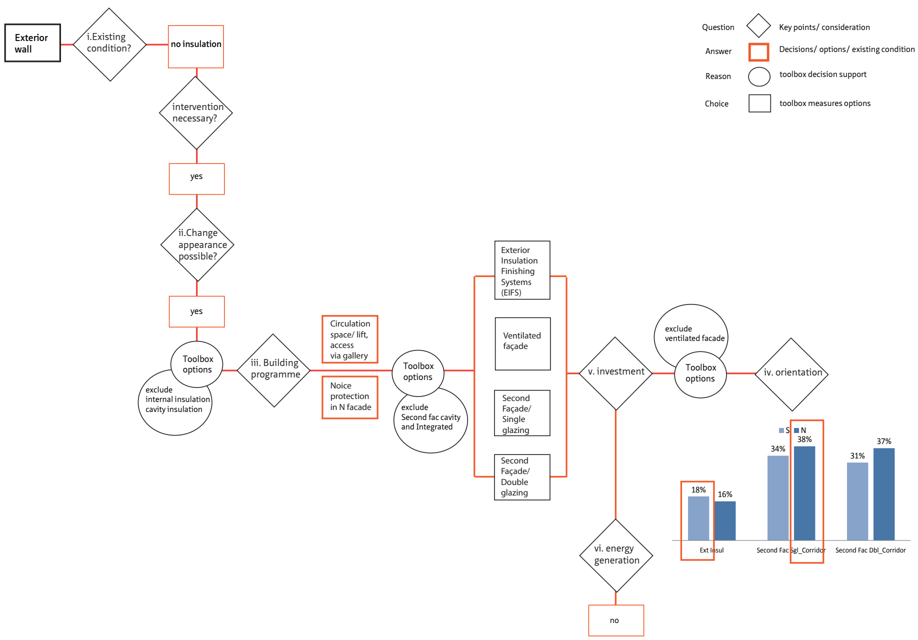

Figure D.1

Decision path to external wall retrofitting measure of the four-storey apartment block of the Breslauer complex.

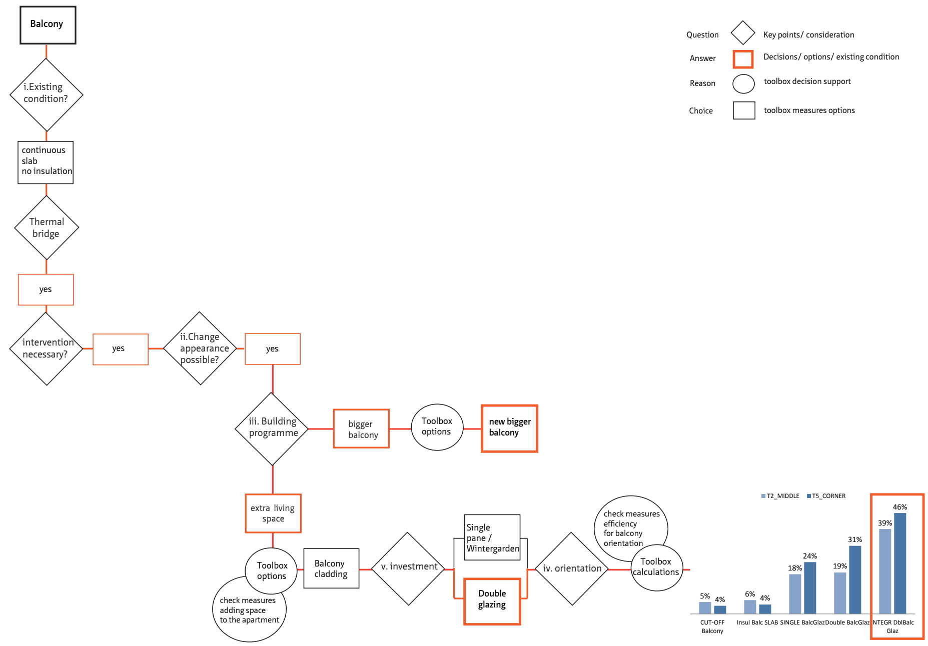

Figure D.2

Decision path to balcony retrofitting measure of the four-storey apartment block of the Breslauer complex

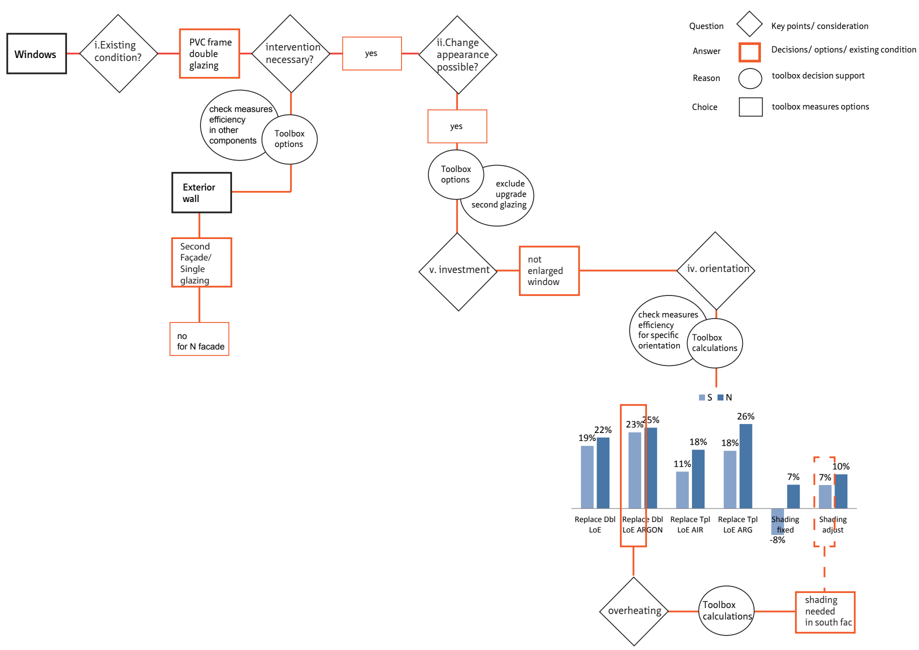

Figure D.3

Decision path to window retrofitting measure of the four-storey apartment block of the Breslauer complex

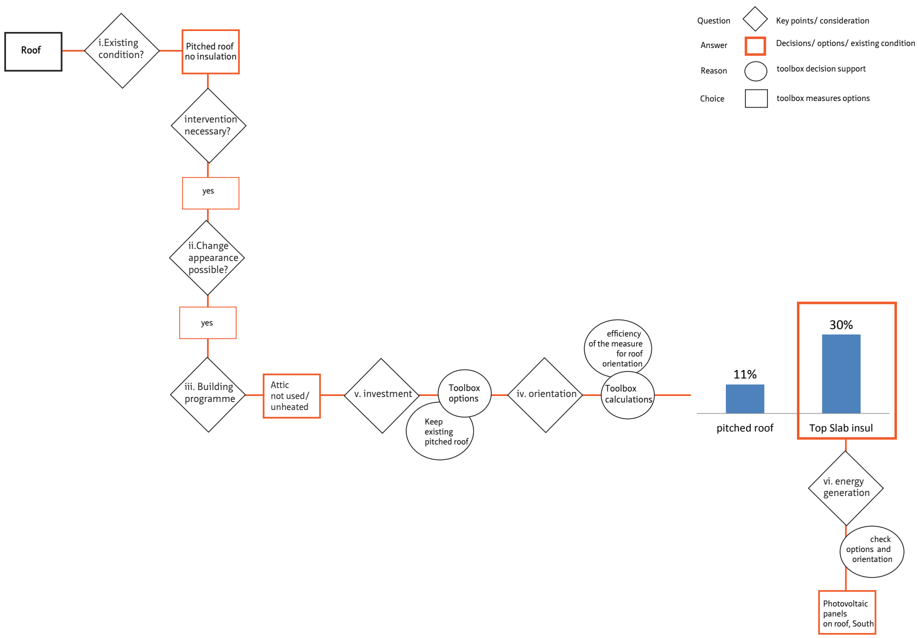

Figure D.4

Decision path to roof retrofitting measure of the four-storey apartment block of the Breslauer complex

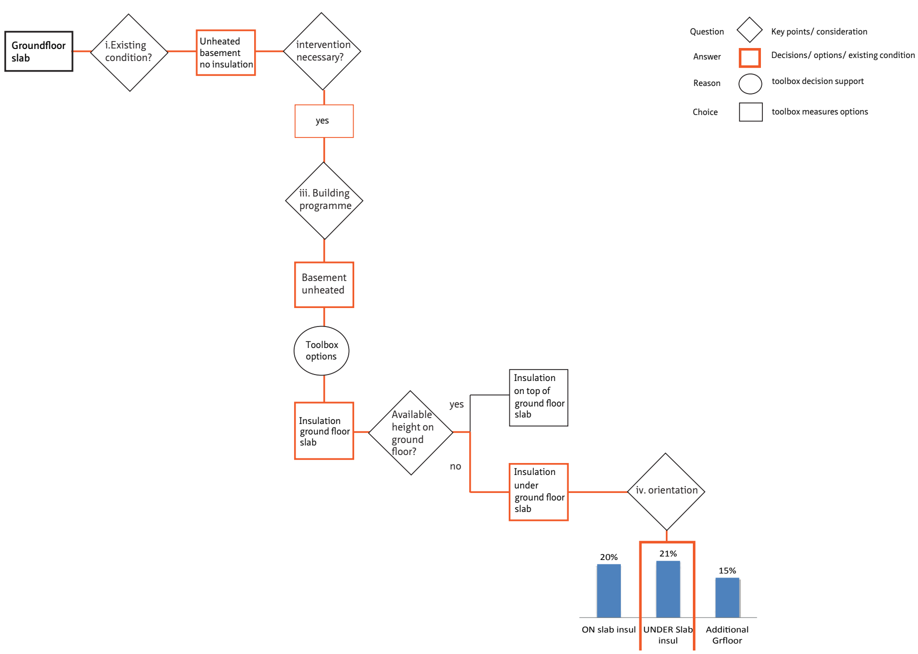

Figure D.5

Decision path to ground floor retrofitting measure of the four-storey apartment block of the Breslauer complex

Breslauer Complex, 3-storey building

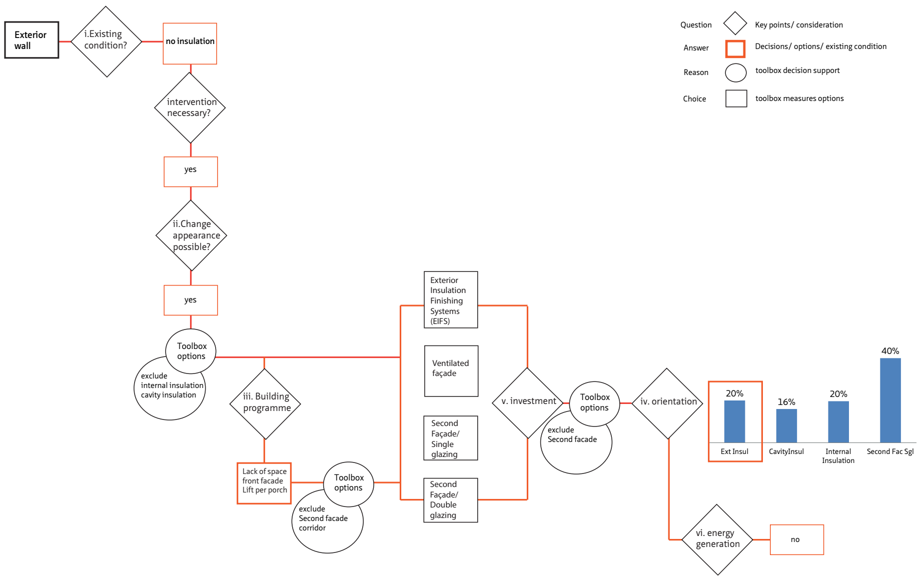

Figure D.6

Decision path to external wall retrofitting measure of the three-storey apartment block of the Breslauer complex

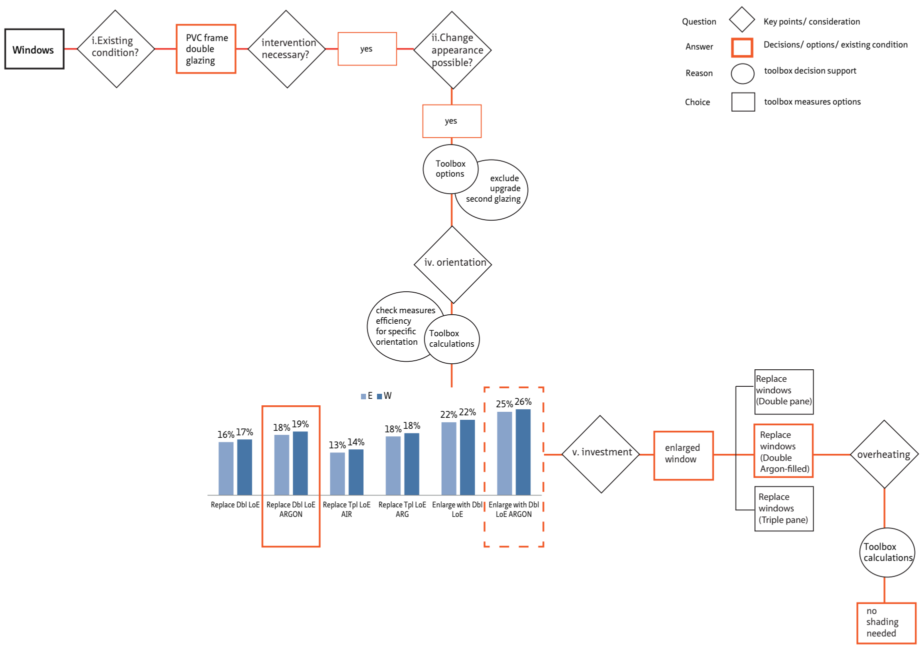

Figure D.7

Decision path to window retrofitting measure of the three-storey apartment block of the Breslauer complex

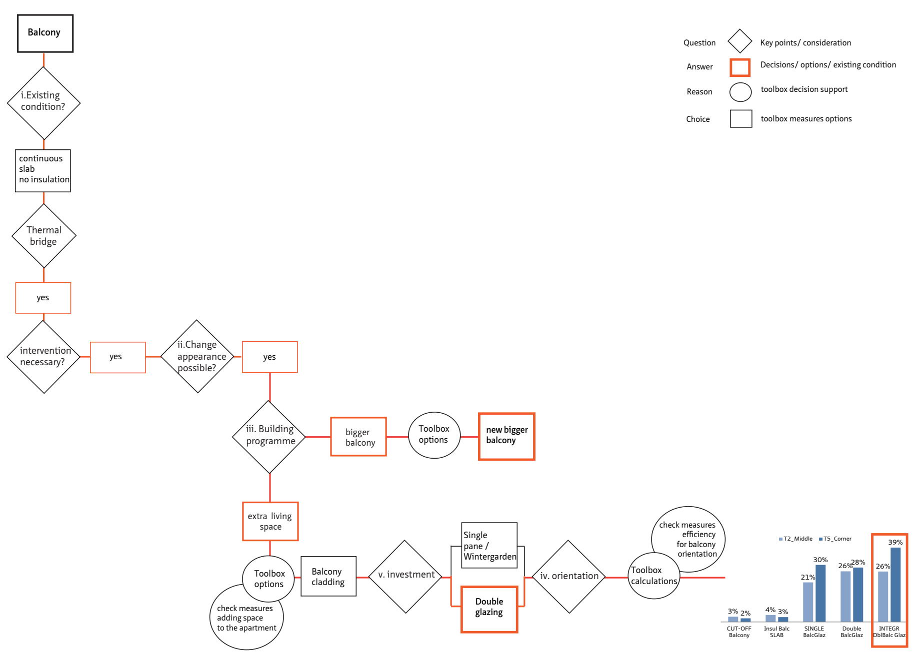

Figure D.8

Decision path to balcony retrofitting measure of the three-storey apartment block of the Breslauer complex

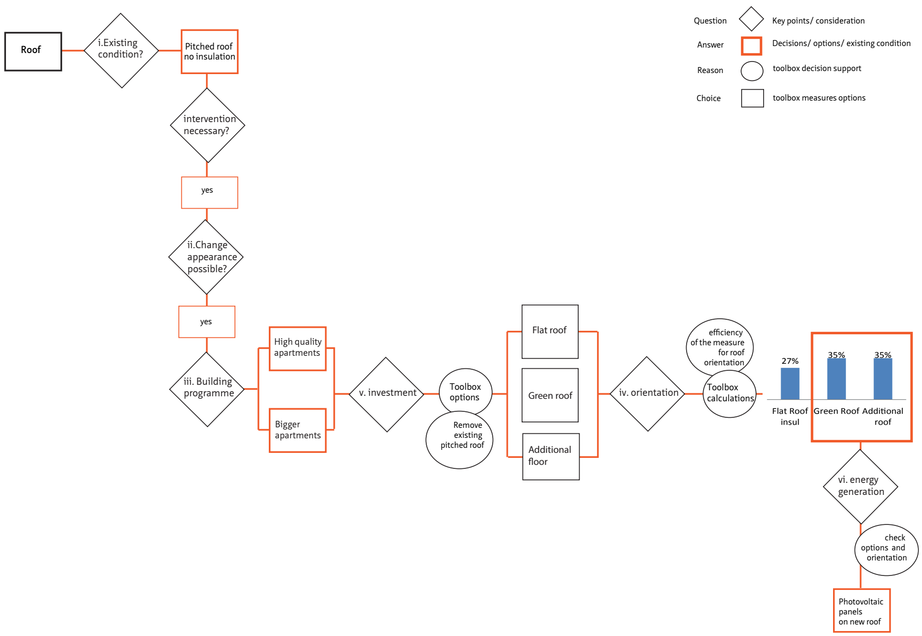

Figure D.9

Decision path to roof retrofitting measure of the three-storey apartment block of the Breslauer complex

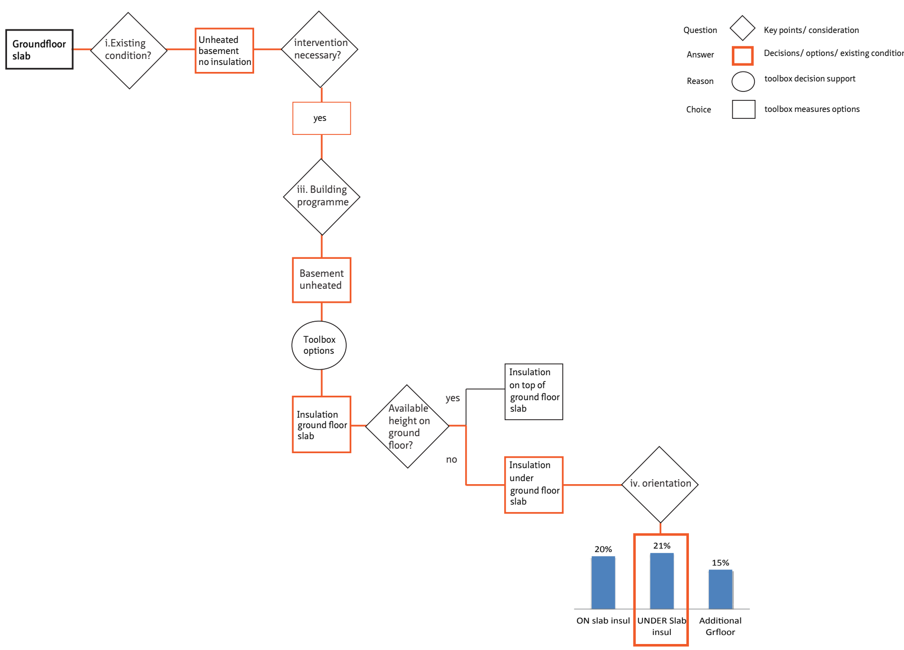

Figure D.10

Decision path to ground floor retrofitting measure of the three-storey apartment block of the Breslauer complex

Platanen Complex

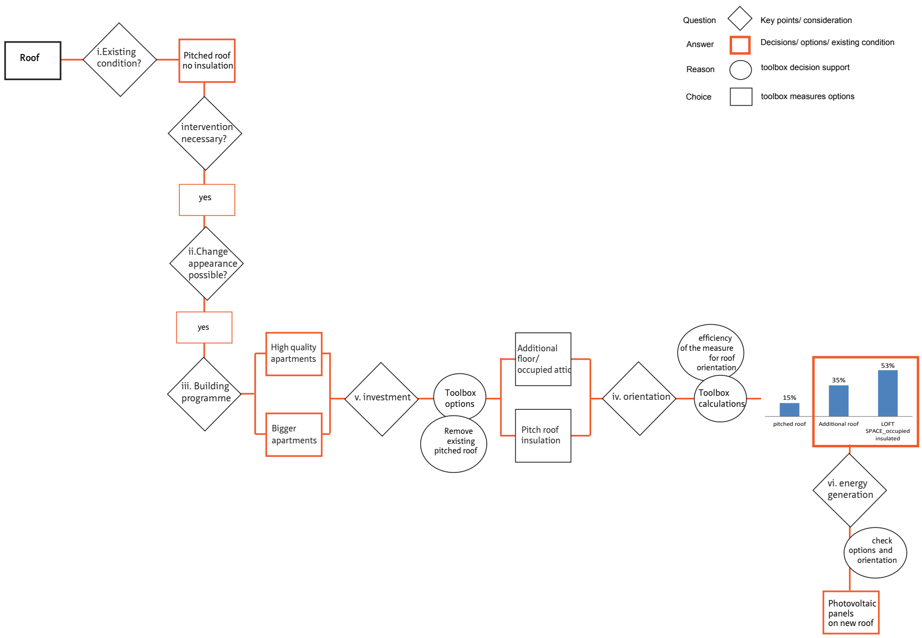

Figure D.11

Decision path to roof retrofitting measure of the Platanen complex apartment block

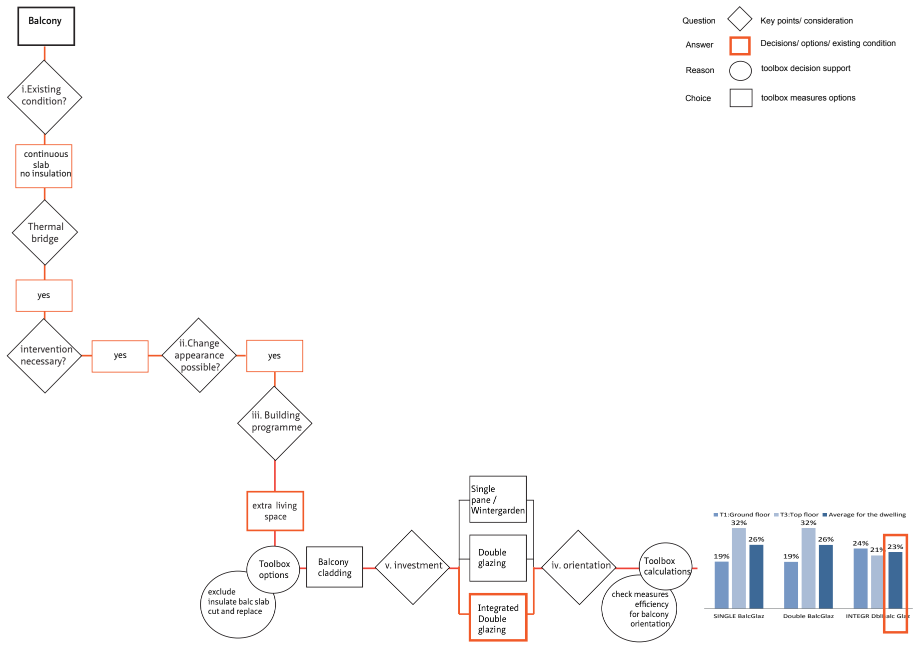

Figure D.12

Decision path to balcony retrofitting measure of the Platanen complex apartment block

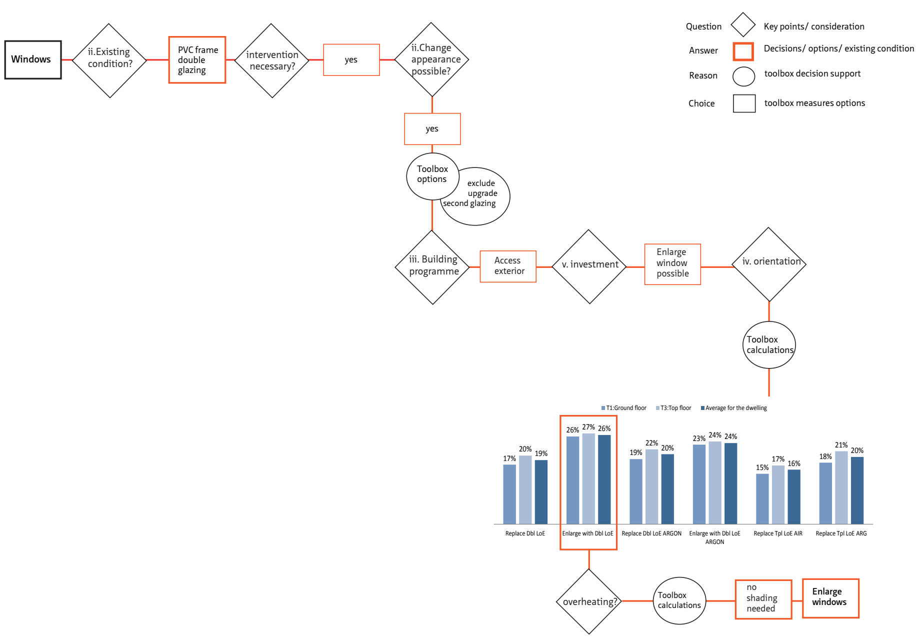

Figure D.13

Decision path to window retrofitting measure of the Platanen complex apartment block

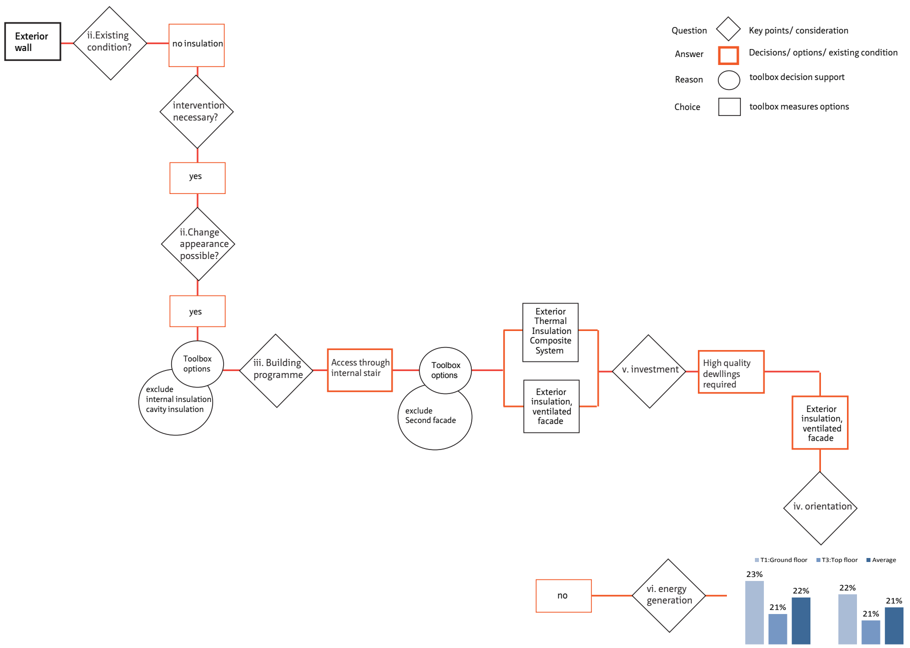

Figure D.14

Decision path to external wall retrofitting measure of the Platanen complex apartment block

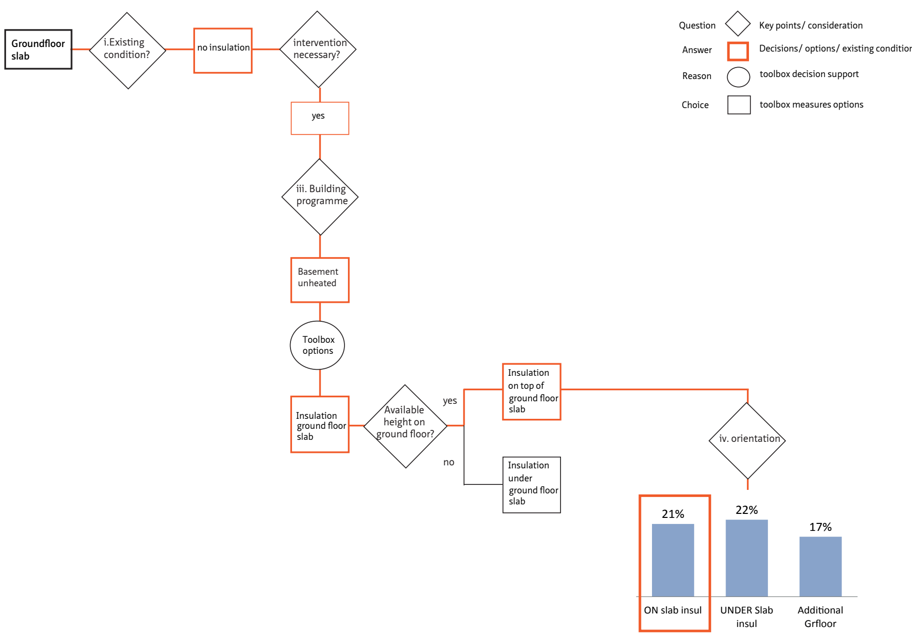

Figure D.15

Decision path to ground floor retrofitting measure of the Platanen complex apartment block

Suringarflat Complex

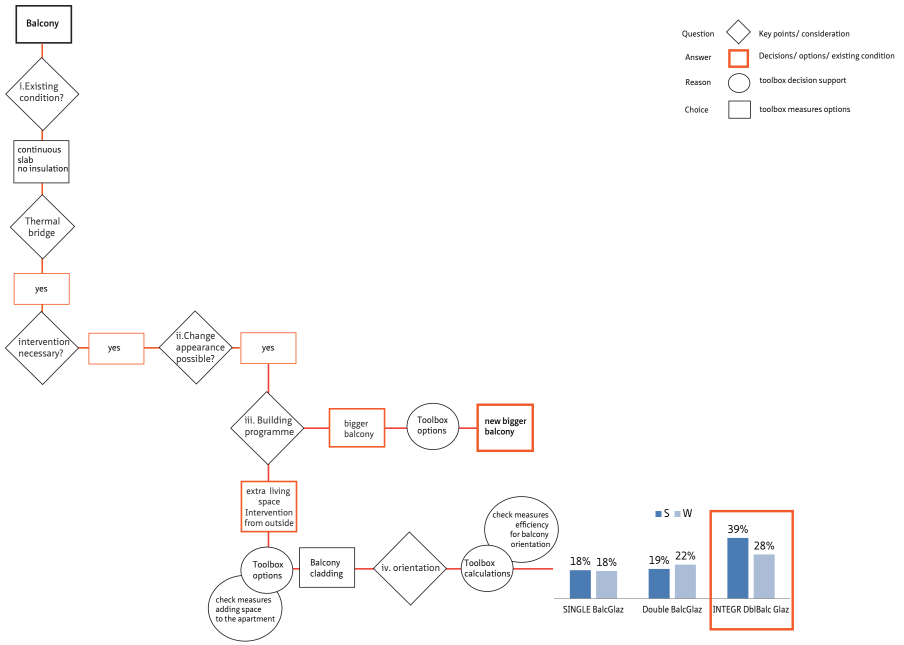

Figure D.16

Decision path to balcony retrofitting measure of the Suringarflat complex apartment block

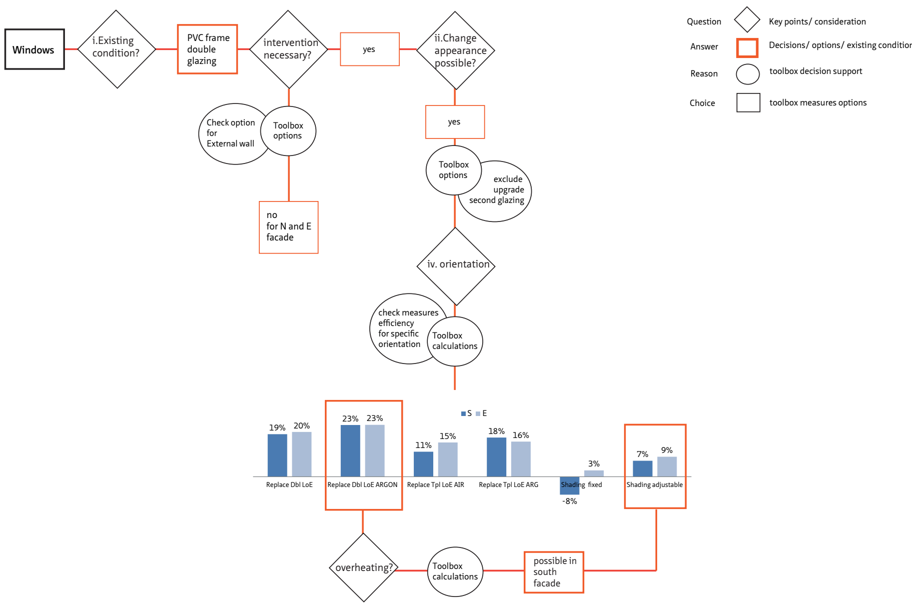

Figure D.17

Decision path for the windows of the Suringarflat complex apartment block

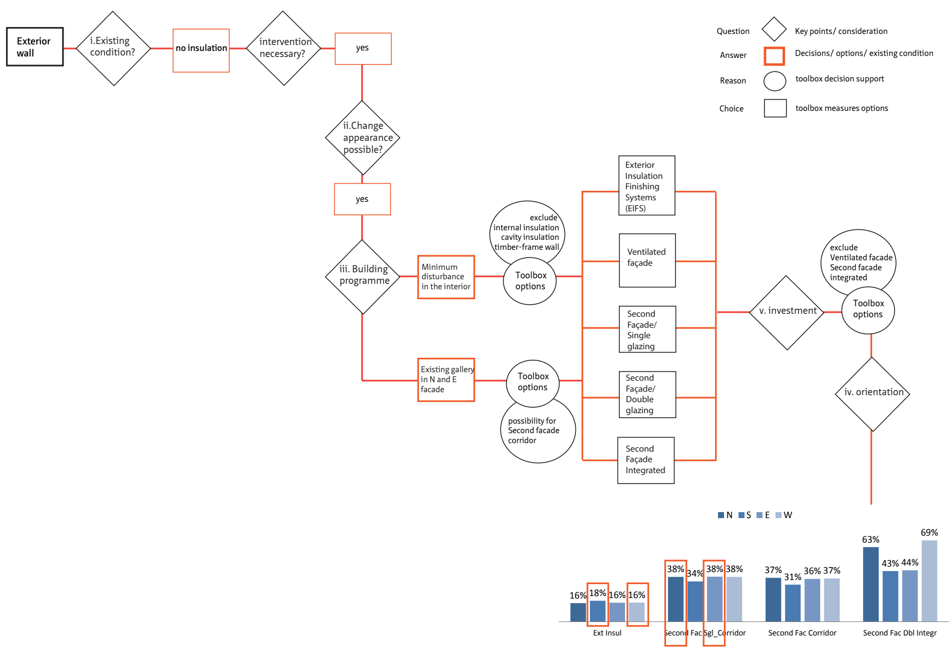

Figure D.18

Decision path to external wall retrofitting measure of the Suringarflat complex apartment block

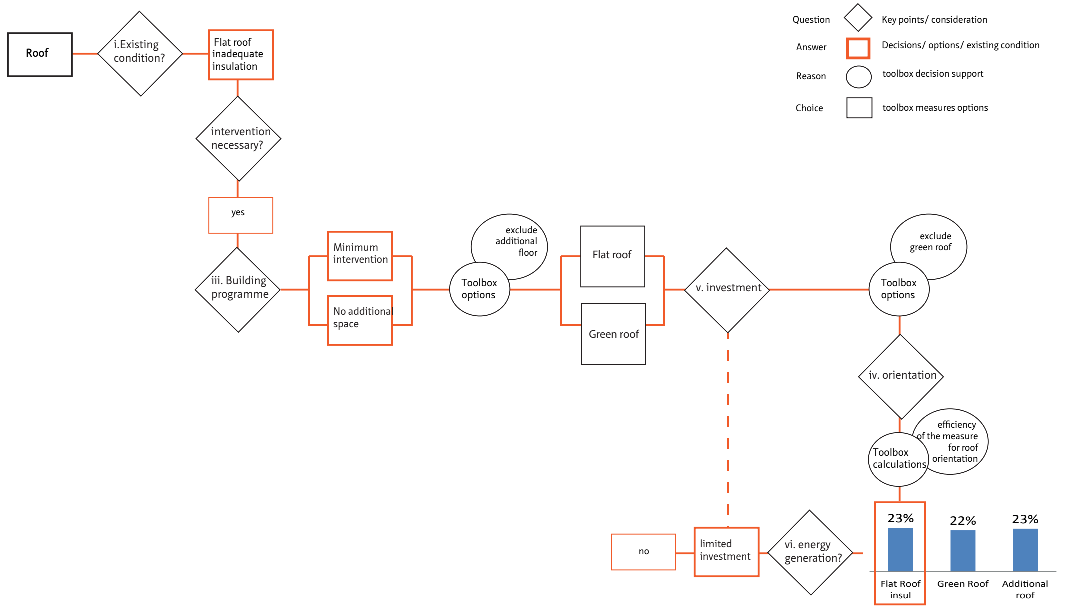

Figure D.19

Decision path to roof retrofitting measure of the Suringarflat complex apartment block

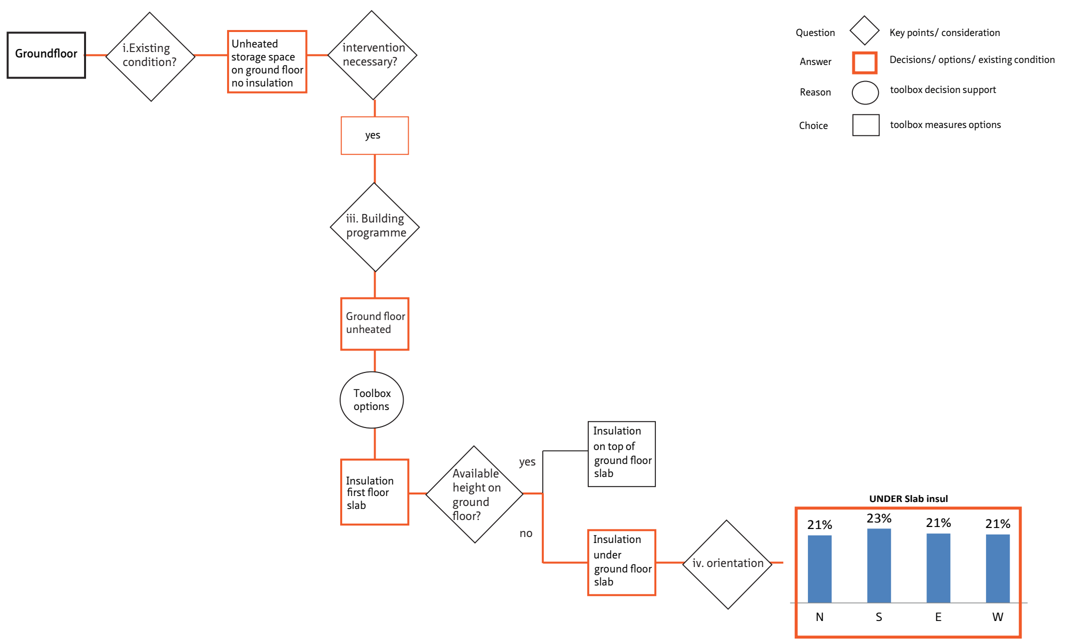

Figure D.20

Decision path to ground floor retrofitting measure of the Suringarflat complex apartment block

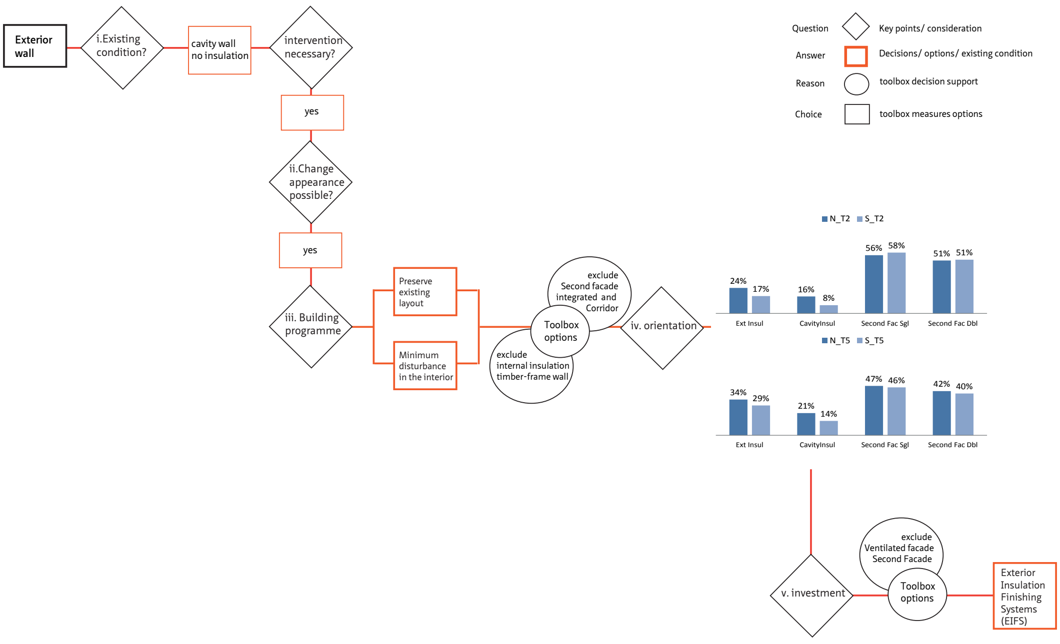

Figure D.21

Decision path to external wall retrofitting measure of the Coevordenstraat complex.

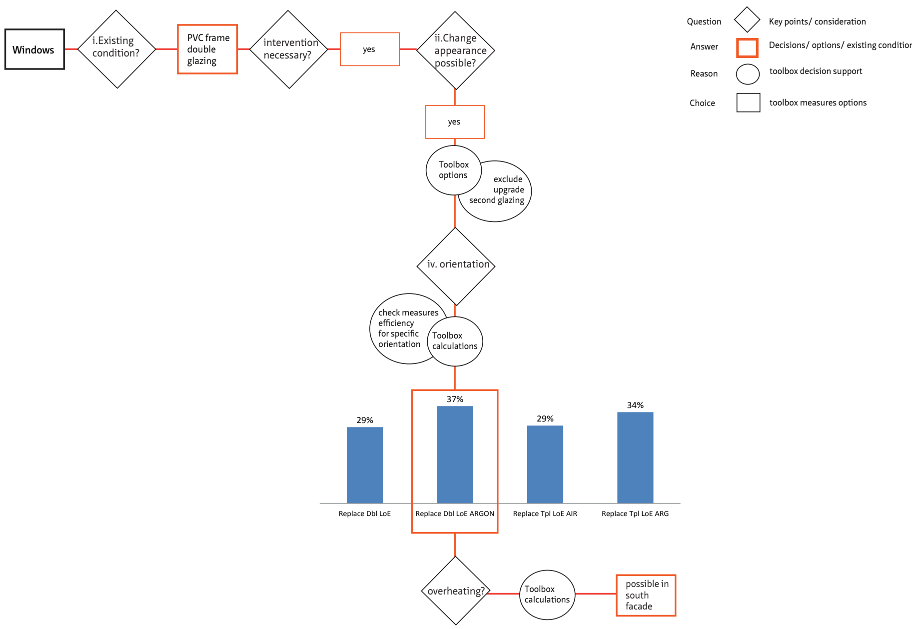

Figure D.22

Decision path to windows retrofitting measure of the Coevordenstraat complex

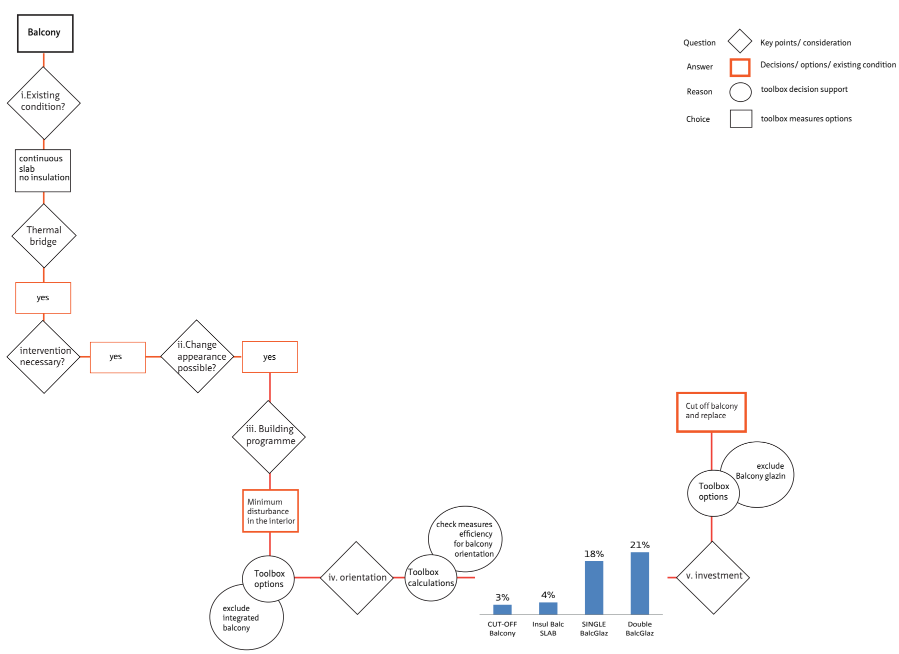

Figure D.23

Decision path to balconies retrofitting measure of the Coevordenstraat complex

Appendix E Interview Schedule

	Name	Affiliation	Company	Interview date
Architecture students				
1	Linda Miedema	Student	TU Delft	17-12-2013
2	Michiel van der Veen	Student	TU Delft	17-12-2013
3	Sanne Knoll	Student	TU Delft	17-12-2013
4	Marieke de Graauw	Student	TU Delft	17-12-2013
5	Marieke Zegwaart	Student	TU Delft	17-12-2013
6	Zelda Meeuwsen	Student	TU Delft	11-01-2014
7	Roel van Tatenhove	Student	TU Delft	28-01-2014
8	Timo van Deven	Student	TU Delft	28-01-2014
9	Esmee Mlihi	Student	TU Delft	28-01-2014
10	Susanne de Zwart	Student	TU Delft	28-01-2014
Architects				
1	Arjan Goijer	Architect	van Schagen Architecten	16-01-2014
2	Lidwine Spoormans	Architect Instructor at RMIT studio	Studio LS TU Delft	18-12-2014
3	Thijs Asselbergs	Architect	aTA architectuurcentrale Thijs Asselbergs	13-03-2014
4	Hielkje Zijlstra	Architect/ Academic refurbishment expert	TU Delft	17-12-2013
5	Joep Windhausen	Architect	Nieuwe Architecten	14-01-2014
6	Job Roos	Architect	Braaksma & Roos	07-03-2014
Refurbishment experts and stakeholders				
1	Eric van den Ham	Building physics consultant	Vennoot /Climatic Design Consult	14-01-2014
2	Hans van der Krogt	Director	Smits Vastgoedzorg /Housing Maintenance consultants and contractors	21-01-2014
3	Christian van Gruijthuijsen	Project developer		
4	Annelinda van Dijck - van Eck	Asset manager	Vesteda/Housing Corporation	29-01-2014
5	Yuri Pelser	Sustainability specialist at	Ymere/Housing Corporation	29-01-2014
6	Paul Tuijp	Policy and Innovation Advisor		
7	Ben Pluijmers	Director strategy & real estate portfolio	Havensteder / Housing Corporation	12-02-2014
8	Tillmann Klein	Architect/ Home owner,		17-12-2013
9	Leander Ross	Home owner		21-12-2013

Table E.1
List of interviewees

Interview Schedule

A General questions on company, position, experience

Name

Company Name

Company activities

Positions in the company

Date of interview

B Design Process

1 In what phase of refurbishment strategy development and execution do you participate?
Phase 1 Pre-design (specification set-up)
Phase 2 Concept Design of refurbishment strategy
Phase 3 Final design
Phase 4 Execution
Phase 5 Refurbished Building

2 What are the parameters normally considered in t refurbishment project?

3 What are the parties that take the decisions, in each phase?

4 Is the energy upgrade a requirement of the strategy?

5 At which point during the design process is the energy upgrade considered?

C Evaluation of the approach

Usefulness and usability of the toolbox

1 Are the approach and the information easily comprehensive?

2 Does the toolbox database help in organising possible options

3 Did you consider the options overview and potential energy reduction provided by the approach during the design phase of a current project?

4 Regarding one of your past projects, do you believe the decisions taken would be facilitated by the toolbox information? Would they change any of the decisions?

5 What type of information would be useful for you?

6 Do you think the information about the potential energy upgrade can help support your design decisions? Can it be useful arguments in discussion with the different parties involved (owners, users, constructors, services experts etc)

Relevance of the roadmap

7 Does the key points highlighted in the roadmap reflect considerations you have during the design process?

8 Please indicate how important/ useful they are during your design process
Key points
Existing condition
Change of appearance
Building programme
Investment/ budget
Orientation/energy reduction potential
Energy generation

9 What can be added?

10 The examples presented (case studies), do they help you/motivate you to use the information in future refurbishment projects?

Curriculum Vitae

1982	Born in Cholargos, Athens, Greece
2000-2006	Degree in Architecture, Faculty of Architecture, National Technical University of Athens
Since 2006	Certified architect, member of Technical Chamber of Greece and the Greek Association of Professional Architects
2005-2007	Associate Architect at Basilis Grigoriadis, Architect, Athens, Greece
2007-2008	MSc Built Environment: Environmental Design and Engineering, The Bartlett School of Graduate studies, University College London. Degree obtained with Distinction
2008-2009	Architectural Assistant at Abbink X De Haas architectures, Amsterdam, the Netherlands
Since 2009	Member of the Façade Research Group, TU Delft, the Netherlands
Since 2014	Post doctorate research associate at Faculty of Architecture, TU Delft, the Netherlands
Contact:	thalkon@gmail.com

Publication

Books

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Knaack, U., Hildebrand, L., Konstantinou, T., & Wieland, H. (2012). imagine 07: Reimagining housing. Rotterdam: nai010 publisher.

Journal papers

Konstantinou, T., & Knaack, U. (2013). An approach to integrate energy efficiency upgrade into refurbishment design process, applied in two case-study buildings in Northern European climate. Energy and Buildings, 59(0), 301-309. doi: http://dx.doi.org/10.1016/j.enbuild.2012.12.023

Konstantinou, T., & Knaack, U. (2011). Refurbishment of Residential Buildings: A Design Approach to Energy-Efficiency Upgrades. Procedia Engineering, 21(0), 666-675. doi: 10.1016/j.proeng.2011.11.2063

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Konstantinou, T., & Knaack, U. (2013). An Integrated Refurbishment Design Process to Energy Efficiency. Paper presented at the CLIMA 2013 - 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, Prague.

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Konstantinou, T., & Knaack, U. (2011). Refurbishment of residential buildings: A strategic approach to energy-efficiency upgrades. Paper presented at the 2ND WTA-INTERNATIONAL PHD SYMPOSIUM, Brno, Czech Republique.