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# Integrating Building Functions into Massive External Walls

Ahmed Hisham Hafez



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# Integrating Building Functions into Massive External Walls

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# Abstract

Well into the twentieth century, brick and stone were the materials used in external walls. Bricklaying and stonemasonry were the construction technologies employed for the exterior walls of virtually all major structures. However, with the rise in quality of life, the massive walls alone became incapable of fulfilling all the developed needs. Adjacent systems and layers had then to be attached to the massive layer. Nowadays, the external wall is usually composed of a layered construction. Each external wall function is usually represented by a separate layer or system. The massive layer of the wall is usually responsible for the load-bearing function.

Traditional massive external walls vary in terms of their external appearance, their composition and attached layers. However, their design and construction process is usually a repeated process. It is a linear process where each discipline is concerned with a separate layer or system. These disciplines usually take their tasks away and bring them back to be re-integrated in a layered manner..

New massive technologies with additional function have recently become available. Such technologies can provide the external wall with other functions in addition to its load-bearing function. The purpose of this research is to map the changes required to the traditional design and construction process when massive technologies with additional function are applied in external walls. Moreover, the research aims at assessing the performance of massive solutions with additional function when compared to traditional solutions in two different contexts, the Netherlands and Egypt.

Through the analysis of different additional function technologies in external walls, a guidance scheme for different stakeholders is generated. It shows the expected process changes as related to the product level and customization level. Moreover, the research concludes that the performance of additional insulating technologies, and specifically Autoclaved Aerated Concrete can provide a better construction compared to the traditional external wall construction of the Netherlands and Egypt.



# Contents

1	Introduction	15	.....
1.1	Background	15	.....
1.2	Problem	16	.....
1.3	Objectives	16	.....
1.4	Research Questions	17	.....
1.5	Research Relevance	18	.....
1.5.1	Development of Environmental Concerns	18	
1.5.2	Market Competition	19	
1.5.3	Scientific Relevance	20	
1.6	Research Methodology and Thesis Structure	20	.....
1.6.1	Research Background	21	
1.6.2	Study of Massive Technologies Applicable to External Walls	21	
1.6.3	Performance Assessment of Insulating Technologies for External walls in Netherlands and Egypt	22	
1.6.4	Thesis Structure	22	
1.7	Definitions	24	.....

2	External Walls in the Netherlands and Egypt	27
2.1	Introduction	27
2.2	Development of Massive External Walls in the Netherlands and Northwestern Europe	28
2.2.1	Massive External Walls in Ancient Times	28
2.2.2	Massive External Walls after the Industrial Revolution	29
2.2.3	Early Cavity Walls of the Nineteenth Century	30
2.2.4	Cavity Walls of the Twentieth Century	32
2.2.5	Modern Movement and Massive External Walls	33
2.2.6	Energy Crisis and Insulation	34
2.2.7	Scheme for External Wall Development in the Netherlands	35
2.3	Development of Massive External Walls in Egypt	36
2.3.1	Massive External Walls in Ancient Times	36
2.3.2	Massive External Walls after the Industrial Revolution	38
2.3.3	Massive External Walls in Modern Times	38
2.3.4	Scheme for External Wall Development in Egypt	39
2.4	Today's Massive External Walls in the Netherlands and Egypt: A Comparison	40
2.5	Conclusions	43
3	Schemes for Analysing Functional Massive External Wall	45
3.1	Introduction	45
3.2	Component-Function Relations	46
3.2.1	Product Architecture	46
3.2.2	Definition of Product Level	50
3.2.3	Definition of External Wall Functions	52
3.2.4	Component-Function Scheme	57

3.3	Design and Construction Process	61
3.3.1	Development of Design and Construction Process	61
3.3.2	Design and Construction Process Scheme	64
3.4	Application to Traditional Dutch and Egyptian External Walls	65
3.5	Conclusions	67
4	Integral Technologies in Massive Construction: An Overview	69
4.1	Introduction	69
4.2	Massive Walls: An overview	70
4.3	Technologies Selection Criteria	72
4.4	Technologies in Massive Construction Providing Additional Functions	74
4.4.1	Lightweight Aggregate Concrete	74
4.4.1.1	Expanded Clay Concrete	76
4.4.1.2	Expanded Glass Concrete	78
4.4.1.3	Aerogel Concrete	80
4.4.2	Aerated Concrete	82
4.4.3	Perforated Clay Bricks	84
4.4.4	Thermally Activated System	86
4.4.5	PCM Concrete	88
4.4.6	Air Permeable Concrete	90
4.4.7	Translucent Concrete	93
4.4.8	Functionally Gradient Concrete	95
4.4.9	Summary of Additional function Technologies and Discussion	97
4.5	Conclusions	98

5	Analysis of External Wall Construction Technologies	101
5.1	Introduction	101
5.2	Analysis of Massive technologies with additional function in External Walls	102
5.2.1	Analysis of Technologies	102
5.2.2	Observations Regarding Process Changes	116
5.3	Product-Designed Solution: A Possible Approach	120
5.3.1	Approach Explanation	120
5.3.2	Case Studies	121
5.3.3	Observations Regarding Product-Based Solutions	128
5.4	Observations and Guidance Scheme	132
5.5	Conclusions	140
6	Design for Insulating Massive External Walls in the Netherlands and Egypt	143
6.1	Introduction	143
6.2	Reasons for Focusing on Additional Insulating Massive Technologies	144
6.3	Comparable External Wall Designs	146
6.3.1	Defining Typical Building Case	146
6.3.2	Determining Building Rules and Regulations for Each Context	150
6.3.3	Comparable Insulating Massive External Wall Designs for Each Context	154
6.4	Defining Assessment Criteria For comparison	164
6.5	Summary	168

7	Insulating Massive External Walls Assessment and Results	171
7.1	Introduction	171
7.2	Massive External Wall Performances: the Netherlands	172
7.2.1	Construction Time	173
7.2.2	Construction Cost	176
7.2.3	Embodied Energy	181
7.2.4	Carbon Dioxide Emission	185
7.2.5	Recyclability	189
7.2.6	Operational Energy	192
7.2.7	Lifetime and Durability	194
7.3	Massive External Wall Performances: Egypt	196
7.3.1	Construction Time	197
7.3.2	Construction Cost	201
7.3.3	Embodied Energy	207
7.3.4	Carbon Dioxide Emission	211
7.3.5	Recyclability	215
7.3.6	Operational Energy	217
7.3.7	Construction Thickness	218
7.3.8	Lifetime and Durability	219
7.4	Scoring System and Results	220
7.5	Summary and Conclusions	230
8	Conclusions and Recommendations	233
8.1	Introduction	233
8.2	Answers to Research Questions and Conclusions	233
8.3	Required Changes in the Construction Industry	241
8.4	Possible Future Related research	243

References 247  
Summary 253  
Samenvatting 255  
Imagery credits 259

Appendix 1 Air Permeable Concrete 261  
Appendix 2 Interviews 265  
Appendix 3 Design Process in an Integrated External Wall: Zollverein Design School Project 267  
Appendix 4 Structural calculations 279  
Appendix 5 Heating & cooling loads for the Egyptian designed walls 287  
Appendix 6 Questionnaire 291

Curriculum vitae 293





# 1 Introduction

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## § 1.1 Background

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Archaeologists believe that the basic construction materials used in creating human shelters over several millennia were the same in all parts of the world. Construction materials were all acquired from earth or plants and used according to the climatic conditions and their availability. As society developed, the building requirements exceeded the capabilities of these primitive shelters. This gave rise to massive external walls constructed from heavy materials, giving more security and protection against outdoor conditions (Haseltine, 2012).

Until the twentieth century buildings were constructed from bricks and stones. The bricklaying and stonemasonry technology were the technologies used in almost all exterior walls. Walls generally were seen as the primary elements of construction that according to a writer on the topic of masonry and bricklaying in 1891 “a floor may be in one sense said to be a wall, only posed or placed horizontally.” (Ochshorn, 1992).

However, with the rise in quality of life, the massive external walls alone became incapable of fulfilling all the developed needs. Adjacent systems and layers had then to be attached to the massive layer. Nowadays, the external wall is usually composed of a layered construction.

Massive external walls vary in terms of their external appearance, their composition, and attached layers. However, their design and construction process is usually a repeated process. Usually, an architect in the early stages decides about the load-bearing system of the external wall (concrete, masonry, etc.). Then the structural engineer in a later stage designs the wall giving the exact dimensions. The building physics engineer works separately on calculating the amount of insulation needed for the external wall. Similarly, the mechanical engineer starts his work separately, may be even after the building is partially erected. Finally, the cladding may come separately, based on the architect’s demands, to give the building its unique appearance.

Following the traditions and norms of the construction industry, the execution of the massive external wall is achieved by a different party. The contractor executes the design, assisted by suppliers and subcontractors. With more attached layers and systems, more suppliers and subcontractors become involved.

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## § 1.2 Problem

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Each external wall function is usually represented by a separate layer or system. Then all layers and systems are attached together. The massive layer of the external wall is usually responsible for the load-bearing function.

In a layered strategy, where each function represents a layer, more functions are always translated into new layers. This means that the façade will be getting complex with more layers and more interfaces. In addition, more materials will be continuously added to the external wall. This does not comply with the basic sustainability concepts that call for reduction of materials.

Nowadays, new massive technologies with additional function have become available. Such technologies can provide the external wall with other functions in addition to its load-bearing function. Some of these technologies existed quite some time before such as Autoclaved Aerated Concrete, which provides an insulation function in addition to its load bearing function. Recently, more technologies have become available, either as market products or as developed in research work. These technologies have not been necessarily developed for implementation in external walls. However, they have potentials for providing the external wall's massive layer with additional functions such as insulation, heating/cooling, ventilation and light transmittance.

The implementation of such technologies would change the traditional design and construction process. Involved disciplines might need to come together in a new different way, abandoning the scattered decision making process and construction steps. Not only this, but every integrated design solution is likely to be implemented with a unique design process since requirements of every solution are different. Such process changes if recognized before the technology being available in the market, the technology will be successfully implemented.

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## § 1.3 Objectives

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In light of the above-mentioned background, the following are the objectives of this research:

- 1 To understand the impact of additional functional massive technologies on the traditional design process, and how to adapt our traditional design process in order to apply additional functional technologies in external walls.

- 2 To compare the performance of new additional functional massive technologies with the traditional ones. However, fulfilling this objective on a general scale for all additional function technologies is difficult due to the wide range of available technologies. For this reason, this objective will be limited to the additional insulating massive technologies, and the comparison will be restricted to the traditional wall construction in the Netherlands and in Egypt.

The main reason for selecting these two countries is the different contexts they possess. Each of the two countries presents a region that has its own climate, culture and construction methods. This results in different methods of construction of traditional external walls in the two countries (The differences will be explained in more details in Chapter 2). The comparison between additional function massive external walls and the two different traditional external walls in the two countries will likely generate different and more interesting results. It is worth mentioning here that the research was conducted at the TU Delft in the Netherlands, whereas Egypt it is the author's home country.

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## § 1.4 Research Questions

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The main two questions that this research is trying to answer are the following:

- What changes are required to the present traditional design and construction process if massive technologies with additional function are implemented in external walls?
- Will these technologies provide a more successful construction in Egypt and the Netherlands (with a closer view on insulating function)?

Accordingly, the following sub-questions are investigated in this research:

- How did the traditional wall in Egypt and the Netherlands develop?
- How can a scheme be developed to analyse and understand external walls with additional function and their design and construction process?
- What are the existing and new additional functional massive technologies?
- How do these technologies affect the traditional process?
- How can additional insulating massive external wall technologies be compared with the traditional massive external walls in the Netherlands and Egypt?
- How do the additional insulating massive external walls perform in comparison with the traditional massive external walls?

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## § 1.5 Research Relevance

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### § 1.5.1 Development of Environmental Concerns

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The oil crisis in 1973 was the first significant move towards considering energy and the environment. This crisis actually shaped the external wall as we know it today. However, in the 1990's, more holistic environmental concerns took place. People became more aware of the influences on nature and climate change. Environmentalism became a new focus on the social and political level (Hildebrand, 2012).

From the definitions of sustainable development by the World Commission in 1987, a separate definition was derived for sustainable construction. It was defined as "those materials and methods used to construct and maintain a structure that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Tinker & Burt, 2004). The focus on energy in buildings since the 1990's became not only limited to the reduction of the operational energy but more environment concerns came into being. These concerns are constantly changing and developing. However, there are six fundamental principles, which are: Optimizing Site Potentials, Optimizing Energy Use, Protecting and Conserving Water, Optimizing Building Space and Material Use, Enhancing Indoor Environmental Quality, and Optimizing Operational and Maintenance Practices (WBDG, 2013).

Because of this movement, many researchers believe that the current legal regulations for buildings that focus on defining the minimum standards for operating energy consumption will most likely change in the future. More consideration will be given to other environmental issues like materials usage and embodied energy (Haynes, 2013; Hildebrand, 2012; Reddy & Jagadish, 2003). Already nowadays many governmental agencies and owners demand sustainability to be a key component in the design and construction of structures and to fulfil the environmental certificate ratings (Tinker & Burt, 2004).

This environmental movement is changing the way buildings are designed and built. It is even causing design and construction organizations to reconsider their approaches in nearly every step of their operations (Nobe & Dunbar, 2004). Therefore, the external wall, being part of the building components, will need to adapt to these requirements.

It is clear that the modular layered external wall development and the continuous addition of functions in a separate layer are growing in response to the demand for a better energy performance building. However, with new approaches driven by

sustainability like minimizing materials use, recycling and durability; additional function components, solutions, and technologies for massive external walls become worth of reconsideration.

## § 1.5.2 Market Competition

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Increasingly competitive market environment today forces companies to continuously create new products to serve the widening range of customer's needs. To be able to survive and succeed, companies need to develop new products faster while being cost-effective. Moving to more integral products was a successful strategy for some companies to keep their position in the market. Several means were used to fulfil this objective including weight reduction, quality improvement, and faster production.

In Manufacturing Industries for the example, the Delphi Automotive Company has reduced the car parts. The company has provided a cockpit that can be used as a duct to distribute air, removing parts that formerly served the same function and providing a cheaper solution (Kieran, 2004). In the airplane industries, Boeing designers and engineers are developing an intergal monolithic body design which results in reducing plane parts and weight, and consequently reducing cost.

In addition, this characterization applies to analogue-type household appliances that continue to get smaller or lighter. This has been achieved through the careful coordination of activities and functionalities in an integral manner. Such integral products require sophisticated design coordination of product-specific components and product-specific interfaces. However, it is an approach that keeps companies in competition.

Following the same approach, companies involved in the building envelope are seeking to expand their market range by integrating more functions in their products. For example new modular insulation boards are found nowadays in the market serving as both insulation boards and load bearing elements capable of supporting a two-floor house (Figure 1.1).

Competition for the massive industry is seen not only within companies providing the same products, but from companies providing different products yet fulfilling the massive layer functions. This makes integration in massive industry an approach that deserves being considered to secure the industry and survive the market competition.



FIGURE 1.1 Insulation panels providing load-bearing function

### § 1.5.3 Scientific Relevance

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In the external wall industry, the scientific background regarding the design processes and how to enhance them is readily available in literature. It mainly exists in the area of curtain walls and cladding systems in the work done by Tillmann Klein and Stephen Ledbetter (Du, Yang, & Ledbetter, 2011; and Klein, 2013). For massive external walls, the development of integral massive technologies has recently become available.

These technologies are worth being considered as mentioned above. However, their link to the design and construction process is missing in the scientific literature. Linking them to the design and construction process is the scientific aims of this research. Moreover, these technologies show promising approach in terms of material reduction and compactness. However, due to their newness, their exact potentials, drawbacks and performances still do not exist in scientific literature.

### § 1.6 Research Methodology and Thesis Structure

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In order to answer the research questions, the research is subdivided into three parts: research background, study of massive technologies applicable to external walls, and performance assessment of insulating technologies applicable to external walls in the Netherlands and Egypt. The contents of each of these parts are briefly outlined below followed by the thesis structure.

### § 1.6.1 Research Background

---

This Research Background part aims to answer the following sub-questions:

- How did the traditional wall in Egypt and the Netherlands develop?

In order to answer this question, the changes occurring to the external massive walls through history are highlighted. What changes happened to the massive external walls and what were the influences behind those changes? The focus of this part is directed more towards the Dutch and Egyptian contexts. Moreover, this part explains the design and construction process of the traditional external wall.

- How can a scheme be developed to analyse and understand additional functional façades and their design and construction process?

In addition, this part aims to find a scheme that links these functional and physical changes/developments occurring in the external wall to its design and construction process. This scheme will be used to analyse different new massive technologies.

The Research Background is based on literature review, the author's personal experience as an Architect, and interviews with specialists.

### § 1.6.2 Study of Massive Technologies Applicable to External Walls

---

This part aims to answer the following sub-questions:

- What are the existing and new massive technologies with additional functions?

In order to answer this question, the massive technologies with additional functions are introduced and their states are presented. Data to answer this question was gathered from existing products in the market, products currently being developed, existing projects, projects currently being developed, and finally research work done by educational and research institutes.

- How do these technologies affect the traditional process?

In this part, the considered technologies for external wall construction are analysed as per the developed schemes. The purpose of the analysis and subsequent discussion is to find an answer to the first main research question: What changes are required in

the present traditional design and construction process if massive technologies with additional functions are implemented in external walls?

### § 1.6.3 Performance Assessment of Insulating Technologies for External walls in Netherlands and Egypt

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This part aims to answer the following sub-questions:

- How can additional insulating massive external wall technologies be compared with the traditional external walls in the Netherlands and Egypt?

This section focuses on designing insulating massive external walls comparable with the traditional external walls in both the Netherlands and Egypt. Moreover, this part sets the criteria for the comparison. The framework of this assessment is derived from literature regarding the topic of “construction project success”.

- How do the additional insulating external walls perform in comparison with the traditional external walls?

Finally, in this part, the different wall performances are compared to the performance of traditional external wall construction in each country according to the set criteria.

### § 1.6.4 Thesis Structure

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According to the Research Methodology, Figure 1.2 shows the thesis structure, which includes the following eight chapters:

**Chapter 1** includes an introduction to the research topic, methodology, and thesis structure.

**Chapter 2** reviews the history of external wall construction, especially in the Netherlands and in Egypt.

**Chapter 3** introduces schemes for analysing additional function massive external wall.

**Chapter 4** highlights the new developments and technologies in massive construction.

**Chapter 5** presents the analysis of external wall construction technologies according to Chapter 3 scheme, and provides the conclusions regarding the first main research question.

**Chapter 6** introduces comparable wall designs using insulating massive technologies for Egypt and the Netherlands, as well as the criteria used in the assessment.

**Chapter 7** presents the assessment of the insulating massive external walls and provides the answer for the second main research question.

**Chapter 8** outlines the conclusions drawn from the present research.

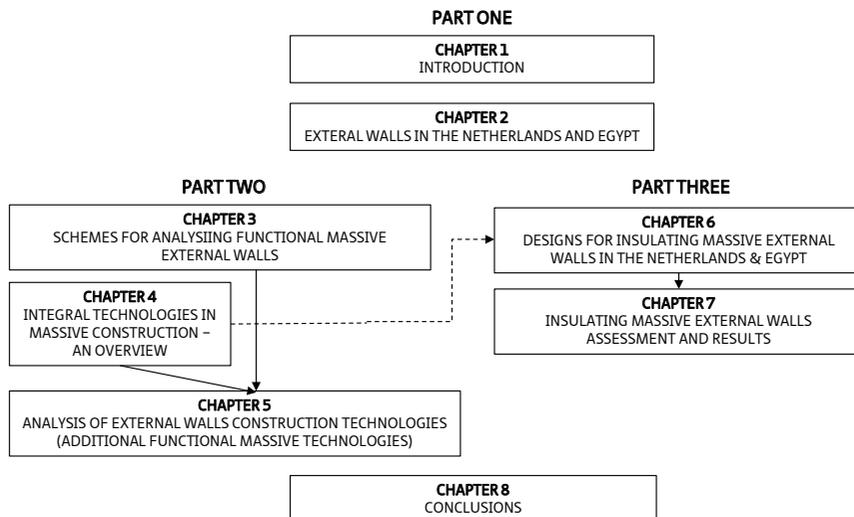


FIGURE 1.2 Thesis structure

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## § 1.7 Definitions

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The following terms are used throughout the thesis, and their definitions are stated below:

### Wall

The term 'Wall' as defined by Oxford Dictionary refers to a continuous vertical construction that encloses or divides space (Simpson & Weiner, 1989).

### External Wall

According to the previous definition, 'External Wall' can be defined as the continuous vertical construction that separates the indoor spaces from the outdoor spaces.

### Layered Wall

The term 'Layered wall' as defined by Ciampi refers to a non-homogeneous wall composed of a sequence of layers made from different materials (Ciampi, Fantozzi, Leccese, & Tuoni, 2001).

### Massive Material

The term 'Massive' in Oxford Dictionary is defined as large and heavy (Simpson & Weiner, 1989). Accordingly, the term 'Massive Material' in this research refers to heavy materials used in construction.

In former times, such materials were mostly natural earth materials such as natural stones. Nowadays, massive materials mostly refer to fired clay, lime or cementitious composite materials.

### Massive Layer

According to the definition of the term 'Massive' as stated above, 'Massive Layer' refers to the wall layer that is erected from massive material. In this research the term is limited to walls that define the enclosure and not walls used as cladding. These walls do not necessarily have a load-bearing function.

### Massive External wall

It refers to an external wall incorporating a massive layer. It can have either a monolithic structure or a layered structure.

### Traditional External wall

The term 'Traditional Construction' is defined by Echeverry as the common construction practice used in a specific location (Echeverry, 1991). Similarly, the term 'Traditional External Wall' refers to the common external wall typology used in a specific country/location. For example in the Netherlands, the traditional external wall construction for residential building is the cavity wall, whereas in Egypt the traditional external wall construction for residential buildings is the single leaf wall.

### Solid Wall

It is the opaque part of the wall. It can refer to a massive wall or a lightweight wall.

### Construction Technology

As defined by Tatum, 'Construction Technology' is either the physical product or process used in performing a construction operation (Tatum, 1987).



## 2 External Walls in the Netherlands and Egypt

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### § 2.1 Introduction

---

Massive external walls are still used in most parts of the world. However, they developed differently in different places. An example of such differences is the difference in the massive external wall layer used in the Netherlands and that used in Egypt. In order to understand today's external walls in both contexts, it is important to recognize how the external walls generally developed in these two contexts.

This chapter deals with the development of the traditional massive external wall in Egypt and the Netherlands. The literature review in this chapter focuses on *how such external walls have progressed in these two countries, how their designs are, and how their construction processes are shaped*.

First, the external wall development in the Netherlands is presented, then the external wall development in Egypt. The external wall developments in the two countries are outlined in two diagram forms. Second, the comparison between today's massive external walls in the two countries is illustrated in a table. Finally, the external walls design and construction process is explained in general, followed by a detailed explanation of the external walls in the Netherlands and Egypt.

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## § 2.2 Development of Massive External Walls in the Netherlands and Northwestern Europe

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### § 2.2.1 Massive External Walls in Ancient Times

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The Netherlands is located in Northwestern Europe. In terms of climate, the Netherlands has a humid climate. The average temperature varies between 2°C to 6°C in winter and 17°C to 20°C in summer (Weather Online, 2015).

The massive external walls of traditional buildings in Europe were usually of substantial thickness. They were made from masonry stone embedded in lime or earth mortar (Figure 2.1). Such external walls were wrongly interpreted as being homogenous through their cross-section. However in reality, they were not uniformly constructed as shown in Figure 2.2. They were usually constructed from an outer and an inner leaf of larger stones. These leaves had their inside faces left rough. The middle part was usually filled with smaller stones. Mortar was used to bind the stones together forming the wall (Baker, 2011). Wattle and daub system was also another massive system used for external walls in which wooden beams were woven together then filled with a mixture of soil, clay, sand, animal dung and straw (Figure 2.3).



FIGURE 2.1 Stone building, Appletreewick, England



FIGURE 2.2 Section in old traditional stone external wall



FIGURE 2.3 Wattle and daub system, Heimbach, Germany

However, in the Netherlands the art of brickmaking was flourishing instead (Hourihane, 2012). The natural building stones were hardly used in building construction, except for the central southern part of the province of Limburg, known for its building stone quarries. Nevertheless, the technique of brick making disappeared with the retreat of the Romans. Construction of most of the medieval buildings depended on perishable materials such as timber and loam. Imported stones were used only for more substantial buildings as they were costly and laborious.

Brick making appeared again in the building process at the beginning of the thirteenth century in the northern provinces of Friesland and Groningen (Harskamp & Dijstelberge, 2013). The abbey of Klaarkamp at Rinsumageest (Friesland) was constructed with bricks in 1163, followed by many brick churches which still exist today in the Netherlands from the thirteenth century (Figures 2.4 and 2.5) (Hourihane, 2012). By the sixteenth century, the use of brick in constructing both public buildings and houses became common and widespread. The external walls were generally thick and monolithic (Douma, 2005).



FIGURE 2.4 The Old Church in Delft from the thirteenth century



FIGURE 2.5 The brick pattern of the Old Church in Delft

## § 2.2.2 Massive External Walls after the Industrial Revolution

---

The Industrial Revolution brought major changes, from the use of manual labour to the use of power-driven machinery in the brick making. The first mechanical fabricated bricks appeared in 1858 (Y. Liu, 2009).

After the industrial revolution, brickmaking may have been the building material industry with the largest market in Europe. Bricks were the main building material because of the speed and competitive cost of construction with bricks, even where stones could be easily obtained (Figure 2.6) (Goldthwaite, 1982).



FIGURE 2.6 External walls of the Digbeth Cold Storage building

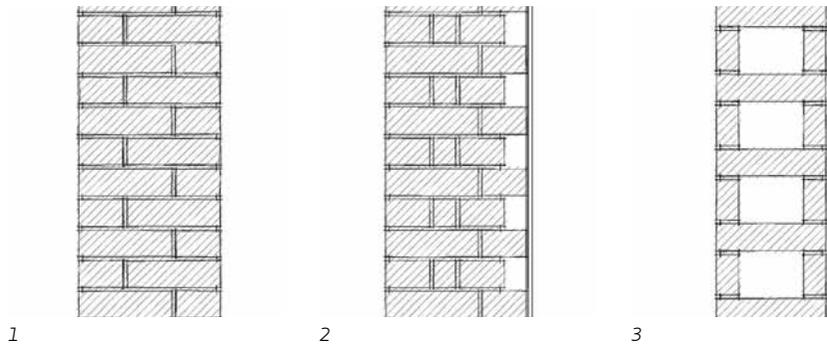
### § 2.2.3 Early Cavity Walls of the Nineteenth Century

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Because brick, stone, and mortar are permeable with respect to water; traditional monolithic external walls had to be thick to prevent water from reaching the inside surface. The entrapped water used to dry out completely between periods of rain. Relatively impermeable coatings were a potential problem during the drying out process since the water that finds its way in, does not find a way to get out. Nevertheless, external walls of that period (Figure 2.7) had the capacity to breath (Handisyde, Haseltine, & Association, 1976; Ochshorn, 1992).

In other cases, the brick external walls were not so thick. This is due to either the modest scale of the structure, or the pressure to reduce the weight of non-load-bearing exterior walls in skeleton construction. In these cases, other means had to be found in order to prevent dampness from reaching the inside surface (Ostrander & Satko, 2011). The first primitive version of cavity walls originated in the early nineteenth century to prevent such problem. In this version the “Old English” bonding pattern was modified through placing the alternating stretcher courses on their edge rather than their bed. This created intermittent air spaces between the monolithic header courses as shown in Figure 2.7 (Ochshorn, 1992).

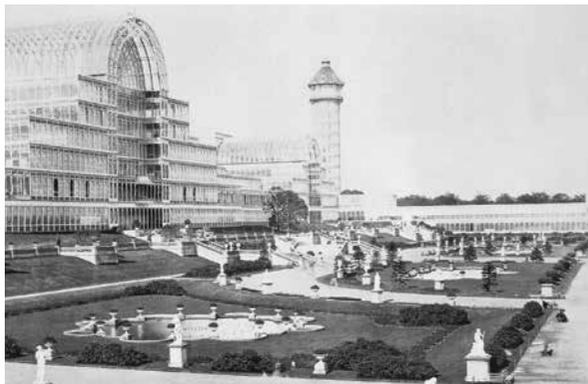
Another early effective solution was used to stop the migration of water from the exterior. This was done by projecting a number of bricks slightly beyond the face of the interior surface. A furring for plaster finish was then attached to these projected bricks creating air space between the brick wall and the plaster as shown in Figure 2.6 (Ochshorn, 1992).



1 2 3  
**FIGURE 2.7** Illustrations: (1) Thick single-leaf masonry Wall, (2) Wall with intermittent air spaces modified from the English bond, (3) Wall with projected bricks slightly beyond the face of the interior wall. (Ochshorn, 1992)

In terms of materials, alternative modern massive materials during this period were discovered. The modern Portland cement was discovered in 1824 giving rise to concrete as an alternative to clay bricks. Moreover, in 1866, the calcium silicate brick's method of curing under steam pressure was patented in England, and in 1894 their industrial production took place in Germany (Bowley, 1994).

In addition, in the nineteenth century non-massive external wall solutions showed up, affecting the way massive external wall developed. The nineteenth century was the beginning of the development of large panels of glass-characterizing structures, such as Paxton's Crystal Palace constructed in 1851 (Figure 2.8). Although Paxton used load bearing wall, it was one of the first attempts to utilize large panels of glass creating an alternative non-monolithic image for the exterior wall (Ochshorn, 1992). In 1864, the Oriel Chamber building (Figure 2.9) was erected in London with the first metal-framed glass curtain wall construction (Pevsner, 2005; Sharples, 2012). It was the first real attempt in our modern world to free walls from their load bearing function.



**FIGURE 2.8** Crystal Palace, England



**FIGURE 2.9** Oriel Chamber, England

## § 2.2.4 Cavity Walls of the Twentieth Century

Composite massive external walls were extensively used at the beginning of 1915 in order to reduce the weight of the external walls in high-rise framed structures. The composite external walls consist of masonry brick backed up directly with a hollow tile (Ochshorn, 1992). However, it was not until 1924 that the two leafs of the massive wall became separate constructions connected by a separate non-masonry sub-system, specifically metal ties (Figure 2.10). This system was first used by Constain house builders in England (Burnett, 1986; Scaysbrook, 2011).

### Possibility of Disappearance of the Massive Layer

The division within the wall created a conceptual space in which a layering system can be introduced. Once the task of coupling the two leafs was allocated to a separate sub-system, new variation of walls came into being. Just few years after the metal ties were introduced, a new wall version appeared. In such version, the outer massive leaf of the wall was replaced with a non-massive system, while the inner leaf was kept massive for fireproofing. In another version, the inner leaf of the wall was replaced with a non-massive system while the outer leaf was made of a single thickness of veneer brick (Figure 2.10). Later with the development of new materials for fireproofing, the elimination of massive layer from the external walls became possible for the first time (Ochshorn, 1992).

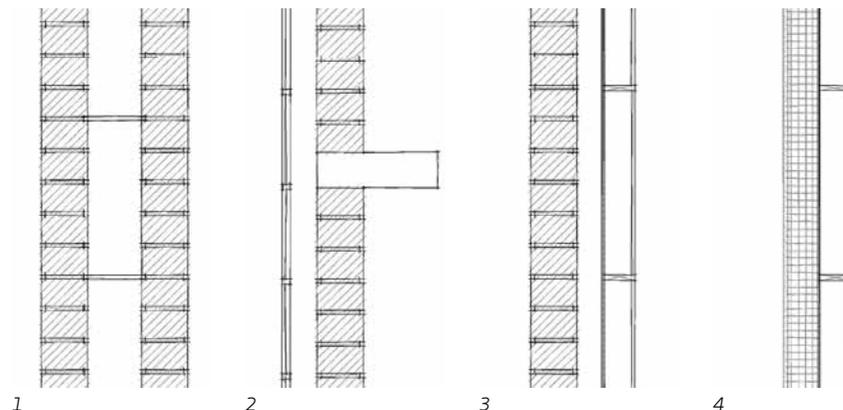


FIGURE 2.10 Illustrations: (1) Cavity wall with metal ties, (2) Curtain wall with massive backup, (3) Masonry veneer and nonmassive backup layer, (4) Layered non-massive wall. (Ochshorn, 1992)

## § 2.2.5 Modern Movement and Massive External Walls

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The modern architectural movements, which took place after the Second World War, accentuated new openness and lightness concepts. These new concepts opposed the thick load-bearing heavy walls. The structural trend of transferring the load-bearing role of the exterior wall to the columns and girders allowed the building skin to get rid of its structural role (Xue, 2006). Now most new buildings, whether using massive walls or non-massive walls, witness an organic separation between the load-bearing structure and the outer skin of the external wall.

However, it is worth mentioning that such separation has been applied long time ago. In the medieval period, there was a desire to build taller churches. Because the vaults were the system carrying the roof, higher walls meant longer lever arm of the vault pressure and thicker walls. The system of flying buttresses (Figures 2.11 to 2.13) then came with the idea of moving the structural element away from the wall and redirecting the lateral forces pushing a wall outwards to the ground. In this system, the wall no longer served as a structural element. The structural element became a separate layer attached to the exterior wall (Grinnell, 1946).

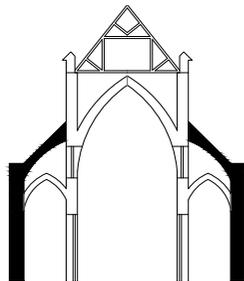


FIGURE 2.11 Flying Buttresses in section



FIGURE 2.12 Flying Buttresses of Abbaye de la Trinité, France



FIGURE 2.13 Flying Buttresses of Salisbury Cathedral, England

## § 2.2.6 Energy Crisis and Insulation

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In 1973 due to the Arab oil embargo crisis, there was a significant rise in energy costs. Designers and builders started to become concerned about the energy cost of buildings. This transitional shift affected the building industry, in general, and the building envelopes, in particular. Minimizing the energy necessary for heating the building became the envelope's main concern. Requirements for minimum R-values for various types of construction came into being. Masonry and concrete industries were given credit for their mass storage. An insulation layer became necessary to reduce the amount of heat gained and lost in buildings (Ostrander, 2008).

The cavity within the envelope was the best place to accommodate the insulation layer (Figure 2.14). The cavity was partially filled with an insulation material. In addition, the cavity kept retaining its original function of moisture prevention (Council, 1992; Ostrander, 2008)

This period resulted in major development steps for the external walls industry in Europe. The focus on enhancing the envelope's energy performance led to major changes in the external wall building industry. New materials were developed. New specializations such as building Physics Engineering became more attached to the building envelope focusing their efforts on enhancing the operational thermal envelope performance. The new energy regulations are being constantly developed putting more restrictions on external wall construction.

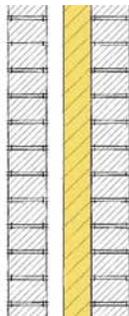


FIGURE 2.14 Cavity wall partially filled with insulation

## § 2.2.7 Scheme for External Wall Development in the Netherlands

By mapping the external wall development in the Netherlands (Figure 2.15), the following scheme shows the external wall development in terms of physical products, functions, and regulations.

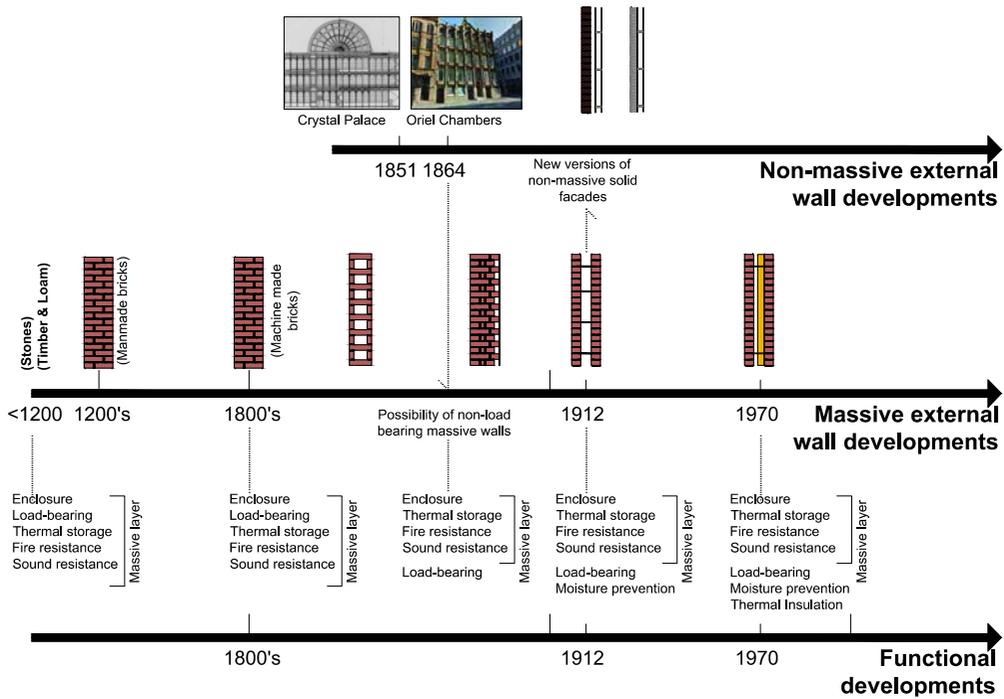


FIGURE 2.15 Scheme showing external wall development in the Netherlands and Northwestern Europe

## § 2.3 Development of Massive External Walls in Egypt

### § 2.3.1 Massive External Walls in Ancient Times

Egypt is characterized by dry/arid and hot climatic zone. Most of Egypt is desert (the Sahara desert of North Africa) except for the linear narrow valley extending around the Nile River across the country (Figure 2.16). Egypt has almost no rain and high diurnal temperature difference throughout the year. The weather temperature varies from 9°C to 19°C in winter, and 22°C to 34°C in summer. In summer peak temperatures could reach +43°C (Robaa, 2008).

Egyptians since ancient times used traditional passive cooling devices and shading systems in order to reduce heat impact and have a feel of thermal comfort. The passive elements include Courtyard, Malkaf, Mushrabiya, and Shuksheika and Thick Walls. These were always used in the construction of the buildings (Fathy, 2010; Mady, 2010). All the elements worked integrally together, including the external wall, and provide a controlled climate and an environmental-friendly construction as shown in Figure 2.17.

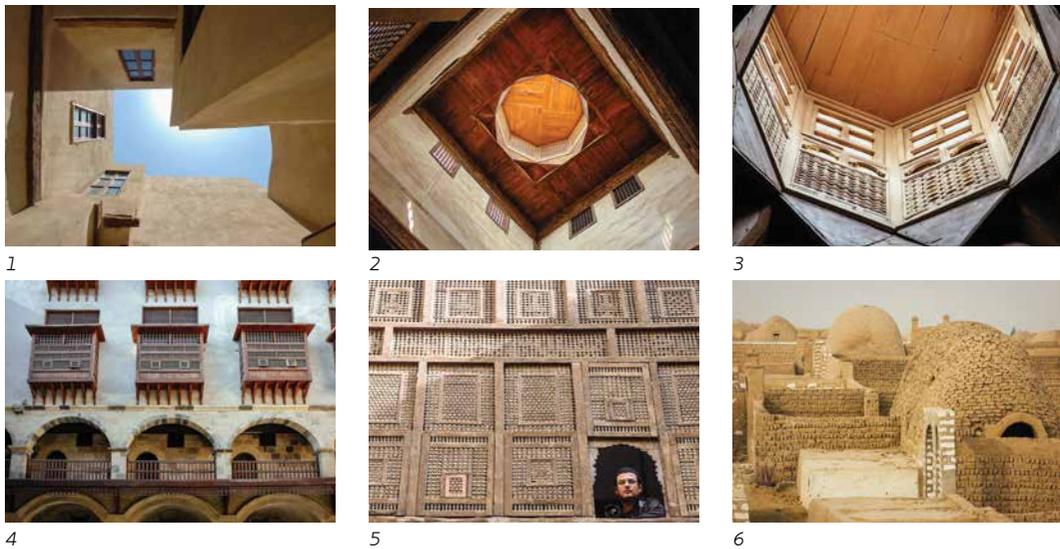


FIGURE 2.16 Egypt (Google maps, 2015)

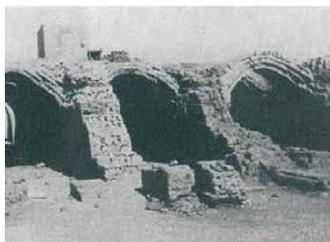
All systems yielded perfect responses to the climatic pressures they endure. The building envelope was a crucial and effective part of the system. It included architectural elements such as arches, vaults, domes, screens and thick walls; which had an effective role in adjusting the climate. Moreover, their application resulted in enriching the architecture of that period (Fathy, 2010).

Walls were constructed from adobe clay bricks (earth material). The average thickness of external walls ranged from 35 cm to 80 cm (Dabaieh, 2011). Thick walls served as load bearing elements, heat insulators and created natural thermal regulation (Figures 2.18 and 2.19). A mixture composed of 70% clay and 30% sand, with some straw added for binding, was used in the internal plastering. Whereas, a mixture composed of 65% clay, 30% sand and 5% lime was used in the external plastering. Lime acted as a waterproofing agent (Dabaieh, 2011).

Egyptians used hand moulded clay bricks (Figures 2.20) as far as 14000 BC (Pfeifer, 2001). Both fired and unfired, i.e. sun-baked bricks, were used in the early Egyptian civilization as discovered by archaeologists (Pfeifer, 2001).



**FIGURE 2.17** Illustrations: (1) Courtyards in private buildings (2) Malqaf 'Wind catcher' (3) Shuksheika (4) Mushrabia (5) Mushrabia (6) Domes



**FIGURE 2.18** Thick walls in Old Gournah, Luxor, Egypt. (3400 years ago)



**FIGURE 2.19** Building traditional vaults using clay bricks in Egypt



**FIGURE 2.20** Traditional method for casting mud brick, still used in few places, Dakhla oasis, Egypt

### § 2.3.2 Massive External Walls after the Industrial Revolution

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With the advent of industrial revolution, the integral passive building systems slowly became neglected. Many passive elements, which were traditionally used in buildings like courtyards and malqaf, became neglected. Even on the urban scale considerations, like studying the street profile in terms of building heights to street width ratio and using natural shading (trees) and artificial shading in streets, such practices were not considered anymore. However, the external wall still maintained its relatively thick profile (Figure 2.21) (Michel & Elsayed, 2006).



FIGURE 2.21 Typical building constructed in the beginning of the twentieth century

### § 2.3.3 Massive External Walls in Modern Times

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Around mid-twentieth century, with the widespread of concrete frame construction in Egypt, the external wall lost its load bearing function (Figure 2.22). There was no structural necessity to build thick walls. In parallel to the structural changes in walls, *modernization* trends in building designs in Egypt imported new technologies from abroad. Such technologies include exaggeration in the use of metal and glass and relying completely on mechanical air conditioning. No effort was done in design to adapt foreign technology to local conditions (Michel & Elsayed, 2006).

Unlike the Netherlands and Europe, Egypt's building industry was not subjected to any energy regulations. The external external wall constructions were not bounded to any energy restrictions. This lack of energy restriction, together with the loss of structural function and the desire of people to save internal space, allowed the external wall to continuously lose thickness and mass. The external wall thickness was reduced from about 35 - 80 cm to 25 cm (Figure 2.23).

The Egyptian masonry code states that the minimum thickness for external walls should not be less than 20 cm. Walls are commonly constructed with a thickness of 25cm. However nowadays, with the lack of supervision from the responsible authorities and in order to save internal space, external walls constructed with a thickness of 12 cm can sometimes be seen. The gradual neglect of passive systems, together with the gradual continuous loss in external wall thickness in our modern times, led to the high dependency on mechanical equipment in order to overcome overheating in buildings (Attia, Evrard, & Gratia, 2012).



FIGURE 2.22 Concrete frame construction replacing load bearing walls, Dakhla oasis, Egypt



FIGURE 2.23 Single-leaf brick wall, Egypt

### § 2.3.4 Scheme for External Wall Development in Egypt

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By mapping the external wall development in Egypt (Figure 2.24), the following scheme shows this development in terms of physical products, functions, and regulations.

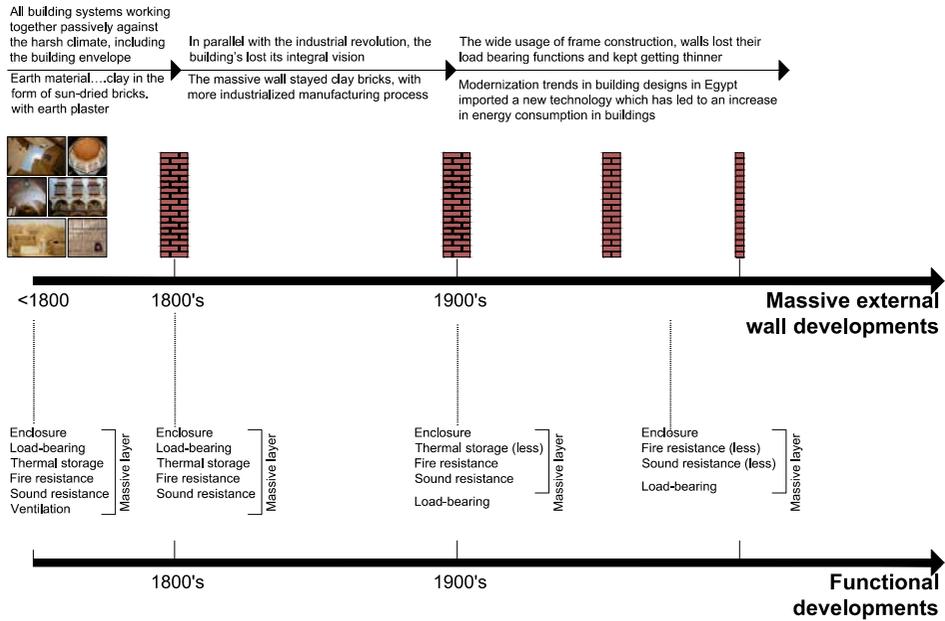
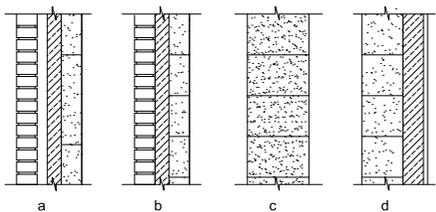
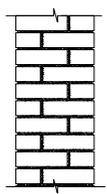
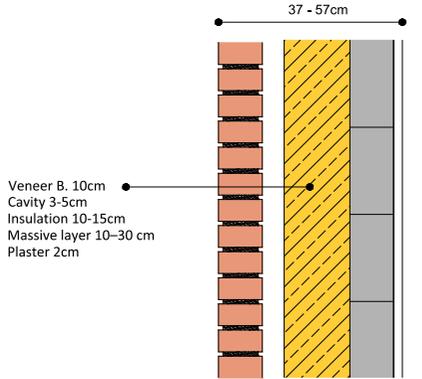
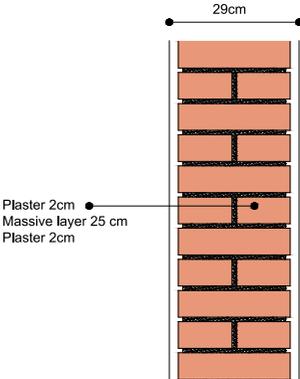


FIGURE 2.24 Scheme showing external wall development in Egypt

## § 2.4 Today's Massive External Walls in the Netherlands and Egypt: A Comparison

A comparison between massive external walls in the Netherlands and Egypt is given in Table 2.1.

	THE NETHERLANDS	EGYPT
External wall typologies found	<p>Types of massive external walls found today in the Netherlands are shown in figure 2.25. They can be summarized as follows (Santos, 2006):</p> <ul style="list-style-type: none"> <li>- Cavity wall with air cavity not or partly filled with thermal insulation (Figure 2.25 a)</li> <li>- Cavity wall with cavity completely filled with thermal insulation (Figure 2.25 b)</li> <li>- Single leaf masonry wall with rendering. The light weight blocks are used to meet the thermal insulation requirements (Figure 2.25 c)</li> <li>- Single leaf masonry wall with cladding that is combined with thermal insulation (Figure 2.25 d)</li> </ul>  <p><b>FIGURE 2.25</b> Wall typologies found in the Netherlands</p> <p>Based on (1) a report done by Santos under the title 'enclosure masonry wall systems worldwide' with one of its chapter focusing on the typical Dutch walls and (2) the author's experience as a façade researcher in the Netherlands, the cavity wall (type a, Figure 2.25) is the most common typology used for erecting massive external walls in the Netherlands (Santos, 2006).</p>	<p>In Egypt, based on (1) the author's experience working as an architect for 5 years in the Egyptian building market and (2) relevant literature studies, the single leaf masonry wall is almost the only wall typology used for erecting massive external walls in Egypt as shown in Figure 2.26 (Fahmy, Mahdy, &amp; Nikolopoulou, 2014; Sheta &amp; Sharples, 2010).</p>  <p><b>FIGURE 2.26</b> Wall typology found in Egypt</p>
Traditional massive external wall	 <p><b>FIGURE 2.27</b> Cavity wall partially filled with thermal insulation</p>	 <p><b>FIGURE 2.28</b> Single leaf masonry wall</p>

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About its components	THE NETHERLANDS	EGYPT
	<p><b>1- Massive layer</b>  <b>Masonry:</b> In the Netherlands, different types of masonry are used as the massive layer. These include calcium silicate, fired clay and concrete blocks. However, calcium silicate blocks are the most common type used in the Dutch external walls (Figure 2.29 and 2.30) (Santos, 2006). Calcium silicate masonry is made from blends of sand, stone with high silica content and lime as binder. It requires autoclaving (baked at about 200°C for 8 hours). Thin mortar or Glue, are its common bonding materials.</p> <div style="display: flex; justify-content: space-around;"> <div>  <p><b>FIGURE 2.29</b> Calcium silicate masonry</p> </div> <div>  <p><b>FIGURE 2.30</b> Layered cavity wall using calcium silicate masonry</p> </div> </div> <p><b>Onsite casted concrete:</b> Not commonly applied in external wall construction. However, it is usually applied on the side external walls when the tunnel construction system is used. The Tunnel system is reported to be used to construct 40% of new dwellings in the Netherlands and Belgium because of its speed and cost-effectiveness for larger developments (Energy Saving Trust, 2009).</p> <p><b>2- Veneer layer</b>  90% of veneer walls in the Netherlands are made of clay brick masonry (Santos, 2006).</p> <p><b>3- Ties</b>  Made usually from galvanised or stainless steel. These ties provide stability to the slender wall leaves and transmit wind loading from the outer wall leaf to the inner wall leaf. Depending on the height of the building and the exposure to wind loading, 4 to 6 wall ties per m<sup>2</sup> are used.</p> <p><b>4- Insulation</b>  Usually in the form of Wool or EPS boards that mechanically and/or adhesively fixed. Its thickness is dependent on the R-value required. With a current requirement of R-value of 4.5 m<sup>2</sup>k/w, a thickness of 15 cm of insulation (wool) is required.</p> <p><b>5- Cavity</b>  Usually between 3 - 5 cm for water drainage</p>	<p><b>1- Massive layer</b>  <b>Masonry:</b> Clay Brick are mostly used in both, internal and external walls in Egypt for all building typologies. The brick dimension is 25 x 12 x 6 cm and usually has 8 to 10 holes (Figure 2.31 to 2.33). Bricks are characterized by their low quality for two reasons. First, low raw materials quality are used by most manufacturers. Second, manual labour is used in many factories.</p> <div style="display: flex; justify-content: space-around;"> <div>  <p><b>FIGURE 2.31</b> Concrete frame skeleton and bricks as infill</p> </div> <div>  <p><b>FIGURE 2.32</b> Common used brick</p> </div> </div> <div>  <p><b>FIGURE 2.33</b> Single leaf brick wall building</p> </div> <p><b>Concrete hollow Blocks</b> are sometimes used in external walls when faster construction is required compared to clay brick. It is not commonly used in regular construction because it is more expensive than clay bricks. Moreover, it requires more detailed designs in area that has openings. (These areas require combination of solid bricks and blocks work).</p> <p><b>Onsite casted concrete:</b> Rarely applied in external wall construction in Egypt.</p> <p><b>2- Plastering</b>  A plastering layer is usually used as a finishing layer for both sides of the wall. The plastering ingredients are used mixed on site (cement, sand and water) with a minimum thickness of 2 cm on wall side.</p>

TABLE 2.1 Comparison between massive external walls in the Netherlands and Egypt

## § 2.5 Conclusions

This chapter gave an insight about how the massive external walls are shaped differently in two different contexts, the Netherlands and Egypt.

In the Netherlands, the techniques by which the traditional external walls were erected have changed dramatically. The traditional external wall had been known to be monolithic and of a single layer. This has been transformed with time into several sub-systems, each having a separate purpose and identity. The external wall gained more functions. However, the massive layer became more a mono function element. Many typologies of massive external walls can be found nowadays in the Netherlands. However, the cavity wall partially filled with thermal insulation is the most commonly used massive wall typology.

In Egypt, a different case has developed. The former traditional external wall that has been part of an integral system gradually lost its functions and became merely responsible for the enclosure function (fire and sound). In Egypt, with time, the external wall massive layer became more a mono function. Few massive wall typologies are seen in Egypt. However, the single leaf masonry wall with renderings on both sides is the commonly used external wall typology.



# 3 Schemes for Analysing Functional Massive External Wall

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## § 3.1 Introduction

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In the previous chapter, the massive external wall development in both the Netherlands and Egypt were mapped. Two main reasons caused changes in the building envelope. First, there were functional changes because of either an extra function needed or a function lost. Second, there were developments of new materials. This chapter aims to find a method that links these functional and physical changes/developments occurring in the external wall to its design and construction process. Particularly, the chapter investigates *how to develop a method to analyse and understand external walls with additional function and their design and construction process*. In order to find an answer to this question, this chapter focuses on defining two main schemes for analysing the external walls, the Component-Function scheme and the Design and Construction Process scheme.

The chapter is divided into three parts. The first part focuses on the Component-Function scheme in which the topic of product architecture is first discussed, followed by an explanation of external wall components, then an illustration of external wall functions. In the second part, the design and construction process of massive external walls is explained and the process scheme is generated. Finally, examples of Dutch and Egyptian walls are analysed.

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## § 3.2 Component-Function Relations

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The theory of product architecture gives a good insight on how realization of functions within a product can affect the product composition and its behaviour. In his research about curtain walls, Klein used the theory of product architecture as a base for his analysis scheme, in which he analysed different curtain wall constructions (Klein, 2013). Similarly in this research, the theory of product architecture serves as a base for developing the analysis scheme for massive external walls.

### § 3.2.1 Product Architecture

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Karl Ulrich in 1995 presented his paper 'The Role of Product Architecture in the Manufacturing Firm'. In this paper, he tried to enhance the performance of manufacturing firms through some product decisions made during the early phases of manufacturing (Ulrich, 1995). The paper mainly collects information from different research communities such as those dealing with design theory, software engineering, operations management and product development. However, it offers a valuable vocabulary to analyse external wall construction, especially in terms of their functions and components behaviour.

Karl Ulrich discussed in his paper the importance of functions when developing or analysing products as functions constitute the main objective a construction is designed for. He discussed how the decisions about the way functions are realized within a product affect the behaviour of the product in all its stages, from the way the product is designed to the way it is recycled.

To support this idea, Ulrich used the term Product Architecture. He defined it as *the scheme by which the function of a product is allocated to physical components*. In a later more precise definition, Daniel Whitney defined Product Architecture as *the scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact* (Whitney, 2004).

As described by Ulrich, the scheme is determined as follows (Ulrich, 1995):

## Functional Structure

The functional structure is the set of functions the product needs to perform. These functions can be created at different levels of abstraction. For example, the functional structure of a vehicle trailer can consist of a single function like *expanding cargo capacity*. In a more detailed level, its functional structure can consist of functional elements such as *connecting to vehicle*, *protecting cargo from weather*, *minimizing air drag*, *supporting cargo loads*, *suspending trailer structure*, and *transferring loads to road*.

## Mapping from Functional Elements to Physical Components

Mapping explains the way different functions are linked to the components of a product. This mapping can indicate three different relationships between the functions and components of a product as illustrated in Figure 3.1. In a one-to-one mapping relation, one function is performed by only one component. In a many-to-one mapping relation, one component performs more than one function. In a one-to-many mapping relation, one function performed by several components.

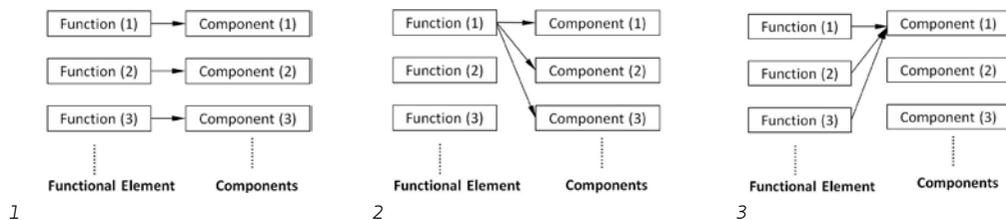
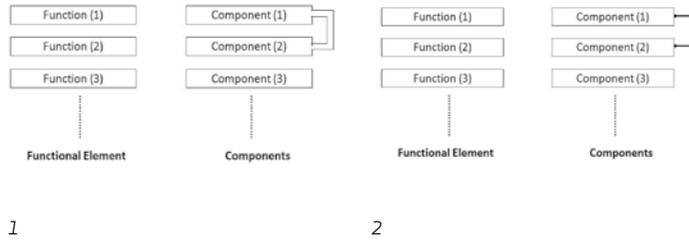


FIGURE 3.1 Illustrations of (1) One-to-one mapping, (2) One-to-many mapping, and (3) Many-to-one mapping (Ulrich, 1995)

## Types of Interfaces between Physical Components

The interface between physical components can be either a coupled interface or a decoupled interface as illustrated in Figure 3.2. In the coupled interface, any change made to one physical component requires a change to be made to the other component in order for the overall product to work correctly. In the decoupled interface, the components are independent; i.e. any change in a component will not affect the other components.



1 2  
 FIGURE 3.2 Illustrations of (1) Coupled interface between components, and (2) Decoupled interface between components (Ulrich, 1995)

Based on Ulrich’s Theory, the previously-mentioned aspects result in one of two extreme product typologies: Modular Product Architecture and Integral Product Architecture. These two typologies are outlined in the following paragraphs, then the importance of defining product architecture is discussed.

### Modular Product Architecture

A modular product is defined by as a product that includes a one-to-one mapping from its functional elements to its physical components, and having de-coupled interfaces (Ulrich, 1995). A good example of a modular product is the Desktop Computer shown in Figure 3.3 (Klein, 2013).

The desktop computer is a an example that displays one-to-one mapping from its functional elements to its physical components; i.e. for every functional element, there is a specific component. The content is displayed visually through a monitor screen. Communication is carried out manually through a mouse. The information is entered through a keyboard and data is processed through a tower. In addition, the Desktop Computer presents a decoupled relation between its components. Any of its components can be changed or upgraded without necessity to apply changes to other components.



FIGURE 3.3 Modular product architecture of a desktop computer

## Integral Product Architecture

---

An integral product is defined as a product that includes complex (not one-to-one) mapping from its functional elements to its physical components and/or having coupled interfaces between its components (Ulrich, 1995). A tablet shows an integral product architecture if analysed on the same functional and component levels as the desktop computer was analysed. All the required functional elements are achieved by one component, showing a many-to-one mapping. Moreover, it shows a more coupled interface between its components (Figure 3.4).



FIGURE 3.4 Integral product architecture of a tablet

## Importance of Defining Product Architecture

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The typology of product architecture provides a vocabulary for understanding and discussing the implications of the choice of a product architecture on the product composition, as well as its managerial and market behaviour. Some of these implications are listed below (Whitney, 2004).

### *With Modular Product Architecture*

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- Predesigned standard interfaces can be applied. They can remain even if internal characteristics change.
- Chunks can be tailored to their individual contributions to the overall function. They can be interchangeable.
- Unpredictability of module choice requires over-design to accommodate the possible mismatches.
- Interfaces are physically separated from the chunks. This can make the interfaces weaker, with a possibility of losing other design potentials such as space or weight reduction.
- Interface management, if planned well, can provide flexibility during production and assembly.

- Interfaces are tailored to the chunks. They are dependent on the functional performance of the chunks.
- Chunks are tailored to their applications. They cannot be interchanged.
- The overall design can be optimized according to a predictable set of functions.
- Interfaces can be integrated with the chunks. This can make interfaces stronger, with a possibility of saving space or weight.
- Interface management is not aimed to provide flexibility. It is frozen once the design is set.

It is important here to mention that no single architecture is optimal in all cases (Ulrich, 1995). Each architecture has its own merits and drawbacks. However, understanding the architecture behaviour is important to effectively choose an architecture for a particular product.

Most products show a combination of characteristics depending on the level of the overall system and the level of components or individual parts. In the Desktop Computer example mentioned previously, the Desktop Computer was analysed as a modular product. However, its components, like the screen, may exhibit integral characteristics.

### § 3.2.2 Definition of Product Level

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In the previously mentioned Tablet case, the Tablet as a component showed an integral architecture as an overall system. However, if analysed on a more detailed level, its parts may show a modular behaviour. Similarly for a massive external wall, in order to define architecture of the product and its behaviour, a more detailed analysis of the massive external wall components is necessary. The level of components that make up the overall system needs to be defined before to taking further steps in developing the scheme.

In Figure 3.5, Eekhout explains a hierarchical range of industrial building products (Eekhout, 2008). In this range, raw materials and building complex act as starting and ending points simultaneously. Moving within these product ranges requires special treatments and steps. For instance, the change from raw material to material requires refining. In addition, the change from a material to composite material requires mixing.

The product level made by Eekhout is general for all building products (Eekhout, 2008). However, in this research, this range has been simplified and slightly redefined to the massive external walls context (Figure 3.6).

The following gives a definition for each product level:

- 1 *Material* refers to both raw material, which is the base ingredient not involving any treatment such as sand, and a material, which requires special refining such as cement.
- 2 *Composite Material* is shaped as a result of a mixing process of several materials. Ready mixed concrete bags/mixtures are considered a composite material.
- 3 *Element* requires shaping and is available in a standardised form such as clay/concrete bricks.
- 4 *Sub-component* is an assembly of elements. However, it is still not an independent functional component. It still requires assemblies to achieve its purpose. An example of a sub-component is a preassembled brick work.
- 5 *Component* is an independent functioning building unit, which is built up from a number of composing elements and/or sub-components. An example of a component is the massive layer of the wall, which consists of bricks and mortar, and which is capable of transmitting structural loads.
- 6 *Building Part* is defined as a collection of elements and components. An example of a building part is an external wall with all its layers, which fulfils all external wall functions.

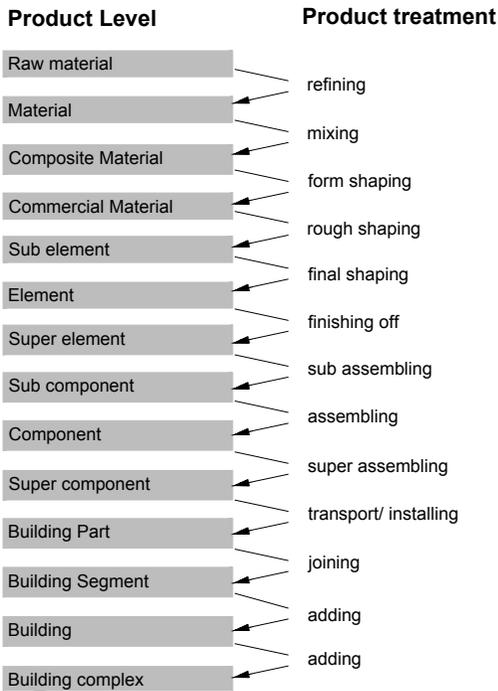


FIGURE 3.5 Hierarchical levels of industrial building products based on Eekhout

Product Level	Examples
Raw Material	Sand/ Clay
Material	Cement
Composite Material	Concrete
Element	Concrete Block/ Clay Block
Sub component	Pre-assembled bricks
Component	Masonry Wall (Blocks + Mortar)
Building Part	Complete Wall (with all layers)
Building	

FIGURE 3.6 Simplified version for massive external walls with examples

### § 3.2.3 Definition of External Wall Functions

To develop the Component-Function scheme, a detailed analysis of the external wall functions, similar to the component level analysis, needs to be defined with its different levels. In the following paragraphs, the external walls functions are discussed based on literature. Then, the massive external wall functions adopted in this research are outlined.

#### External Wall Functions in Literature

Many researchers have attempted to sort external wall functions in different ways according to their points of view. In the book, "External wall Construction Manual", Herzog et al. divide the external wall functions into protective and regulatory functions (Herzog, Krippner, & Lang, 2004). Protective functions are the functions responsible for protection against external influences, whereas regulatory functions are the functions responsible for providing comfortable interior climate conditions.

Straube and Burnett in their book “Building Science for Building Enclosures” categorize the building envelope functions in a different way (Straube & Burnett, 2005). The first group of functions are the support functions, which are responsible for resisting and transferring mechanical loads. The second group are the control functions, which control the flow of matter and energy of all types like rain control, air control, heat control, and vapour control. The last group of functions are the finish functions, which are responsible for meeting the human desires on the inside and outside.

Kazmierczak divides the external wall functions into two primary categories: tangible and intangible functions (Kazmierczak, 2010). Tangible functionality includes all physical attribute such as protection against external influences, providing a comfortable climate, constructability and maintenance. On the other hand, the intangible functions include unphysical attributes, like giving the building the symbol for power or wealth.

Finally, Klein uses a function tree to sort external wall functions as shown in Figure 3.7 (Klein, 2013). The external wall function tree is organised in five categories with increasing detail level: main function, primary and secondary functions, supporting functions, and detailed supporting functions. The first three categories provide a general description of functions, while the supporting and detailed supporting functions offer indications on how to solve the functional requirements. The function tree serves as an overview of the complex requirements an external wall has to fulfil.

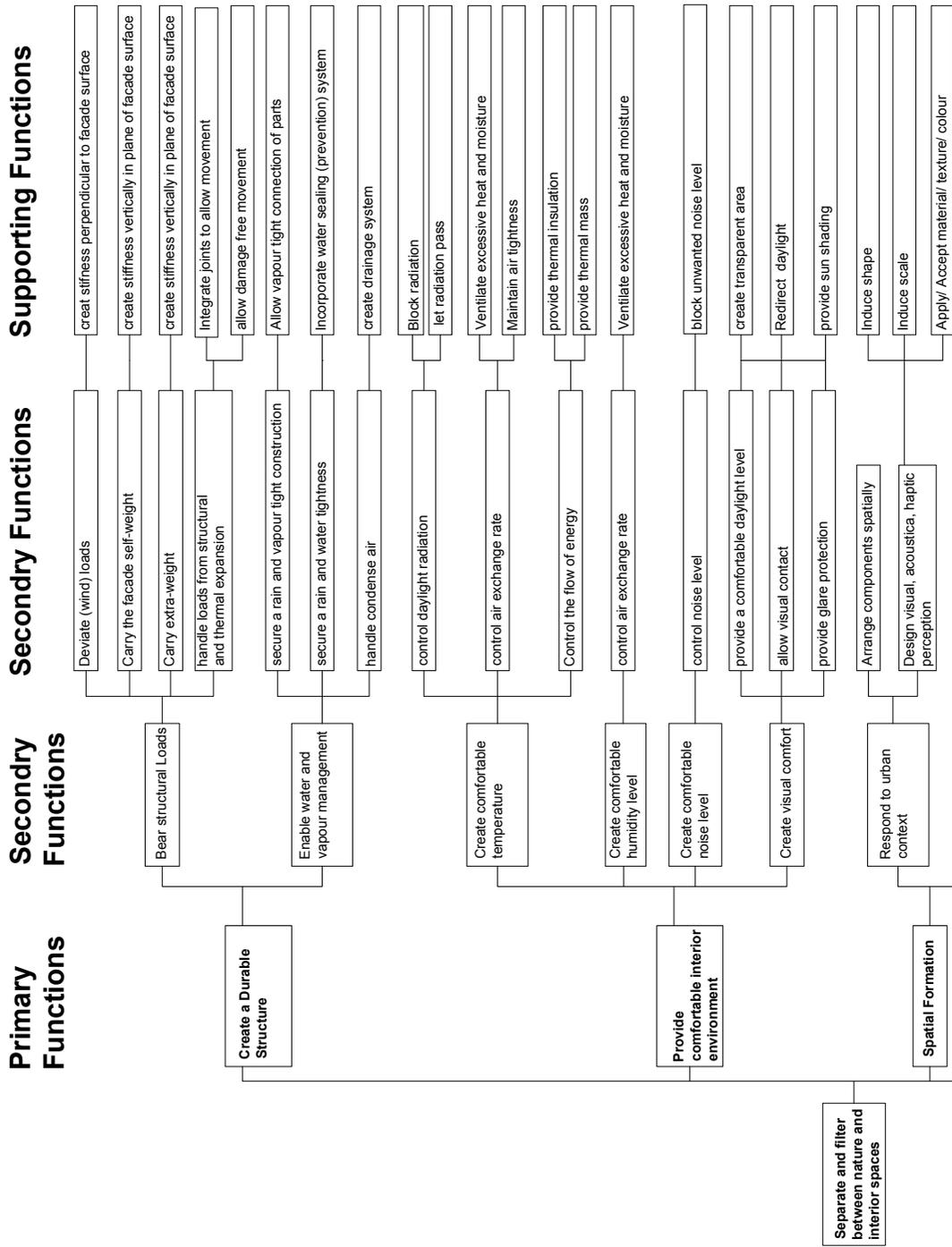
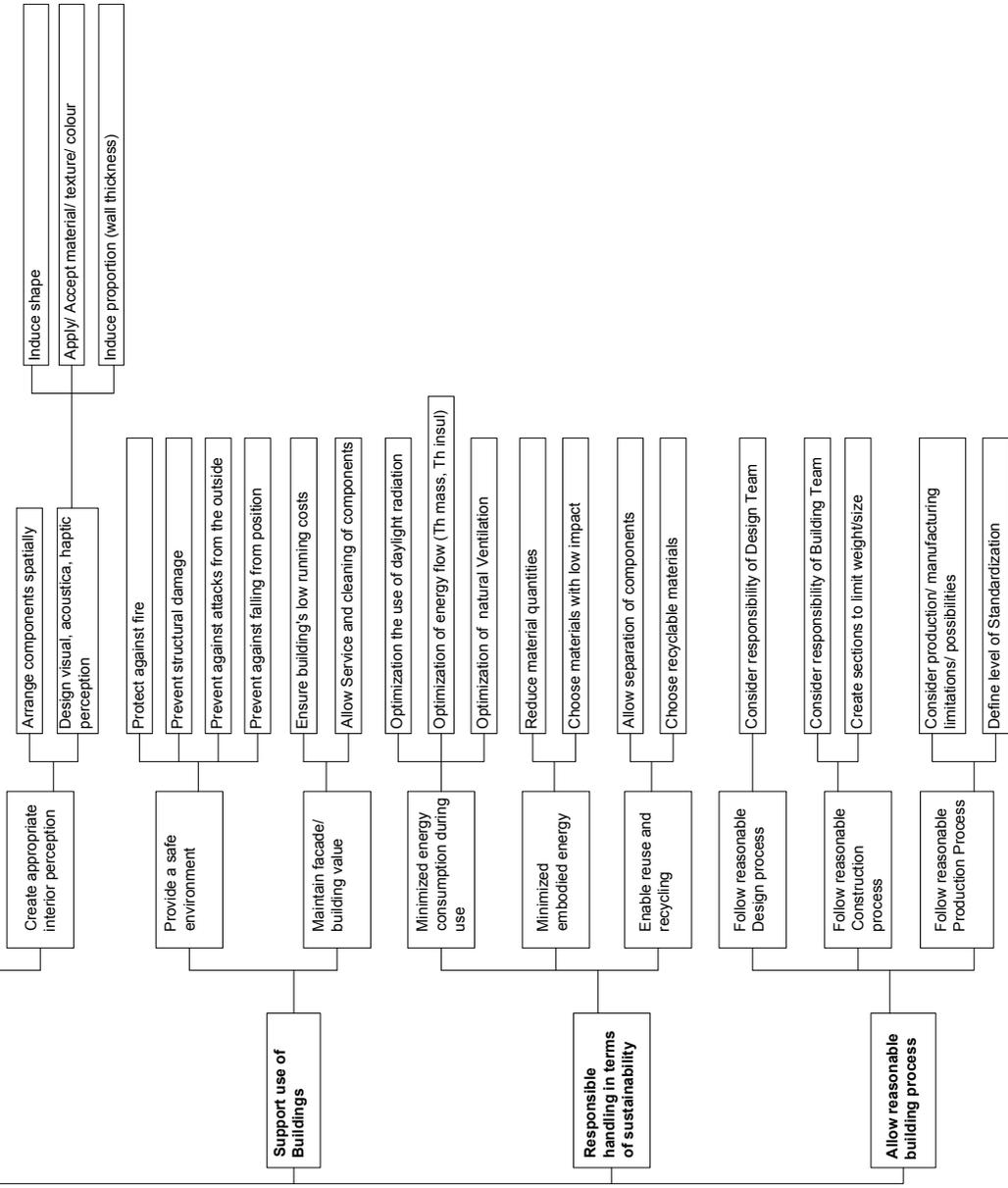


FIGURE 3.7 Klein's function tree



## Massive External Wall Functions

Based on the previous literature review about external wall functions, Klein’s functional tree will be used as a base for external wall functions in the proposed Component-Function scheme. Klein’s functional tree provides the most extensive external wall functions in the reviewed literature. However, to be applied in this research, Klein’s functional tree will be adapted to include only the following functions:

- 1 Solid wall functions. Therefore, functions like ‘Provide a comfortable daylight level’, which is allocated to the window, are not applicable.
- 2 Supporting functions. This is because supporting functions are the basis for considering the physical components (Klein, 2013). Connection to actual physical components can be made at this level. Higher levels (main function, primary functions and secondary functions) are more general, while the lower level (detailed supporting functions) becomes more complicated.
- 3 Functions that can be linked to physical components. Therefore, functions; which are related to the process and supply chain, for example; are not applicable.

This resulted in the function levels and functional elements shown in Figure 3.8.

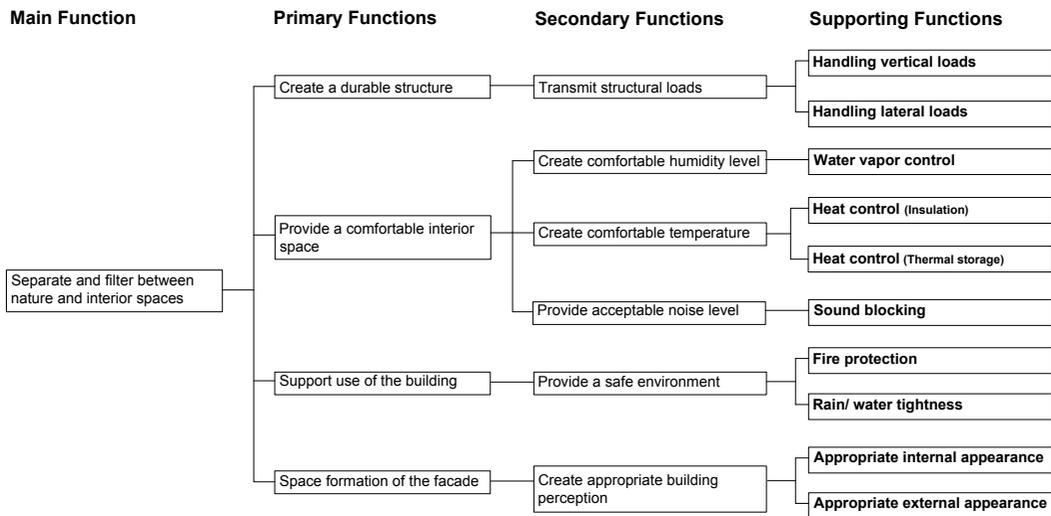


FIGURE 3.8 Simplified functional tree for massive external walls

### § 3.2.4 Component-Function Scheme

Considering the product architecture and massive external wall components and functions as discussed in the previous sections, a scheme for the analysis of massive external wall construction can be developed as shown in Figure 3.9.

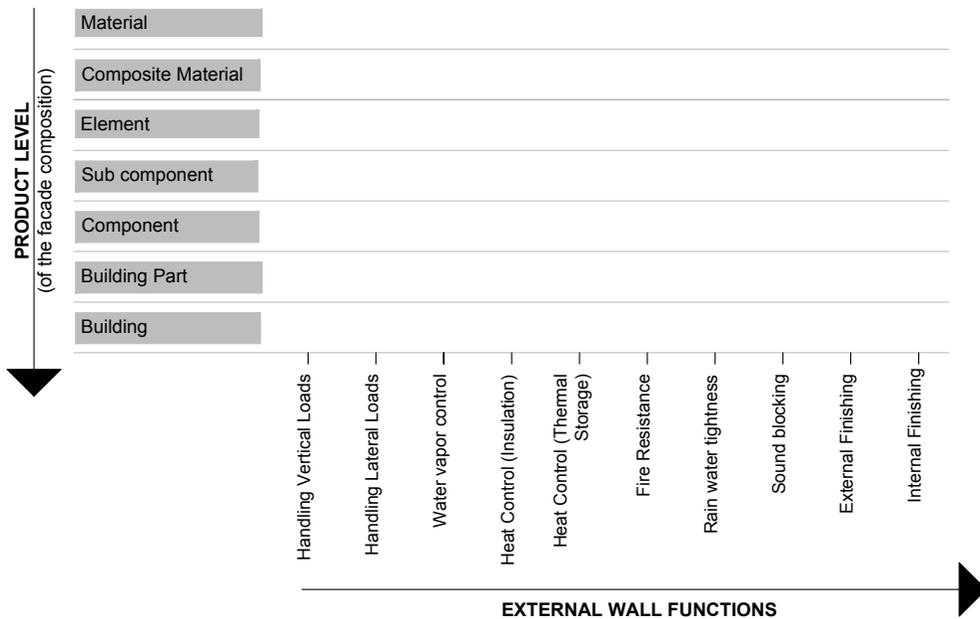


FIGURE 3.9 Analysis scheme for massive external walls

The analysis scheme is based on the following:

- 1 The hierarchical scheme of product levels. It shows the construction composition of the external wall. It ranges from material to elements and from components to building parts.
- 2 The external wall function elements as simplified from Klein's functional tree. The elements cannot be claimed to be complete, but they can serve well in developing the scheme.
- 3 The theory of product architecture describes the relations between the physical components of the external wall and its functional elements.

In the following part, the traditional external walls of the Netherlands and Egypt are analysed using the proposed scheme. The main purpose of this part is to understand how the scheme works, and how data can be extracted from it.

**SCHEME FOR A TRADITIONAL DUTCH MASSIVE EXTERNAL WALL (FIGURE 3.10) ILLUSTRATED IN FIGURE 3.12**

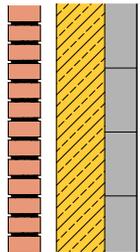


FIGURE 3.10 Traditional Dutch massive external wall

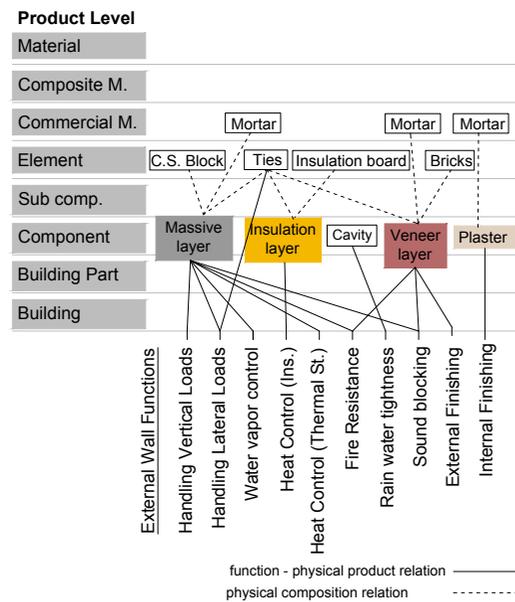


FIGURE 3.12 Scheme for traditional Dutch massive external wall

**SCHEME FOR A TRADITIONAL EGYPTIAN MASSIVE EXTERNAL WALL (FIGURE 3.11) ILLUSTRATED IN FIGURE 3.13**

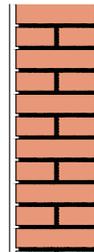


FIGURE 3.11 Traditional Egyptian massive external wall

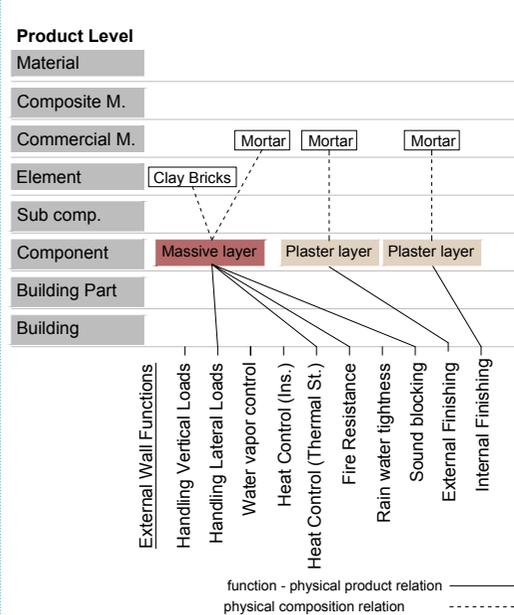


FIGURE 3.13 Scheme for traditional Egyptian massive external wall

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## Explanation

### Function structure

By mapping the functional elements to the physical components as illustrated in Figure 3.14, it can be seen that the external wall has both modular and integral architecture. The modular architecture is apparent because each component is responsible for a function or a set of functions (one-to-one mapping), separate from other components (Figure 3.14).

However, it also shows an integral aspect within its components as its massive layer performs a set of functions (many-to-one mapping) as shown in Figure 3.14. Moreover, the interface between its components is mostly a coupled interface. Layers are usually attached together with metal ties that do not provide a flexible solution when changes in components are required.

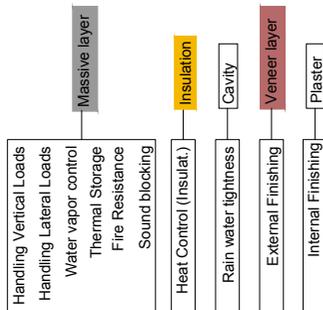


FIGURE 3.14 Functional structure of traditional Dutch massive external wall

### External Wall Composition

The modular one-to-one mapping behaviour of the Dutch external wall is what mostly shapes the external wall to have a layered profile.

The external wall main components are outlined as follows:

- The massive layer (component level). It is assembled from CS blocks (element level) and mortar (commercial material level)
- The insulation layer (component level). It is assembled from insulation boards (element level) and ties (element level).
- The cavity.
- The veneer masonry layer (component level). It is assembled from veneer brick (element level) and mortar (material level).
- The plaster layer (component level). It is composed of mortar (element level).
- The ties (element level), serving as connections

## Explanation

### Function structure

By mapping the functional elements to the physical components as illustrated in Figure 3.15, it can be seen that the external wall performs fewer functions, and is composed of fewer components when compared to Dutch wall. However, similar to the Dutch Wall, it has both integral and modular architecture.

It shows a modular product architecture because each of its three components performs a different set of simple functions. In addition, it shows an integral aspect within its components as its massive layer performs a set of functions (many-to-one mapping) as shown in Figure 3.15. Moreover, the interface between its components is a coupled interface because the plaster layers are directly applied on the massive walls.

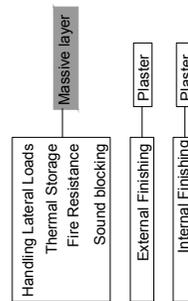


FIGURE 3.15 Functional structure of traditional Egyptian massive external wall

### External Wall Composition

The external wall performs few functions through a more single-leaf format.

The external wall main components are outlined as follows:

- The massive layer (component level). It is assembled from clay bricks (element level) and mortar (material level).
- The inner plaster layer (component level). It is composed of mortar (element level).
- The external plaster layer (component level). It is composed of mortar (element level).

The previous two analysed examples show how data can be extracted from the scheme. In addition, they highlight the following points:

- 1 In both traditional external walls of the Netherlands and Egypt, some functions can be developed separate from each other, such as the external finishing function and the load-bearing function. The two functions are performed by two separate layers. Therefore, a change in the performance of one function is independent from the performance of the other. Other functions are related to each other, such as the thermal storage and the sound resistance function. Both functions are performed by one layer. Therefore, a change in the performance of one function affects the performance of the other function. This functional behaviour affects the way in which stakeholders interact together, as will be explained in the following section.
- 2 The Dutch external wall shows a more complex composition compared to the Egyptian wall. This is because the Dutch external wall performs more functions, particularly related to the climate, through a more modular construction. Therefore, more separate systems are required to perform the climate functions.

## § 3.3 Design and Construction Process

### § 3.3.1 Development of Design and Construction Process

In former times, buildings were simply constructed and designed according to the local needs of people, without the need for an architect. The owner was the designer and sometimes he was also the builder.

Design depended more on experience gained from trial and error and on the accumulated knowledge of the builders (Haseltine, 2012). Nowadays buildings became more complicated, following various rules and regulations, and with a wide variation of material options. This resulted in a more complicated design and construction process.

As design continues following a number of steps, more and more details and layers are added. The phases of design and construction separate the task into viable chunks, in which client approval becomes required at the end of each phase to move to the next phase.

The process in most countries is carried now through more or less the same phases. These phases include:

- 1 Pre-design
- 2 Schematic (Conceptual) Design
- 3 Design Development
- 4 Construction Drawings and Specifications
- 5 Production/Construction
- 6 Operation/Use
- 7 End-life

Table 3.1 describes the different phases as related to massive external walls. Data in the table are based on literature review and the author's experience as an architect.

PROJECT STAGE	EXTERNAL WALL DEVELOPMENT LEVEL
Pre-design Phase	At this stage, external walls are not being developed yet. Only the project's scope and the basic requirements for the project are being defined.
Schematic Design	The process of designing the massive external wall starts at this stage (Karhu, 1997). The Building elevations are developed by the architect concentrating more on the visible objects. The process begins with the definition of the general shape of the external wall, then openings and surfaces. Depending on the project size and complexity, more disciplines can become involved in the external wall's schematic design.
Design Development	<p>During the detailed design stage, all external wall consultants (architect, structural designer, and building physics engineers) become actively involved in all building components (Karhu, 1997).</p> <ul style="list-style-type: none"> <li>- Finer architectural external wall details are defined: shape, division, dimension, execution colour, texture and the finishing off.</li> <li>- The structural engineer makes decisions about the external wall structural element in terms of materials and dimensions. If the external wall includes tiling or cladding, the structural engineer makes decisions on the method of attaching the external wall panels to the structural frame of the building with tolerances, movements, etc. (Karhu, 1997).</li> <li>- Element divisions and joints are defined. They may be determined either by the architect or by the structural engineer, depending on the responsibility agreement of each participant (Karhu, 1997).</li> <li>- A building physicist (usually a part of the Consultant's team) models sections and different combinations of materials and assemblies to choose the exact building enclosure assembly. This choice is based on energy modelling for heat and moisture transfer analysis of external wall, roof, window and similar building envelope components (Lemieux, 2010).</li> <li>- Mechanical systems should be concurrently designed, together with the building envelope decisions, and selected materials (Lemieux, 2010).</li> </ul> <p>From these decisions, a refined set of design documents is developed, together with initial material specifications.</p>
Construction Drawings and Specifications	<p>In this stage, the architect and other members of the design team proceed with finishing the external wall's construction documents. This includes all the external wall's technical drawings, its technical specifications, scope of delivery, administrative conditions, time requirements for building phases, and installation conditions.</p> <p>It is worth here mentioning that the way in which external wall components can be specified differs (as well as building components in general). It can be through either prescriptive specification, or performance specification. For example a facing brick can be specified in the prescriptive specification as 'Wienerberger', 'Red Rustic'. This gives both the name of the manufacturer and the type of brick including the performance of the brick in terms of size, colour, durability, water absorption, etc.. In this method, the designer is precise and knows exactly what he expects from his selection. This is why this method is usually favoured by designers for materials that will be visible like the external wall's outer layer.</p> <p>In the performance method, the facing brick is only specified by its size, colour, texture, durability, etc.. A range of different manufacturers may satisfy the required performance, which gives the choice of the product to the contractor. This method is believed to give more room for cost reduction and innovation (Emmitt &amp; Yeomans, 2008).</p>

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PROJECT STAGE	EXTERNAL WALL DEVELOPMENT LEVEL
Tendering	<p>The external wall's tendering depends on the selected project's contractual/procurement method. This can be:</p> <p><b>Design-Bid-Build:</b> It is the most contractual method applied in the building industry (Lam, Chan, &amp; Chan, 2008; Volker &amp; Klein, 2010). The tendering stage takes place in this procurement method as a result of the separate responsibilities for design and execution. The design team is commonly employed by the owner until the end of the CD and specifications. Once the design is completed by the design team, a number of construction companies bid for the work. The bid is either based directly on the design, or on the bill of quantities provided by a quantity surveyor. The owner then awards a contract to the most cost efficient bidder after the bidding evaluation.</p> <p><b>Design-Build</b> Design-Build construction method is when the designer and contractor are the same entity or are on the same team (without tendering stage). Most of the design-build projects are led by the contractor, who hires an architect to design the building, which the contractor then builds for his client. However, recently, some architects have begun to take a lead role in the design-build procurement method (Architect led design-build) (Volker &amp; Klein, 2010). In this case, the architect procures the construction work to a general contractor or to various sub-contractors. Although architect led design-build is new, it gives the architect his role as a master builder, rather than being only the designer.</p> <p>The procurement methods can have a direct effect on the selection of the external wall's system. In the design-bid-build, the contractor is unknown during the design. His capabilities to build systems that can be different is thus unknown. This always pushes the architect and external wall engineers to select the common used external wall systems known for the builders. However, in the design-build (either led by architect or contractor) there is a potential for greater collaboration between the designer and contractor in the early stages with shared risks and reward.</p>
Production/Construction	<p>Prior to the construction of building envelope, the builder has to execute a number of internal design drawings, known as shop/working drawings, to be able to construct the building.</p> <p>According to the agreement done, the designer can require the contractor to provide shop-drawings for all the massive external wall elements (reinforcement, anchors, ties, flashing), mix designs, and connection details of all layers. The designer can also request samples for verification of colours, textures, and pattern specified. Depending on the project's size and external wall complexity, mock-ups and performance testing can be required from the contractor.</p> <p>Based on the shop drawings, the contractor executes the external wall element by element through different subcontractors. The main construction trades related to the massive external wall erection are bricklaying, concreting (formworking, reinforcing, and concrete placing), insulation installation, and applying finishing.</p>
Operation/Use	<p>The operation phase starts with occupation of the building by the users. This is when the external wall's required performance and the actual performance are truly reflected. Maintenance work for the external wall parts takes place at this stage external wall (if necessary)</p>
End-life	<p>The demolition of a building was often regarded as the end of the life cycle. Later, research started to pay attention to the total energy used for production of materials. Reusability and recyclability became important possible scenarios for the end of life cycle (Hildebrand, 2012; Thormark, 2001).</p> <p>For the massive external walls, the concrete and brick material have both potentials of being recycled. However, the way in which the external wall is constructed in a layered manner makes separation of materials a hard process.</p>

TABLE 3.1 Design and construction phases of massive external wall

### § 3.3.2 Design and Construction Process Scheme

Based on Table 3.1, the scheme outline shown in Figure 3.16 can be generated. It represents the different external wall development phases on the horizontal axis and the stakeholders involved in each phase on the vertical axis based on the traditional Design-Bid-Build procurement method. This scheme only gives an outline. However, it does not show the details of how decisions are made or the exact parties involved.

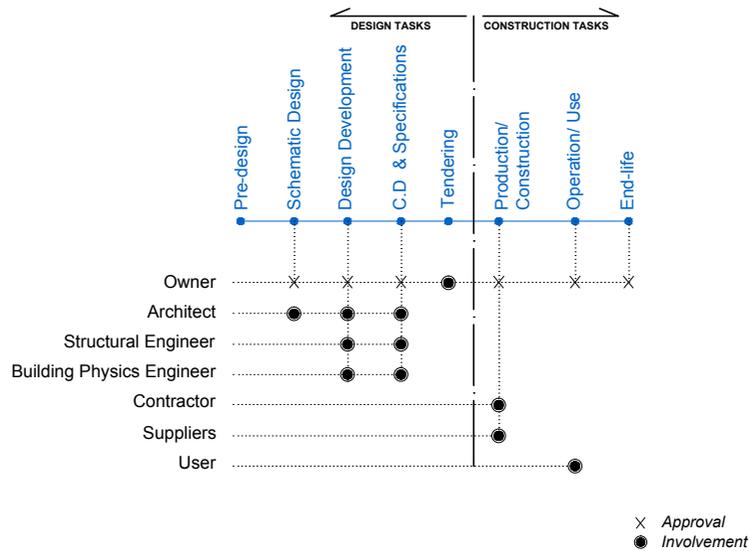


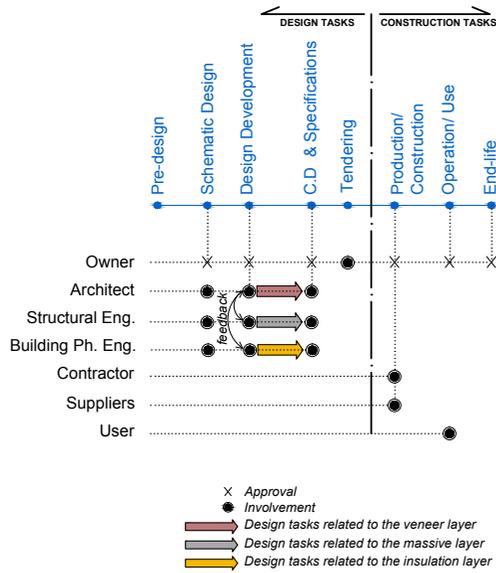
FIGURE 3.16 Scheme of massive external wall design and construction phases, and stakeholders involved in each phase

## § 3.4 Application to Traditional Dutch and Egyptian External Walls

The details of how decisions are made or the exact parties involved in a Design and Construction Process scheme depend on the type and composition of the massive external wall applied. In the following part, the scheme will be applied to the traditional Dutch and Egyptian external walls (presented in Chapter 2). This explains how the scheme works.

The two applications of the Design and Construction Process scheme to the Dutch and Egyptian traditional external walls given below show the involvement of the different external wall parties in the different project stages. Generally, the two traditional external walls follow the same scheme outline of Figure 3.16. However, the only difference is in the number of involved parties at the design development stage, which actually results from the number of different systems and layers. This is explained as follows.

**SCHEME FOR A TRADITIONAL DUTCH MASSIVE EXTERNAL WALL ILLUSTRATED IN FIGURE 3.17**



**FIGURE 3.17** Design and Construction Process of traditional Dutch massive external wall

**Explanation**

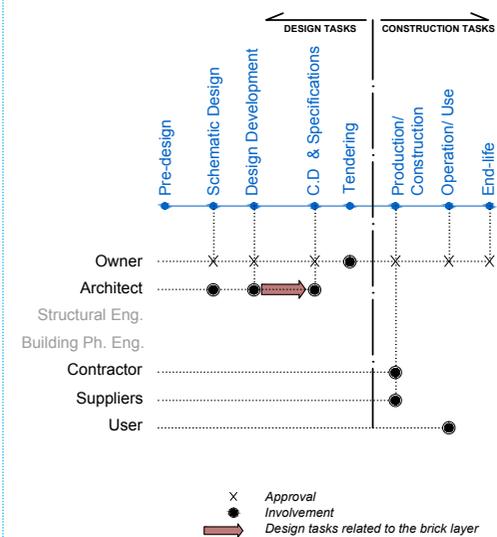
In the Dutch traditional external wall (Figure 3.10), each layer is mostly developed by a specific discipline (Figure 3.17), with a feedback from/to the architect:

- The structural engineer develops the massive layer together with the architect.
- The architect develops the veneer layer.
- The building physicist develops the insulation layer
- The interior designer develops the internal finishing.

The different layers are developed independent from each other. Decisions taken in one layer usually do not affect the performance of other layers.

This separation in the design process and decision making is a result of the modular product nature of the Dutch external wall.

**SCHEME FOR A TRADITIONAL EGYPTIAN MASSIVE EXTERNAL WALL ILLUSTRATED IN FIGURE 3.18**



**FIGURE 3.18** Design and Construction Process of traditional Egyptian massive external wall

**Explanation**

In the Egyptian traditional external wall (Figure 3.12), the architect is the only player involved in the design phase. He decides about the wall thickness (usually 25cm) and appearance (texture and colour).

The structural engineer usually is not involved in wall design decisions due to the lack of the load-bearing function of the wall (all walls are non-load-bearing as loads are transmitted through the concrete skeleton).

The building physics engineering is a field that does not exist in the Egyptian building industry.

The simplicity of the functional structure results in a simple design process in the design development stage (Figure 3.18).

## § 3.5 Conclusions

In this chapter, two schemes are developed to help understanding the design and construction of different massive external walls. These schemes will be used in following chapters to analyse massive technologies with additional function in external walls.

The first scheme is the component-function scheme, which is based on the theory of product architecture from the manufacturing industry. This scheme maps external wall components and their intended functions in a structured way. In the coming chapters, this scheme will allow us to understand how, by adding an extra function to the external wall, the physical composition of the external wall will change and will then reflect on its design and construction process.

The second scheme is the design and construction process scheme. This scheme is developed based on relevant literature together with the author's experience as an architect. The scheme shows the different involved parties in the different external wall construction stages and how design decisions are made. In the coming chapters, this scheme will allow understanding how by changing or by applying new additional function technologies and with changing wall physical composition, the design and construction process and the design decisions will change.

In order to understand how these schemes are used, they are applied to the traditional massive external walls in the Netherlands and Egypt. The analysis shows that the modular behaviour of the traditional Dutch wall with its various functions results in a layered external wall profile. In addition, it results in a separate design decision process for its components. The Egyptian external wall behaves differently. Its simple functional behaviour results in a simple wall construction and a more single-leaf profile. The Egyptian external wall results in a simpler design process with fewer decisions and fewer involved parties than the Dutch external wall.



# 4 Integral Technologies in Massive Construction: An Overview

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## § 4.1 Introduction

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In the previous chapter, the schemes for analysing massive external walls were developed. The main purpose of these schemes is to understand and analyse possible massive technologies with additional function in external walls. This chapter aims to introduce those massive technologies with additional function. It presents the state of such technologies and provides the answer to the question “*What are the existing and new massive technologies with additional function?*” The technologies under consideration are not only the technologies developed specifically for external walls, but technologies showing a potential for being implemented in external walls.

In the first part of this chapter an overview of the different massive technologies is presented. These technologies include adobe/ mudbricks, rammed earth, natural stones, fired bricks and concrete.

In the second part of this chapter the selection criteria which defines the additional function technologies are presented. This includes answers to the questions: What additional functions are provided by the massive technology? How are additional functions performed? What are the types of technologies/materials selected? Which sources are investigated to identify these technologies?

In the third part of this chapter eight different additional function technologies are explained in terms of their production methods and their properties. These technologies include Lightweight Aggregate Concrete, Aerated Concrete, Perforated Clay Bricks, Thermally Activated System, PCM Concrete, Air Permeable Concrete, Translucent Concrete and Functionally Gradient Concrete. In the fourth and last part, the conclusions of the present chapter are drawn.

## § 4.2 Massive Walls: An overview

As stated in Section 1.7., the term massive refers to heavy materials used in construction. In former times, they were mostly natural earth materials such as natural stones. Nowadays, massive materials include modern materials such as concrete, and which are usually produced in mass production and tailored according to the requirements. This section presents an overview about (different) massive materials used in wall construction. This overview includes Adobe/ mudbricks, rammed earth, natural stones, fired bricks and concrete.

### Adobe/ Mud bricks

Adobe is a building material made from earth and organic materials. They have been used for millennia in building durable, well insulated buildings. The mixture is usually moulded into wooden frame. This frame is then removed and the brick is left to dry in the sun for few hours. Slow drying in the shade is recommended to reduce cracks formation. Walls built from Adobe are usually load-bearing with good insulation properties (Grasser, 1982) (Figure 4.1).

### Rammed Earth

Rammed earth is a technique that uses, natural raw materials such as gravel, earth and lime to build construction elements such as walls, floors, and foundations. It has been used in ancient constructions.

The construction is initially formed using temporary formwork of usually wood or plywood. This formwork acts as the mould. It can form the entire wall or individual blocks. However, constructing the wall formwork will require an external support. The damp mixture is compressed in the formwork in layers building up the wall to the top. Additives such as lime and animal blood were sometimes used in the past to stabilize the material. Nowadays, lime, cement or asphalt are used instead.

Once the wall is hardened, the formwork can be removed. This techniques is appropriate for warm climates in order to dry the wall. In order to completely dry out and cure, the wall can take as much as two years. The material gains its full compressive strength once cured.

Rammed earth is known for its high strength and high thermal mass (Walker, Keable, Martin, & Maniatidis, 2005) (Figure 2).

## Natural Stones

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Large buildings and landmarks across the world were usually built with natural stones. They provide extremely strong and aesthetical construction (Figure 4.3). However, because they are non-renewable, quarried stone becomes more expensive by time. Nowadays, many massive stones are merely used as facing surfaces with thin profiles.

Among the natural stones commonly used in massive walls is the Limestone (Figure 4.4). This is because limestone is relatively easy to cut compared to other natural stones. Moreover, it has high durability withstanding harsh climates. However, limestone is a very heavy material. This makes it impractical for tall buildings (Grasser, 1982).

## Fired Bricks

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The term fired bricks refer to units composed of clay which are fired in kiln. This makes them durable. Modern, fired, clay bricks are formed in one of three processes – soft mud, dry press, or extruded.

In the soft mud process, the raw clay is mixed with water to the desired consistency then pressed into steel moulds with a hydraulic press. The brick is then placed in a kiln with a temperature of 900–1000 °C. The dry press process is similar to the soft mud process. However, the clay mix is much thicker. This allows the brick to be formed more accurately. This process usually requires more force in pressing and longer time in the kiln. Finally, in the extruded bricks process, the mixture is pressed through a die creating continuous shaped clay material, which is then cut into the desired length through wires. The bricks are then placed in the kiln to gain its strength. The colour of the bricks depends on the content of raw materials, the firing temperature and the kiln conditions (Pfeifer, 2001; Santos, 2006).

Bricks are used to build walls through laying down the bricks in course and numerous pattern known as bonds (Figure 4.5). Many kinds of mortar can be used to hold the bricks together.

## Concrete

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Concrete is a composite material composed of coarse aggregates and cement. The aggregates are mixed together with dry cement, and once water is added, the mixture becomes a fluid that is moulded in different shapes according to the mould used. The cement reacts chemically with the water and forms a hard mix after drying. Concrete types vary according to the different proportions of the ingredients used forming concrete that varies in density, strength and thermal properties (Figure 4.6).



FIGURE 4.1 Adobe/ mudbrick



FIGURE 4.2 Rammed Earth



FIGURE 4.3 The Pyramids built with natural stone



FIGURE 4.4 Limestone

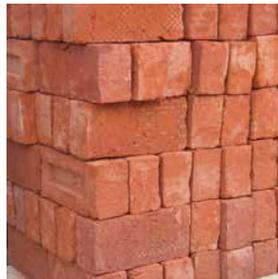


FIGURE 4.5 Fired brick



FIGURE 4.6 Concrete

## § 4.3 Technologies Selection Criteria

In section the selection criteria which defines the massive technologies with additional function are explained based on the following questions:

### What additional functions are provided by the massive technology?

Additional functions include all building functions that are not implemented by the traditional massive layer (traditional functions include handling vertical and lateral loads, sound resistance, and fire resistance as per Section 3.2.4). Additional functions are usually implemented either by adjacent layers attached to the massive layer like Insulation layer, or by separate building systems like heating and cooling systems. External and internal finishing are excluded from the selection because their performance is subjective, making it hard to assess their performance.

### How are additional functions performed?

The additional function should be performed by the massive layer and not allocated to a separate layer or system as in the traditional layered construction.

### What are the types of technologies/materials selected?

The technologies selected are massive technologies, and particularly concrete and brick technologies. That is because:

- Concrete and bricks are the most dominating technologies in the field of massive façades.
- Most additional functional developments are applied to these two technologies/materials as will be seen in the following paragraphs.

### Which sources are investigated to identify these technologies?

The investigated sources include:

- Existing products in the market, such as the Aerated Concrete that provides insulation
- Products currently being developed, in case information about them is available
- Existing projects
- Projects current being developed, in case information about them is available
- Research work done by educational and research institutes

Based on the previous points the following technologies and their corresponding functions were identified:

TECHNOLOGY	FUNCTIONS
1 - Lightweight Aggregate Concrete	Insulation
a) Expanded Clay Concrete	
b) Expanded Glass Concrete	
c) Aerogel Concrete	
2 - Aerated Concrete	Insulation
3 - Perforated Clay Bricks	Insulation
4 - Thermally Activated System	Heating/Cooling
5 - PCM Concrete	Heat Storage
6 - Air Permeable Concrete	Heat Exchange/Filtration
7 - Translucent Concrete	Light Transmittance
8 - Functionally Gradient Concrete	Depending on applied material

## § 4.4 Technologies in Massive Construction Providing Additional Functions

In the following pages, each of these technologies is presented in more details based on literature review and the author's meetings or correspondences with involved people.

### § 4.4.1 Lightweight Aggregate Concrete

The term "Lightweight Aggregate (LWA)" describes a range of aggregates that have densities below normal sand and gravel. This can range from extremely light materials used for isolative non-structural concrete to heavier aggregates used for structural concrete. The lightness of these aggregates derives from the air trapped in each particle (Zareef, 2010).

LWAs can be made of either natural materials or artificial products. Naturally occurring lightweight aggregates are usually mined from volcanic deposits such as lava slag. However nowadays, lightweight aggregates are mostly produced in manufacturing plants. The advantages of industrially produced aggregates is their constant quality and their possibility to be tailored (Holm & Ries, 1994).

One of the first known notable structures utilizing Lightweight Concrete Aggregate (LWCA) is the Pantheon Dome (Figure 4.7). Its concrete varied in density from the dome's bottom to its top. Pumice was used as a lightweight aggregate (Zareef, 2010). It is important here to mention that utilizing the LWCA was only for a structural purpose and not for its thermal behaviour.

The spread of LWCA as both a structural and insulating material is still considered limited. However, recently Architects have started to support the use of lightweight concrete as being a structural, insulating and finishing material. Several buildings in the first decade of the twenty-first century were constructed from direct finish thermo-insulating concrete such as the Gartmann's House in Switzerland, and the Landgericht (District Courthouse) in Frankfurt (Oder), Germany (Figure 4.8). Nowadays remarkable development in insulating LWCA can now be noticed. Different aggregates are available with different properties, and endless concrete mixtures can be achieved.



FIGURE 4.7 Pantheon Dome



FIGURE 4.8 Landgericht (District Courthouse)in Frankfurt (Oder), Germany

Different types of aggregates have been used in concrete, either in implemented projects or in research work. However, the coming section will focus on three types of Lightweight Concrete Aggregates. These are Expanded Clay Concrete, Expanded Glass Concrete, and Aerogel Concrete. They are all industrially produced aggregates. The reason for this selection is mentioned below.

**Expanded Clay** is selected because it is the most known aggregate used. Moreover, it is available in Egypt and the Netherlands and is well established in the market with existing projects.

**Expanded Glass** is selected because literature shows interesting concrete mixtures using this kind of aggregate having good structure and insulation functions. It is relatively new compared to expanded clay.

**Aerogel** is selected because it is the state of the art in lightweight materials. Its combination with concrete is still developing; however, it shows promising results.

### § 4.4.1.1 Expanded Clay Concrete

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#### Production

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Expanded Clay Aggregate is a lightweight ceramic shell with honeycomb core (Figure 4.9). It is produced by firing natural clay in a rotating kiln in a temperature of around 1200°C. During the firing process, the organic components of the clay combust. They expand and ceramic Expanded Clay with very fine pores comes into being. The pellets are rounded in shape and have a grade of approximately 0 to 16 mm with an average dry bulk density of approximately 350 kg/m<sup>3</sup>. Expanded Clay Aggregate started being developed around 1917 (Clarke, 2002; Hammer et al., 2005).

#### Mixture Properties

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Expanded Clay Concrete has been used in the construction industry for many years. Many mixtures were developed in practice. The most notable mixture, which provides good insulation and structural properties, is the Infra-Lightweight Concrete (ILWC).

Inspired by Gartmann's House in Switzerland which utilized Expanded Clay Concrete, Mike Schlaich developed the formula for ILWC. The material has a good balance between its insulating and structural properties (Thermal conductivity = 0.18 W/mk and compressive strength = 7.4 MPa). The ILWC mix consists only of water, cement, light expanded clay as a lightweight aggregate and an air-entraining agent (Figure 4.10). Figure 4.12 shows the mixture properties compared to the one used in Gartmann's House (Schlaich & El Zareef, 2008; Zareef, 2010).

The material was used in walls of a family house in Berlin in 2007 (Figure 4.13). The wall is 50-cm thick of merely ILWC. However, the material does not have enough strength to be used in the roof construction.

Due to the material lightweight, certain special procedures had to be taken. First, since pumping of light-weight concrete with Expanded Clay Concrete was considered to be difficult, the concrete had to be cast using a concrete bucket. To minimize the height of fall, an appropriate tube was attached to the bucket. Second, to reduce the unavoidable cracks due to shrinkage and reduce corrosion, glass-fibre reinforcement bars had to be used.



FIGURE 4.9 Expanded Clay

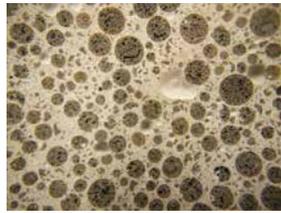


FIGURE 4.10 Infra-Lightweight Concrete



FIGURE 4.11 Gartmann's House

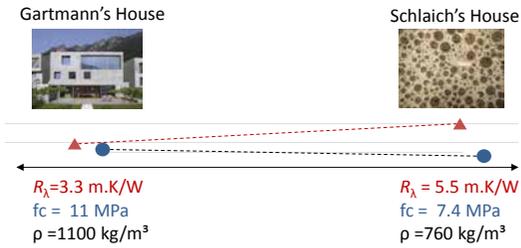


FIGURE 4.12 ILWC properties compared to concrete used in Gartmann's House



FIGURE 4.13 Family House utilizing ILWC

## § 4.4.1.2 Expanded Glass Concrete

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### Production

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Expanded glass is a lightweight aggregate produced from recycled glass. Treated fine glass powder from recycled glass is sintered at a temperature of 750 to 900°C. It expands about 4 times, to leave the oven as a glass foam material. Grain is normally in the range of 0 to 8 mm, having a bulk density between 180 kg/m<sup>3</sup> to 225 kg/m<sup>3</sup>. The aggregate has been produced since 1996 (Benner & Hahne, 1999; Liaver, 2015).

### Mixture Properties

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It was not possible until recently to make structural concrete using expanded glass aggregate. The high water absorption of the aggregate made concrete placing difficult. Moreover, it had low strength. Therefore, only few data is available in literature about Expanded Glass Concrete (Nemes & Józsa, 2006). However, today's expanded glass aggregate has higher crushing resistance and lower water absorption allowing making structural concrete utilizing expanded glass aggregates possible (Figure 4.14) (Bumanis, Bajare, & Korjamins, 2013).

Many projects have been realized with EGC. Roudit House in Chamoson, Switzerland is one of these notable examples. The house was built in 1814 with stone construction. However, it was renovated by Savioz Fabrizio Architects in 2005 using EGC creating a mineral feeling to the whole. The stone external walls have been preserved and lined inside with a layer of EGC. The concrete forms the new load-bearing structure, reinforces the old stone walls and provides thermal insulation (Figure 4.15).

To identify the properties of Expanded Glass Concrete (EGC), research work investigated the different percentages of expanded glass aggregate in concrete and their effect on the mechanical and insulating properties of the material (Heinz, Herrmann, & Sobek, 2011). This is shown in Figure 4.16.

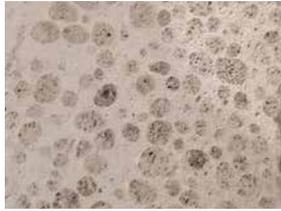


FIGURE 4.14 Expanded Glass Concrete



FIGURE 4.15 Renovation of Roduit House in Chamoson, Switzerland using Expanded Glass Concrete

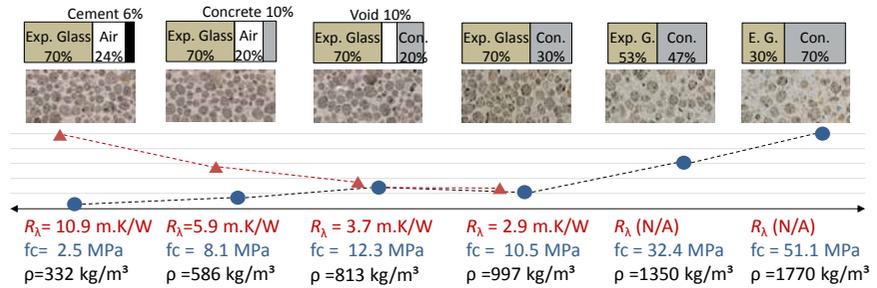


FIGURE 4.16 Different Expanded Glass Concrete mixtures and their properties

### § 4.4.1.3 Aerogel Concrete

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#### Production

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Aerogel is relatively a newly developed material. With air forming up 94 to 99% of its structure, it is known to be the lightest and best insulating solid material having a highly porous structure. It is produced through the controlled condensation of small colloidal particles produced by sol–gel processing in alcoholic aqueous solutions. This is then followed by a supercritical drying process (Gao, Jelle, Gustavsen, & Jacobsen, 2014; Ratke, 2008).

Aerogel properties come from its internal structure that results from the condensation and drying process. Its structure is aggregations of small nanoparticles ( $< 1\text{nm}$ ), linked to form larger porous secondary particles (5 to 10 nm). These porous secondary structures are then linked in a linear manner to form the Aerogel structure with pore diameter of about 50 nm. Figure 4.17 shows schematically the structure of Aerogel (Gao et al., 2014).

#### Mixture Properties

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Incorporating aerogel particles into cement based mixtures has been successfully prepared in recent research (Figure 4.18 and 4.19). Some mixtures showed interesting thermal and structural properties. However, they were all limited to research work, and none of them has been implemented in a real project. Figure 4.20 shows different Aerogel Concrete mixtures and their properties.

Work done by Heinz (Heinz et al., 2011) achieved the highest thermal resistance properties ( $R=12.5 \text{ m.K/W}$ ), but very low compressive strength (0.4 MPa). G.tecz, a research and development company, incorporated Ultra High Performance Concrete (UHPC) with Aerogel, which gave good structural performance (3 MPa) in addition to good insulation performance ( $R=12,3 \text{ m.K/W}$ ) with very low density ( $450\text{kg/m}^3$ ) (G.tecz, 2015). Ratke applied sound and fire testing for some mixtures that showed good sound insulation and fire protection properties (Ratke, 2008). Gao investigated a relatively higher density material ( $1000 \text{ Kg/m}^3$ ) having compressive strength of 8.3MPa and insulation property of  $R=3.8 \text{ m.K/W}$  (Gao et al., 2014). Finally, Hub stated in his research work that Aerogel Concrete does not prevent the application of finishing as primers, paints, putty and adhesives. However, he highlighted concerns about drying shrinkage as some samples showed high tendency to shrink (Hub, Zimmermann, & Knippers, 2013). All mixtures have been produced by simple mixing without the need for special equipment.

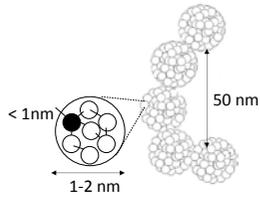


FIGURE 4.17 Aerogel structure



FIGURE 4.18 Aerogel Particles

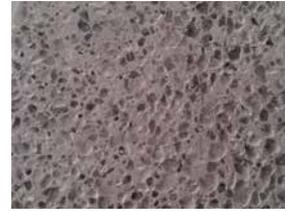


FIGURE 4.19 Aerogel Concrete sample prepared by the author (50% Cement + 50% Aerogel)

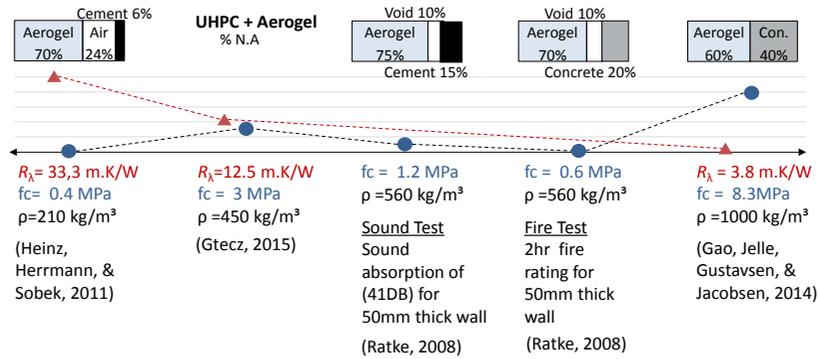


FIGURE 4.20 Different Aerogel Concrete mixtures and their properties

## § 4.4.2 Aerated Concrete

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Aerated Concrete is a mixture of cement, fine sand, water and special foam. This mixture, when hardened, results in a lightweight concrete containing evenly distributed and consistently sized air cells (Figure 4.21) and having good thermal insulation. Unlike conventional concrete, Aerated Concrete does not contain aggregates (Norazila, 2010; Wittmann & Balkema, 1992).

Aerated Concrete is recorded to be used in the early 1920s. However, its application in construction works was not recognized until the late 1970s (Norazila, 2010). It is worth mentioning that such concept already exists centuries ago. The igloo construction, for example, shows a similar concept (Figure 4.22). The used snow blocks contain trapped air pockets making the envelope a good insulator. When the outside is as low as  $-40^{\circ}\text{C}$ , the inside temperature can be  $5^{\circ}\text{C}$  (Bilow, 2012).

### Production

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The material gains its properties from two main production steps. First is the pore formation step, taking place either chemically or mechanically. In the first case, chemicals are mixed into the lime or cement mortar during the liquid stage. This results in volume increase, then the gas escapes, leaving a porous structure. Aluminium powder is the most commonly used aerating agent. In the case of mechanical pore formation a foaming agent is added to the materials without any chemical reaction involved. Various foaming agents are used such as resin soap, glue resins and hydrolysed proteins (Narayanan & Ramamurthy, 2000).

For the curing step, the autoclaving process can be applied. In this case, while the material is still soft, it is cut into blocks or panels and placed in an autoclave chamber for 12 hours. When temperature reaches  $190^{\circ}\text{C}$  and pressure reaches 8 to 12 bars, quartz sand reacts with calcium hydroxide to form calcium silica hydrate, which gives the Autoclaved Aerated Concrete (AAC) its high strength. After this process, the material is ready to be used. The autoclaving method increases the material strength and lowers its drying shrinkage (Gelim & Ali, 2011). In case of non-autoclaved curing, the concrete is cured with steam at atmospheric pressure.

## Mixture Properties

The properties of Aerated Concrete depend on the ingredients and their percentages, the method of pore formation and the curing method. Usually, the autoclaving process is used as a curing method resulting in AAC (Figure 4.23). Limited studies are available on the non-autoclaved product. Many companies produce AAC blocks and panels with different strengths and insulation properties. Figure 4.24 shows the most recent AAC products by Xella indicating their different densities, compressive strengths and insulation properties.

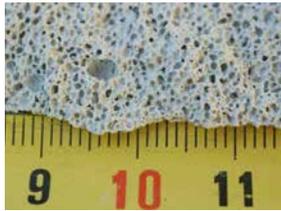


FIGURE 4.21 Air cells of Aerated Concrete



FIGURE 4.22 Igloo



FIGURE 4.23 Autoclaved Aerated Concrete

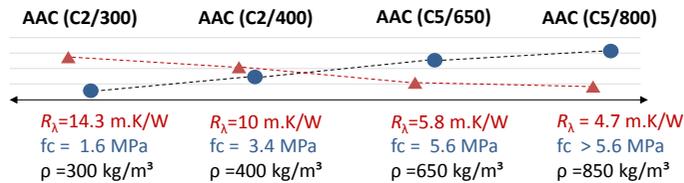


FIGURE 4.24 Different AAC Products and their properties by Xella

### § 4.4.3 Perforated Clay Bricks

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Clay bricks have been used from quite a long time in construction. However, Perforated Clay Bricks only appeared in the mid-twentieth century (Figure 4.25). The first motivation behind having these perforations was that it helped to overcome manufacturing difficulties. Such difficulties arose while making wire-cut bricks with certain clays (BRE, 2015). On the other hand, the perforations changed the brick properties.

Solid bricks were unnecessarily strong, heavy, and with poor thermal performance. The introduction of air cavities reduced brick strength and weight, and improved its thermal performance (BRE, 2015). Brick air cavities are considered until now the most effective method for increasing thermal insulating parameters (Figure 4.26). Lately there is a tendency to integrate insulating materials with low values of thermal conductivity into air cavities (Zach, Hroudová, & Sedlmajer, 2012).

#### Production

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The process of manufacturing of Perforated Clay Bricks is similar to that of regular solid clay bricks. The only difference is in the extrusion step. The extrusion machine is designed to create perforations when soft clay is pushed through it. Figure 4.27 shows schematically the production process of perforated bricks.

#### Brick Properties

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Many efforts have been made until now in order to develop patterns for bricks, which give the optimum thermal and structural performance. This depends on the proportion of air cavity size to size of ceramic frame; and further on shape of the cavities, their layout, thickness of inner and of peripheral walls of brick, and on cavity size (Zach et al., 2012). Many companies produce perforated bricks with different strengths and insulation properties. Figure 4.28 shows some recent perforated brick products, indicating their different densities, compressive strengths and insulation properties.

Nowadays some companies integrate insulating materials with high thermal resistance into the brick cavities (integrated thermal insulation). This raises the thermal resistance of the brick, while maintaining its structural performance (Fig. 4.29).

Figure 4.30 shows a recent product of perforated brick with integrated thermal insulation, indicating its density, compressive strength and insulation property.



FIGURE 4.25 Production of Perforated Clay Bricks in the mid-twentieth century



FIGURE 4.26 Perforated Clay Bricks

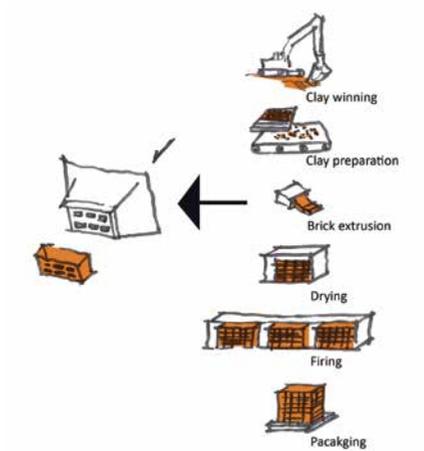


FIGURE 4.27 Perforated Clay Bricks production process

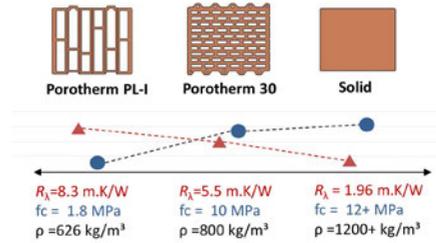


FIGURE 4.28 Different Perforated Clay Bricks and their properties



FIGURE 4.29 Perforated Clay Bricks with integrated insulation

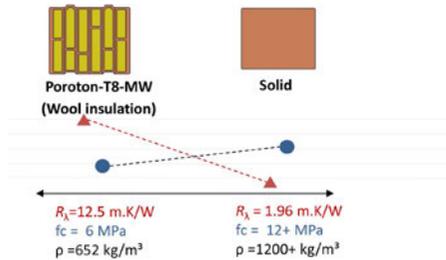


FIGURE 4.30 Perforated Clay Bricks with integral insulation and its properties

#### § 4.4.4 Thermally Activated System

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The principle of thermally activated components depends on bringing the mass of a building up to a certain temperature. This affects the surrounding temperature by either heating or cooling. In addition to direct cooling and/or heating, the system also utilizes thermal mass.

The principle of thermally activated massive components is not new. An early version of using thermally activated technology was the hypocaust systems. Hypocaust was a heating system used by the romans to heat large public baths. Hot gases of temperatures exceeding 100°C used to flow from a furnace to spaces under the flooring and in walls to heat the space (Figures 4.31 and 4.32) (Bansal & India, 1998; Çiçek, 2009). Similar principle used in buildings nowadays is the Concrete Core Activation. In this system concrete slab temperatures are raised/lowered to certain temperatures causing heating/cooling of spaces (Haase & Andresen, 2007).

A more recent form of such principle is its application in walls and external walls. This can be seen in the Thermally Activated Concrete external wall of Zollverein Design School in Essen (Figure 4.33), in the calcium silicate blocks activation of Silka Klimaatwand and KS-Quadro Therm systems provided by Xella and KS-Quadro, respectively (Figures 4.34 and 4.35), and finally in the clay brick walls activation provided by Wienerberger (Figure 4.36) (Hobbie & Zapf, 2011; Lehmden, 2013; Moe, 2010).

#### Production

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The mass is cooled or heated through an integrated piping system, which is placed inside the mass. The heated/cooled water is pumped through these pipes (Figure 4.37). Building simulation programs are usually used to determine the behaviour of the system when installed in a building.

#### Design Parameters

The design of activated components is based on many parameters. These are diameter and spacing of pipes, thickness and properties of the massive component, position of the pipes inside the massive component, and water supply temperature and flow rate (Haase & Andresen, 2007).

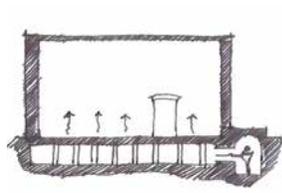


FIGURE 4.31 Concept of Hypocaust system



FIGURE 4.32 Remains of Hypocaust in Flavia Solva, Croatia



FIGURE 4.33 Zollverein Design School, Essen, Germany



FIGURE 4.34 Silka Klimaatwand system

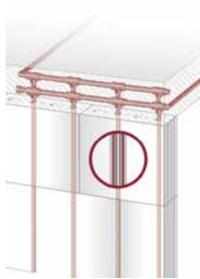


FIGURE 4.35 KS-Quadro Therm system



FIGURE 4.36 Thermally activated clay bricks by Wienerberger

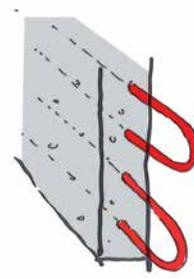


FIGURE 4.37 Pipes embedded in massive component

The concept of Thermally Activated Walls can be applied in different forms rather than just heated or cooled water pumped into the walls. Heat-collecting massive walls consist one of these examples (Figure 4.38). In such walls pipes run on both, the outer wall surface and inner wall surface. The outer surface acts as a heat absorber, while the inner surface acts as heat diffuser. During the day time, the outer layer absorbs heat through water in the pipes, while during night time when the temperature is low, the heated water is pumped into the inner wall surface (Figure 4.38). Such a technology has not been fully investigated yet. However, it has been applied in the Smart Material House proposal designed by Barkoe Leibinger Architekten. The pipes were embedded in Infra-Lightweight Concrete prefabricated panels (Mike Schlaich & Hückler, 2012).

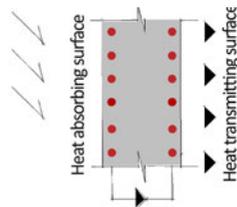


FIGURE 4.38 Heat-collecting wall

## § 4.4.5 PCM Concrete

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A Phase-Change Material (PCM) is a substance with a high latent heat, which melts and solidifies at a certain temperature (Figure 4.39). During this process it stores and releases large amounts of energy.

For many years, the use of PCM in building construction has been an attractive solution, which is intended to reduce the energy consumption and provide an enhanced thermal comfort. Among the wide applications of PCM, is its encapsulation in concrete (Figure 4.40), which increases the thermal storage capacity of the mixture (Eddhahak-Ouni, Drissi, Colin, Neji, & Care, 2014; Pomianowski, 2012). Early tests on concrete with encapsulated PCM (PCM Concrete) dated back to 1992 in the work done by Hawes, Banu and Feldman (Hawes, Banu, & Feldman, 1992).

### Production

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The material is formed by simply embedding PCM particles in the concrete mixture during the concrete production. This increases the thermal storage capacity of concrete.

### Mixture Properties

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Numerous researches developed different mixtures for measuring the effectiveness of adding PCM to concrete. This included variability in the base material mix design, PCMs type and amount, manufacture procedure, and experimental techniques used for measuring the mechanical and thermal characterization of the material. Some important conclusions can be summarized as follows:

- The thermal benefits of combining PCM and concrete are always quite small. It is possible to make a light weight material or building in combination with PCM to behave like a heavy material/building with high thermal storage capacity by using the thermal storage capacity of PCM in day cycles. However, the benefit of PCM in an already heavy building, which is usually the case when concrete is used, is very limited (Pomianowski, 2012). Figure 4.41 shows the experimental and theoretical results of adding different portions of PCM to concrete.
- Adding 7.5% PCM to mixture (based on weight, which is corresponding to almost 15% of volume) is the maximum amount of PCM to be added mixture. With higher level, the mixture loses workability even if super plasticizers are added (Juul Andersen et al., 2013).
- Only the outer 3 to 4 cm of the PCM structure is being activated most efficiently (Juul Andersen et al., 2013).



FIGURE 4.39 PCM substance

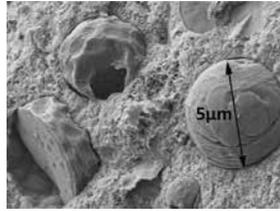


FIGURE 4.40 PCM encapsulated in concrete (Pomianowski, 2012)

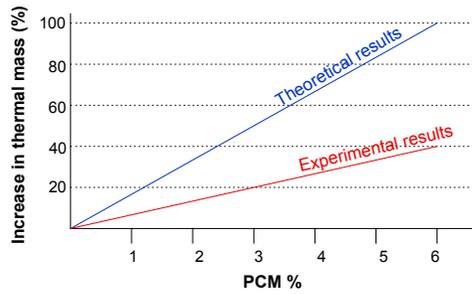


FIGURE 4.41 Experimental and theoretical results of adding different portions of PCM to concrete (Juul Andersen, Poulsen, Passov, & Heiselberg, 2013)

## § 4.4.6 Air Permeable Concrete

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Air Permeable Concrete (APC) is a developing material. It originated from the experimental investigation carried out by Imbabi et al. at the University of Aberdeen in Scotland and later published as a patent in 2010. APC was mainly invented in order to create dynamic insulation systems for improving indoor air quality.

Dynamic insulation is permeable to air flow. This enables fresh air to be drawn, either passively or actively, into the building through appropriate inlet and outlet vents in the building fabric. As air flows through the dynamic insulation layer, its temperature is regulated through the waste heat or cold lost usually through the building fabric. This results in lower energy demand (Figure 4.42). Moreover, this cleans the air from any pollutants before being introduced indoors (Daniels & Nørgaard, 2011; Imbabi, Glasser, & Wong, 2009; Kacejko, 2011; Wong, Glasser, & Imbabi, 2007). The first building utilizing dynamic insulation is the McLaren Community Leisure Centre in the United Kingdom constructed in the year 1998 (PH Baker, 2003).

In order to achieve this breathability property in concrete, the concrete has to fulfil special parameters in its internal structure. First, high porosity of concrete is required. Second, the voids have to be interconnected in order to provide a continuous flow of air through the concrete wall. Finally, regular pore size distribution has to be achieved. Large amount of small voids increases the turbulent flow, compared to smaller amount of larger voids leading to laminar flow. Figures 4.43 and 4.44 show schematically the structure of APC.

### Production

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The properties of APC specimens are optimised through the following (Wong et al., 2007):

- Controlling aggregate size by sieving to a narrow selected size fraction.
- Controlling the shape and angularity of aggregates as it affects the space availability for cement filling.
- Controlling the volume of cement paste with other admixtures, which is determined by the natural packing density of the aggregates used. It is mixed with the aggregates before being cast into a mould.

## Mixture Properties

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No projects have been realized yet with APC. However, different mixtures were investigated by researchers. The best result regarding permeability was achieved by Imbabi. His mixture was 24 times more air permeable than normal concrete (0.6 m<sup>2</sup>/Pa), with compressive strength of 10.8 MPa. Appendix 1 presents the properties of APC with different formulations based on laboratory tests by Imababi (Wong et al., 2007).

An initial performance evaluation of the effectiveness of APC as a heat exchange was investigated by Ole Daniels and Jesper Nørgaard at the Aalborg University using simplified variables (Figure 4.45). The main finding of their work is that APC can be efficient for operating in office buildings (Daniels & Nørgaard, 2011). The performance evaluation is provided in Appendix 1. Due the material newness, its complete thermal behaviour is still unknown. Moreover, casting consistent specimens is difficult, which requires deeper investigation of production methods (Daniels & Nørgaard, 2011).

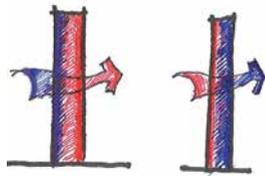


FIGURE 4.42 Dynamic insulation concept

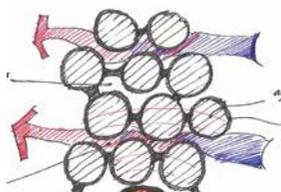


FIGURE 4.43 Conceptual structure of APC



FIGURE 4.44 APC sample by the author showing voids formation



FIGURE 4.45 Air Permeable Concrete by Ole Daniels and Jesper Nørgaard at Aalborg University

Another heat exchanging technology performing a similar function is the self-cooling walls. Such walls depend on water evaporation rather than heat exchanging with concrete particles. This concept has been applied as a passive cooling system in wind catchers in Egypt in ancient times (Figure 4.46).

Figure 4.47 shows a self-cooling concept wall developed for walls by Elliot Glassman (Glassman, 2016)

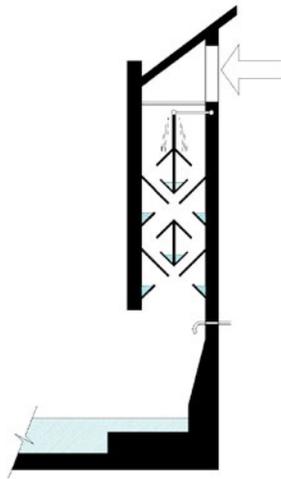


FIGURE 4.46 Wind catcher with water features to cool the air

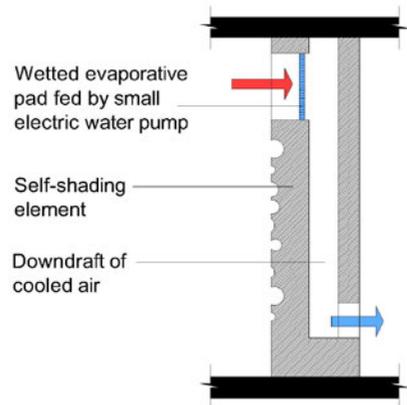


FIGURE 4.47 Self-cooling wall concept

## § 4.4.7 Translucent Concrete

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Concrete has been known to be a rigid opaque material. Recent technologies have succeeded in giving concrete a translucent effect through integrating optical fibres into its mixture. Optical fibres are transparent flexible fibres made of glass (silica) or plastic. They are slightly thicker than a human hair, functioning as a waveguide or “light pipe”, transmitting light between its two ends as shown in Figures 4.48 and 4.49 (Thyagarajan & Ghatak, 2007).

By integrating thousands of optical glass fibres in the concrete, the beam of light will be reflected through the optical fibres embedded in the concrete giving the concrete a notable translucent effect (Figures 4.50 and 4.51). Hungarian architect, Aron Losonczi, first introduced the idea in 2001. In 2003, it was successfully produced in concrete blocks (Shen & Zhou, 2013).

### Production

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In its manufacturing process, highly-fluid cement having specific granular size is casted in layers to join the fine-meshed fibre optics placed in the mould. The mixture is then kept to dry, and then cut into prefabricated building blocks and panels to the required sizes and thicknesses. The surface usually requires treatment after the cutting process (Losonczi, 2012).

### Mixture Properties

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The technology has not been implemented widely in massive construction, but mostly as a decorating element (Figure 4.52). Many companies nowadays provide this technology with different fibre arrangements depending on the required design. However, the amount of fibres is usually around 5% of the whole concrete volume. Companies claim that the strength of concrete is not affected by the portion of fibres added due to its low percentage. Moreover, they claim that walls can be built even a couple of meters thick as fibres can work up to 20 meters without losing their efficiency (Petricone, 2012).

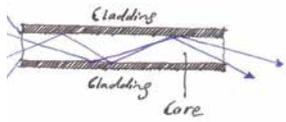


FIGURE 4.48 Light transmittance in optical fibres

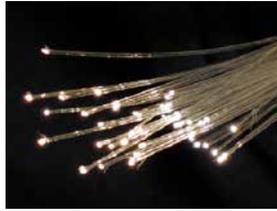


FIGURE 4.49 Optical fibres



FIGURE 4.50 Translucent Concrete in light



FIGURE 4.51 Translucent Concrete in case of no light



FIGURE 4.52 Translucent Concrete as decoration

## § 4.4.8 Functionally Gradient Concrete

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Functionally gradient materials are based on the gradual change in material composition creating a seamless gradual transition between mixtures. This leads to gradual functional change (Figure 4.53). Such concept exists in nature and even vernacular construction. The igloo, for example, possesses such gradient property in addition to the envelope's insulation feature as discussed earlier. The heat generated in the inside (from lamp or fire) melts the interior surface slightly. When this surface refreezes again, it becomes a strong dense layer of ice. This contributes to the strength of the igloo creating a functionally gradient construction (Figure 4.54).

The basic concept of functionally graded materials in modern world was developed by the aerospace industry and was limited to thin surface layers. However, in 2006 the Institute of Lightweight Structures and Conceptual Design (ILEK) at the University of Stuttgart developed the application of gradient technology in the building industry with larger size components. The development focused on the production of Gradient Concrete. The three-dimensional gradation was achieved either by varying the porosity of the material, or by varying the ratio of components in a mixture of materials (Herrmann & Sobek, 2012).

### Production

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Many methods can be used to achieve Gradient Concrete. The ILEK, for example, developed a patented spraying process, in which the consistency of the spray is continuously changed. Then depending on the position of the spray nozzle, the required concrete mix is achieved (Heinz et al., 2011). Figures 4.55 and 4.56 show a Gradient Concrete sample prepared by the author using simple pouring of fresh concrete in layers.

In addition, the technology can be achieved by simple methods such as pouring fresh concrete in layers having different mixture composition, then leaving it to dry as one component (Figure 4.57). Furthermore, it can be achieved using a partitioned mould. After different mixtures are poured in the partitions, the partitions are removed to form one component as shown in Figure 4.58 (Heinz et al., 2011).

## Mixture Functions

Different combinations of functions can be achieved depending on the mixtures used.

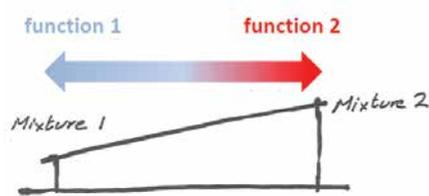


FIGURE 4.53 Sketch showing concept of functionally gradient material

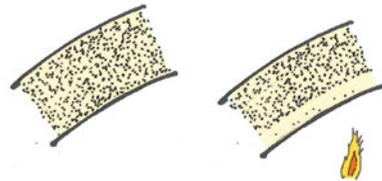


FIGURE 4.54 Sketch showing gradient structure process in igloo construction



FIGURE 4.55 Gradient Concrete sample by the author

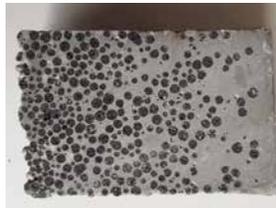


FIGURE 4.56 Cross section in Gradient Concrete

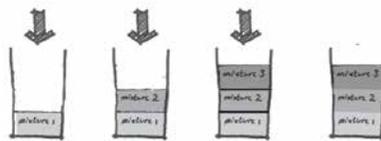


FIGURE 4.57 Sketch showing method of pouring fresh concrete in layers to achieve a gradient material

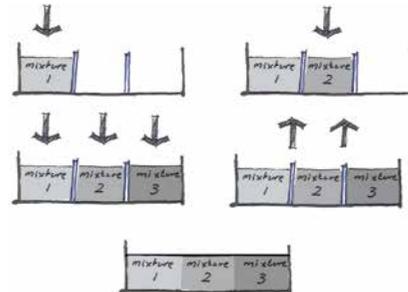
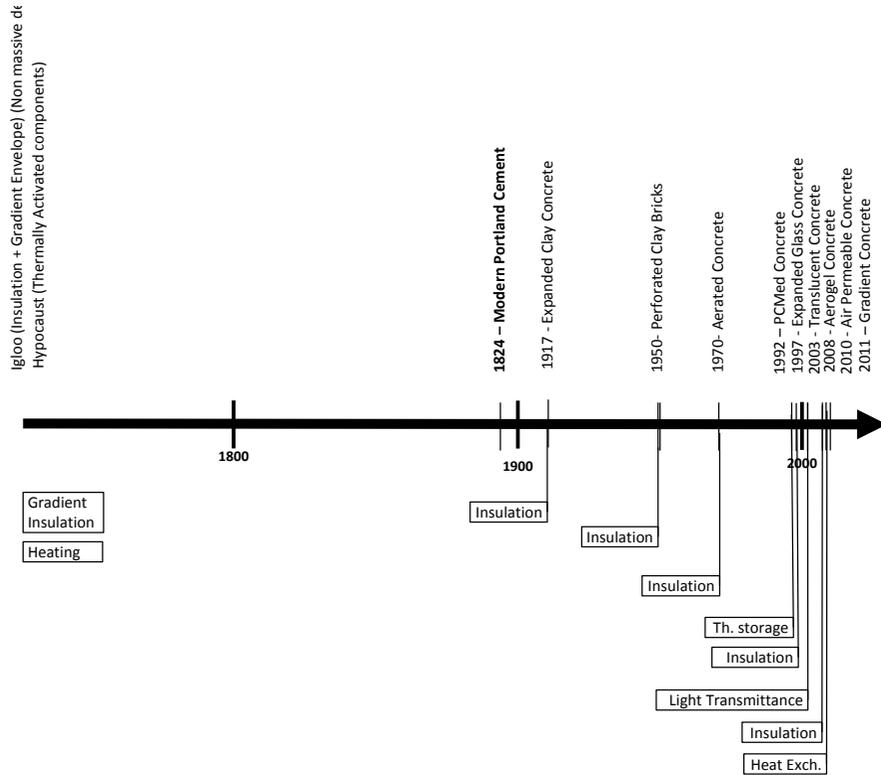


FIGURE 4.58 Sketch showing method of pouring fresh concrete in partitioned mould to achieve a gradient material

## § 4.4.9 Summary of Additional function Technologies and Discussion

The diagram in Figure 4.59 shows the previously investigated additional function technologies organized according to the following:

- Time of technology development (in which they were first investigated)
- Additional function provided by the technology
- Whether they are concrete or brick technologies



**FIGURE 4.59** Diagram showing types of massive technologies with additional function previously investigated, the extra function they provide, and the time they were developed.

Based on Figure 4.60, the following points can be drawn:

- Additional function technologies existed thousand years ago (Igloo and Hypocaust system).
- All technologies listed in the figure are related to concrete technologies except for Perforated Clay Bricks and Perforated Clay Bricks with integral insulation. This indicates that more additional function developments are taking place in the field of concrete compared to bricks. This could be due to the wider range of concrete applications. Concrete is used in more building elements (structural elements, foundations, walls), which leads to more research and developments. Another reason could be because clay bricks require a firing process. This process limits the types of additives, which could be added to clay and which have to stand the high temperatures.
- Figure 4.60 shows the time in which the technologies were initially investigated. However, many of these technologies like Aerogel Concrete, Air Permeable Concrete and Gradient Concrete still require more research and developments to fully fulfil their intended functions.
- Most additional function technologies indicated in the figure are developed at the beginning of the twenty-first century. This indicates that this field of development is recently gaining more importance and consideration in the building industry.

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## § 4.5 Conclusions

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This chapter has presented the additional function technologies that will be used in the coming chapters to analyse the process changes. Selecting these technologies was based on several criteria. First, the extra functions performed by the massive layer can include any building function, except for the structural and the finishing functions. Second, the massive materials can be either brick or concrete. The investigated sources include existing products, developing products, existing projects, projects currently being developed, and research work.

This resulted in the following technologies, which were not necessarily developed for external walls; however, they all have potentials for providing the external wall with an additional building function:

- Lightweight Aggregate Concrete using different types of aggregates, Aerated Concrete, Perforated Clay Bricks, and Perforated Clay Bricks with integral insulation; which provide additional insulating functions.

- Air Permeable Concrete, which provides additional ventilating, heat exchanging, and filtration functions.
- PCM Concrete, which provides additional thermal storage functions.
- Thermally Activated Massive Walls, which provide additional heating/cooling functions.
- Translucent Concrete, which provide additional light transmitting functions.
- Gradient Concrete, which provide different additional functions based on the concrete type used.



# 5 Analysis of External Wall Construction Technologies

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## § 5.1 Introduction

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In Chapter 3, two graphical schemes have been developed. They serve as tools to analyse and compare the different external wall construction technologies and their design and construction process. These schemes are followed in Chapter 4 by an overview regarding technologies providing additional functions to the massive construction external walls.

In this chapter, the overviewed technologies are analysed in external wall construction as per the developed schemes. The chapter aims to discuss and find an answer to the first main research question: *What changes are required to the present traditional design and construction process if massive technologies with additional function are implemented in external walls?*

To answer this question, the chapter is divided into three main sections following this introduction. In the first section, the eight preselected additional function technologies are sketched for external walls and analysed according to the developed schemes. In the second section, product-designed solution as an approach for massive technologies with additional function is explained. Three case studies are analysed to explain this approach and its effect on the process changes. In the third section, a guidance scheme, which provides an answer to the research question, is presented. Finally, the conclusions of the chapter are outlined.

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## § 5.2 Analysis of Massive technologies with additional function in External Walls

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### § 5.2.1 Analysis of Technologies

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In this section, the eight predefined technologies in the context of massive external walls are sketched and analysed. As mentioned in Chapter 4, these technologies include:

- 1 Lightweight Aggregate Concrete
  - a *Expanded Clay Concrete*
  - b *Expanded Glass Concrete*
  - c *Aerogel Concrete*
- 2 Thermally Activated System
- 3 PCM Concrete
- 4 Air Permeable Concrete
- 5 Translucent Concrete
- 6 Gradient Concrete

The analysis of each of these eight technologies is carried out systematically according to the following three consecutive steps:

#### A External wall design parameters and schematic sketch

---

This step is carried out in order to understand the design decisions regarding the implementation of these technologies in external walls. First, the typical external wall design parameters are defined as indicated in Figures 5.1, 5.5, 5.10, 5.14, 5.18 and 5.22 for the technologies under consideration. This is followed by drawing schematic sketches of the external walls illustrating these parameters as shown in Figures 5.2, 5.6, 5.11, 5.15, 5.19 and 5.23 for the same technologies.

#### B Component-Function analysis

---

This step of the analysis is carried out in order to understand the physical composition and the functional performance of the technology. The Component-Function scheme outlined in Chapter 3 is applied, particularly as related to the product levels and functional behaviour. The effect of each component on the different functions provided

by each technology is illustrated as indicated in Figures 5.3, 5.7, 5.12, 5.16, 5.20 and 5.24. In addition, the results of the analysis are outlined in the form of observations given besides the figures.

## C Process analysis

---

This step is carried out in order to understand the design and construction process, and particularly the relation between the different stakeholders when each of these technologies is applied. The design and construction process scheme outlined in Chapter 3 is applied.

Data about the process for the successful performance of each technology is collected from three sources: literature review, interviews with involved parties, and direct correspondences (whenever interviews are difficult to arrange).

For the already-implemented project cases, the interviews or direct correspondences with project stakeholders took place during the period allocated for the present research. The amount of questions dealt with in these communications varied from one project to another, depending on the availability of data in the existing literature. The main objective of the interviews and the correspondences was to cover all the points that were not clear in the literature review.

For new concepts that are not yet implemented, a 'reasonable prediction' about their processes is taken with the assistance of specialized individuals from the Building Physics Department at TU Delft. The interviews and the discussions with TU Delft specialists included Dr Martin Tenpierrick, Dr Truus Hordijk and Ir. Eric van den Ham.

In interviews regarding newly-developed solutions using new technologies, an explanation of the technologies under consideration was first presented (especially if the interviewee was not familiar with such technologies). This introduction was followed by questions and brainstorming about the expected design decisions and possible construction difficulties.

The results of the analysis of the process design and construction of the different technologies under consideration are illustrated in Figures 5.4, 5.8, 5.13, 5.17, 5.21 and 5.25. In addition, clarifications are given besides the figures. On the other hand, Appendix 2 includes the interview and correspondence form used in this research. The form contains the complete set of questions, which were required to be covered, regarding the technology and its design and construction process.

## 1- LIGHTWEIGHT AGGREGATE CONCRETE (LWAC)

### External wall design parameters and schematic sketch

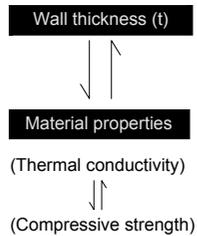


FIGURE 5.1 External wall design parameters for LWAC

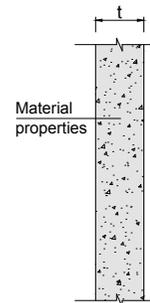


FIGURE 5.2 Schematic sketch of LWAC

### Component-Function analysis

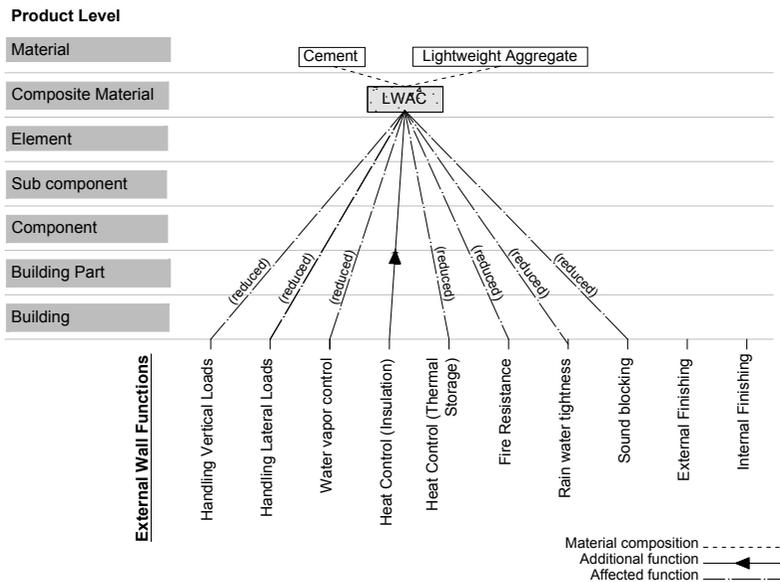


FIGURE 5.3 Scheme analysis for insulating technologies

By applying the scheme to the technologies, the following points can be observed (Figure 5.3):

- 1- Integration occurs at the level of composite material for LWAC (It requires a mixing process to achieve an insulating function).
- 2- With the addition of an insulating function, the other functions originally performed by the massive wall will be affected. The performance related to handling vertical and horizontal loads, water vapour control, thermal storage, fire resistance, rain water tightness and sound blocking will be reduced due to the density reduction of the wall (Figure 5.3)

---

### Process analysis

The process analysis (Figure 5.4) is based on:

- Correspondence with Mike Schlaich, who developed the Infra Lightweight Concrete (Expanded Clay). In addition, he is the Structural Engineer for the Mike Schlaich Project (Section 4.3.1.1)
- Correspondence with Laurent Savioz, the Architect of the Maison Roduit Project (Section 4.3.1.2)

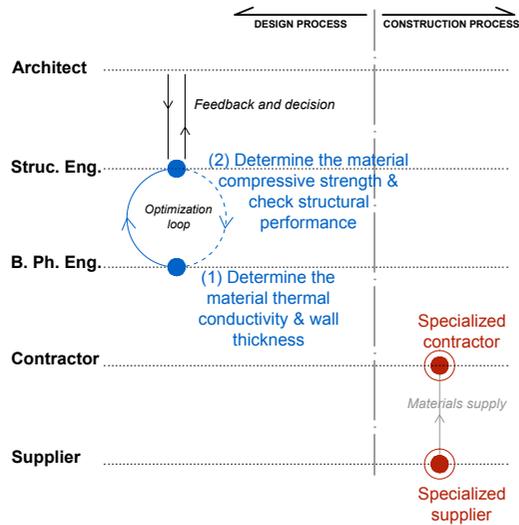


FIGURE 5.4 Scheme analysis for LWAC

#### Design process

Unlike in the traditional construction where the decision making process is scattered, an insulated massive wall is designed in a process of shared decisions between the Architect, the Structural Engineer, and Building Physics Engineer as shown in Figure 5.4.

#### Construction process

Specialized contractor is required, particularly for onsite casting task jobs. Moreover, a specialized supplier for the newly developed mixtures is required.

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## 2- THERMALLY ACTIVATED MASSIVE WALLS

### External wall design parameters and schematic sketch

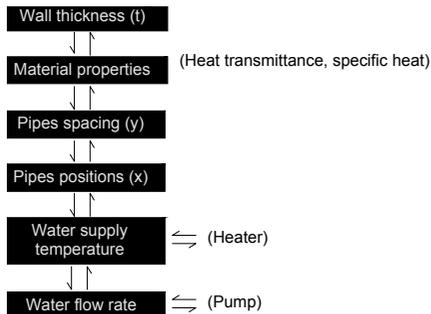


FIGURE 5.5 External wall design parameters for Thermally Activated Massive Walls

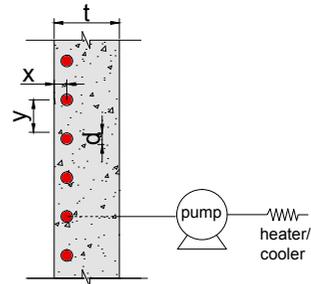


FIGURE 5.6 Schematic sketch of Thermally Activated Massive Walls

### Component-Function analysis

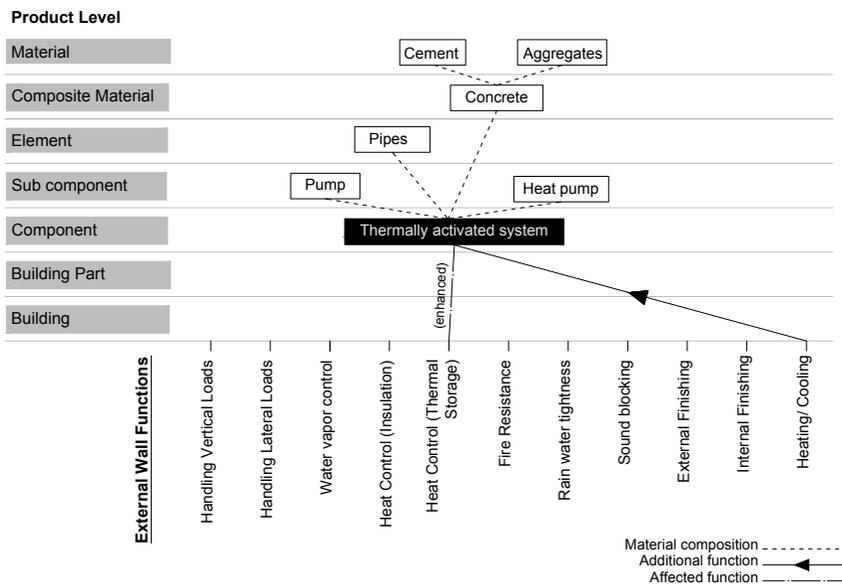


FIGURE 5.7 Scheme analysis for Thermally Activated Massive Walls

By applying the scheme to the technologies, the following points can be observed (Figure 5.7):

- 1- Integration occurs at the component level. (This integration requires the assembly of different elements and sub-components in order to achieve the heating/cooling function).
- 2- With the addition of heating/cooling function through the thermally activated system, the heat control (thermal storage) function originally performed by the massive layer will be constantly activated.

### Process analysis

The process analysis (Figure 5.8) is based on an interview with Holger Techen, the Structural Engineer involved in the Zollverein Design School Project (Section 4.3.2). Appendix 3 includes a paper describing the project generated from the interview.

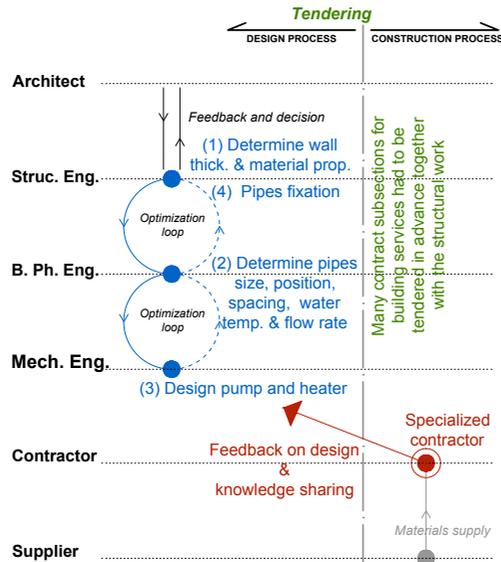


FIGURE 5.8 Scheme analysis for Thermally Activated Massive Walls

### Design process

Thermally Activated Walls require a shared decision process between the Architect, the Structural Engineer, the Building Physics Engineer and the Mechanical Engineer as shown in Figure 5.8.

### Construction process

Due to the construction complexity, the contractor becomes involved in design through sharing his knowledge and experience affecting the decisions by the design team. Consequently, the contract subsections for building services have to be tendered in advance together with the structural work. The specialized contracting tasks are required like in pipes fixation tasks. In addition, well-trained workers are required to handle long pipes running without joints or connections.

**About the Zollverein Deign School:** It is a school of Management and Design in Essen, Germany (Figure 5.9). Due to the Architect's desire of having a monolithic concrete external wall, the external wall was a 30 cm single skin fair-faced concrete wall with thermally activated systems. This allowed the concrete to work as an active insulation system. The project is located near a coal mine providing naturally heated water. The water had a temperature of 30°C and was pumped to the wall pipes at a rate of 600 m<sup>3</sup>/h.

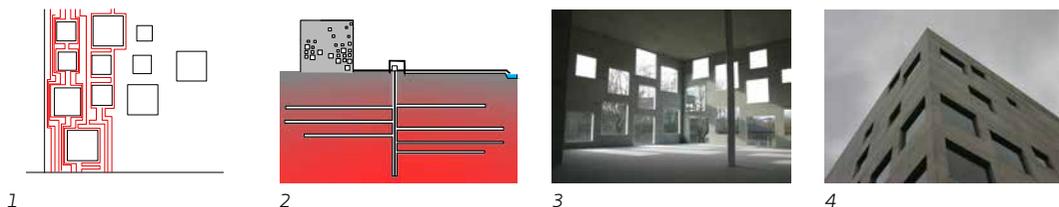


FIGURE 5.9 Illustrations: (1) Pipes in external wall (2) Use of underground water (3) View from inside (4) View from outside

### 3- PCM CONCRETE

#### External wall design parameters and schematic sketch

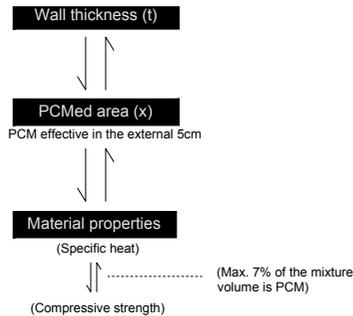


FIGURE 5.10 External wall design parameters for PCM Concrete

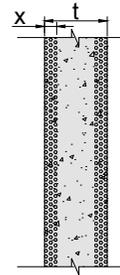


FIGURE 5.11 Schematic sketch of PCM Concrete

#### Component-Function analysis

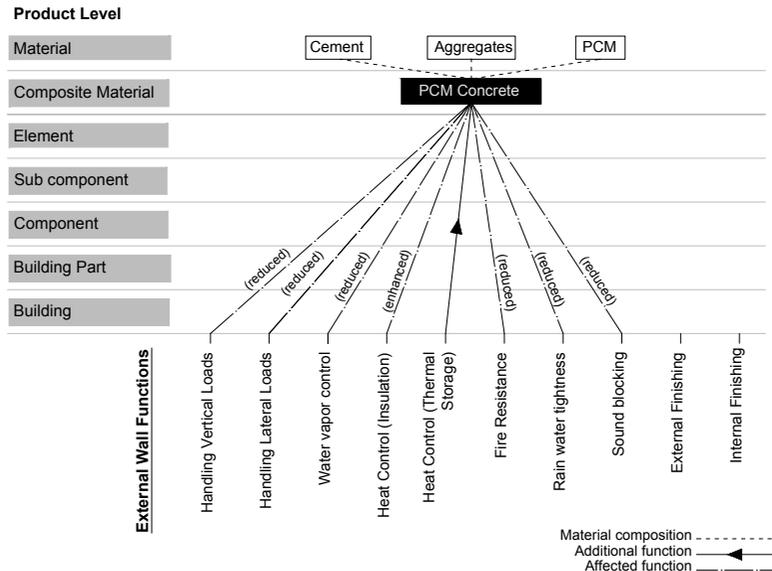


FIGURE 5.12 Scheme analysis for PCM Concrete

By applying the scheme to the technologies, the following points can be observed (Figure 5.12):

- 1- Integration occurs at the level of composite material (The integration requires a mixing process in order to achieve the additional thermal storage function).
- 2- Although the volume of PCM in the mixture is small (maximum of 7% of the mix), still the other functions originally performed by the massive wall will be affected. This is mainly due to the reduction of concrete density resulting from adding PCM, which is of relatively lightweight. The performance related to handling vertical and horizontal loads, water vapour control, fire resistance, rain water tightness and sound blocking will be reduced, while the performance related to insulation will be enhanced (Figure 5.12).

---

### Process analysis

The process analysis (Figure 5.13) is based on an interview with Dr Martin Tenpierrik, Assistant Professor at the Building Physics Department, TU Delft.

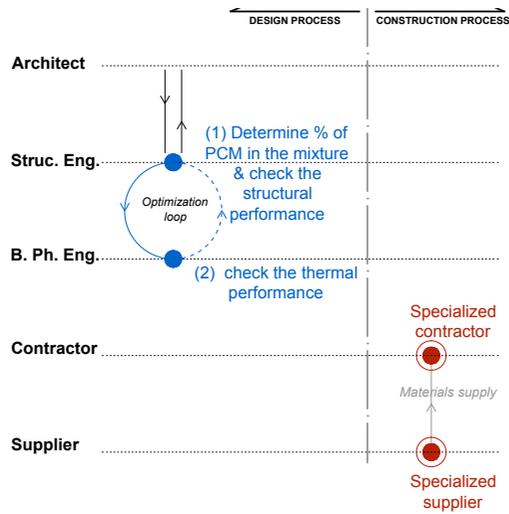


FIGURE 5.13 Process analysis for PCM Concrete

#### Design process

PCM massive wall is designed in a shared decision process between the Architect, the Structural Engineer, and the Building Physics Engineer as shown in Figure 5.13.

#### Construction process

Due to the expected difficulty in dealing with the material during the mixing and pouring process (similar to lightweight aggregates), a specialized contractor is required. Moreover, a specialized supplier for the mixture is required.

---

## 4- HEAT EXCHANGING CONCRETE (AIR PERMEABLE CONCRETE)

### External wall design parameters and schematic sketch

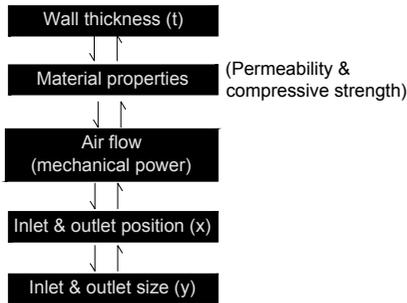


FIGURE 5.14 External wall design parameters for Heat Exchanging Concrete

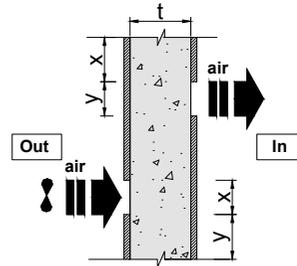


FIGURE 5.15 Schematic sketch of Heat Exchanging Concrete

### Component-Function analysis

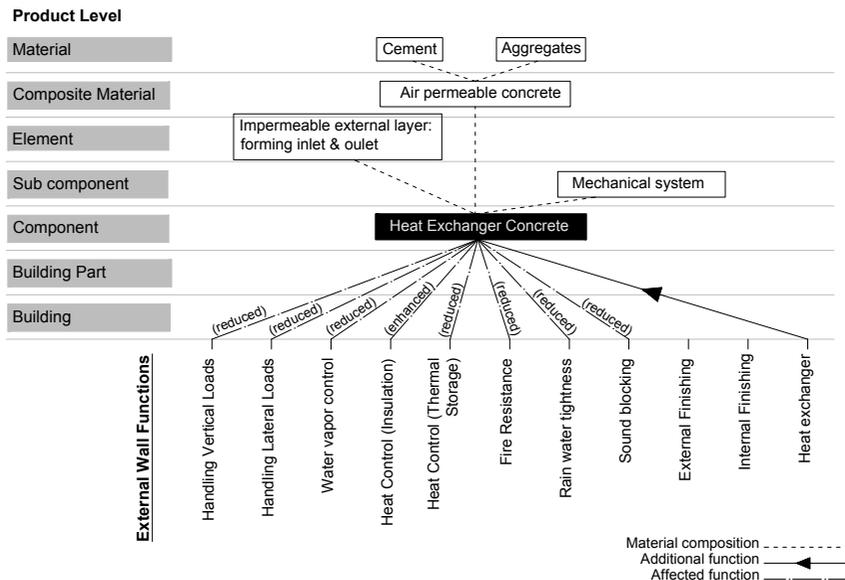


FIGURE 5.16 Scheme analysis for Heat Exchanging Concrete

By applying the scheme to the technologies, the following points can be observed (Figure 5.16):

- 1- The integration occurs at the level of component (Integration requires assembling different elements and subcomponents to achieve the heat exchanging function).
- 2- With APC acting as heat exchanger, other functions originally performed by the massive wall will be affected due to voids formation in the concrete. The performance related to handling vertical and horizontal loads, water vapour control, thermal storage, fire resistance, rain water tightness and sound blocking will be reduced, whereas the performance related to insulation will be enhanced (Figure 5.16).

### Process analysis

The process analysis (Figure 5.17) is based on an interview with Dr Martin Tenpierik, Assistant Professor at the Building Physics Department, TU Delft.

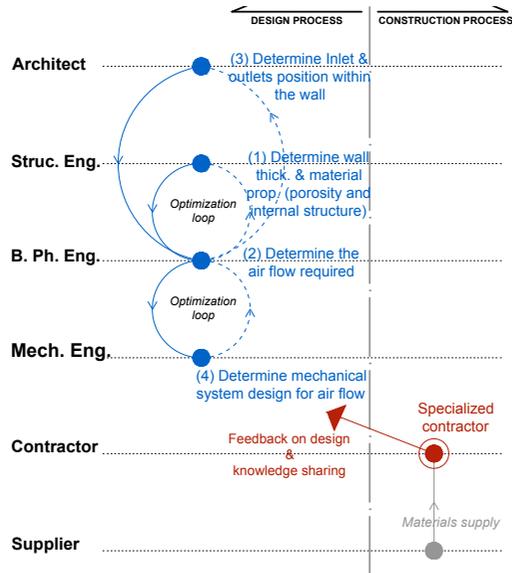


FIGURE 5.17 Scheme analysis for Heat Exchanging Concrete

#### Design process

Heat Exchanging Concrete requires a shared decision process between the Architect, the Structural Engineer, the Building Physics Engineer, and the Mechanical Engineer as shown in Figure 5.17.

#### Construction process

Due to the complexity of the process together with its newness (in both material and systems), it is expected that the contractor's involvement in the design process become important.

The contractor's capabilities to produce Heat Exchanging Concrete can highly limit the design decisions. Specialized contractor will likely be required in the construction process.



---

### Process analysis

The process analysis (Figure 5.21) is based on an interview with Dr Truus Hordijk, Associate Professor at the Building Physics Department, TU Delft :

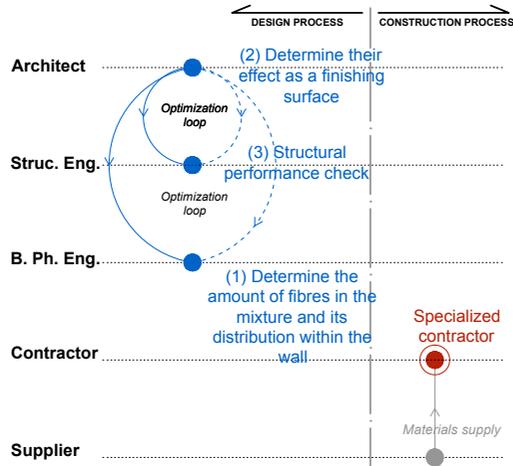


FIGURE 5.21 Scheme analysis for insulating technologies

#### Design process

Translucent Concrete external wall (if used for light transmitting function and not as a decorating element) is designed in a shared decision process between the Architect, the Structural Engineer, and the Building Physics Engineer as shown in Figure 5.21.

#### Construction process

Due to the difficulty of handling and fixing fibres prior to the concrete pouring process, a specialized contractor will likely be required.

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## 6- FUNCTIONALLY GRADIENT CONCRETE

### External wall design parameters and schematic sketch

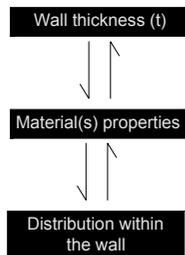


FIGURE 5.22 External wall design parameters for Gradient Concrete

FIGURE 5.23 Schematic sketch of Gradient Concrete

### Component-Function analysis

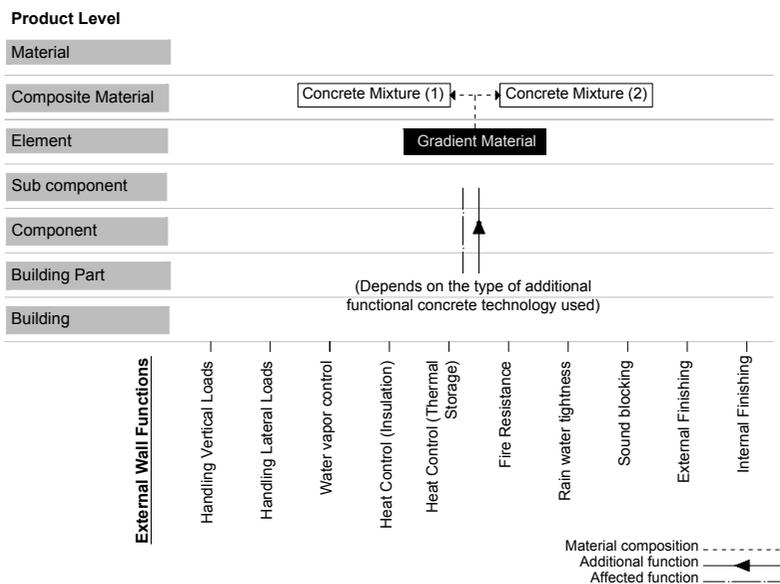


FIGURE 5.24 Scheme analysis for Functionally Gradient External wall

By applying the scheme to the technologies, the following points can be observed (Figure 5.24):

- 1- Integration occurs at the level of the element. (It requires a shaping process when pouring different mixtures into the desired form).
- 2- The functional analysis depends on the type of additional function concrete technology used. This can be for example, insulating Gradient Concrete, PCM Gradient Concrete or translucent Gradient Concrete (Figure 5.24).

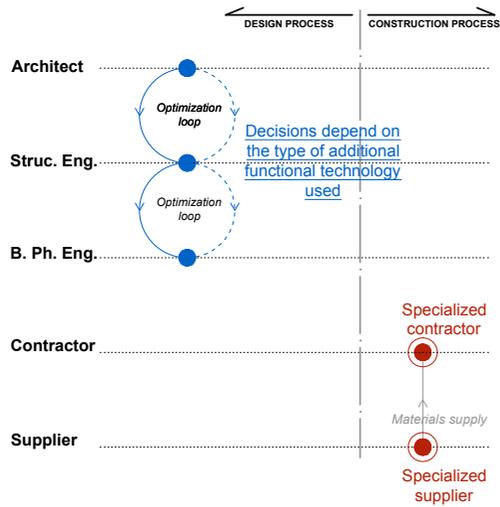


FIGURE 5.25 Process analysis for Gradient Concrete

**Design process**

The type of shared decisions depends on the type of additional function concrete technology used (Figure 5.25).

**Construction process**

Due to the difficulty in pouring concrete in a gradient manner, most likely a specialized contractor will be required. Moreover, a specialized supplier may be required depending on the type of additional function material used.

## § 5.2.2 Observations Regarding Process Changes

Based on the previous technology analyses, the following observations can be drawn:

- Massive technologies with additional function for external walls are seen in many forms. They appear on different product levels (Figure 5.26). They appear in a simple form as materials which only require simple mixing process for gaining the additional function such as Lightweight Aggregate Concrete and PCM Concrete. They appear in a more complex form as elements which require an additional shaping step such as Translucent Concrete and Gradient Concrete. Finally, they appear as components which require an assembly process of different elements and sub-components such as Thermally Activated Walls and Heat Exchanging Concrete.



FIGURE 5.26 Different product levels of massive technologies with additional function in external walls

- All massive technologies with additional function focus on integrating additional functions. On the other hand, they all affect other functions originally performed by the external wall. For example, the addition of an insulating function in Lightweight Concrete Aggregates results in the reduction of its structural functional performance. This requires a good understanding of the effects of each technology and a good balance between its performances depending on the projects requirements.
- The complexity of the wall design parameters is related to the product level of the technology. Material solutions like ILWC indicate few design parameters (wall thickness and material properties). On the other hand, component solutions like Thermally Activated Massive Walls indicate more complicated design parameters (wall thickness - material properties - pipe spacing - pipe positioning - water supply temperature - water flow rate). This reflects on the design process (as explained below).

By comparing the design process of the traditional external wall and the design process of the integral massive external wall as shown in Figure 5.27, the following can be observed:

- Unlike the linear scattered decisions in traditional construction where the design team members take their tasks away then bring them back to be re-integrated, in all integral technologies there is a joint problem-solving and decision-making between the design team. The design of the massive layer becomes the responsibility of all design team members and not only the structural engineer.
- The amount of shared decisions and the degree of interaction between the design team is related to the product level. Material level solutions show simple wall design parameters resulting in few shared decisions and low level of interaction between the design team. On the other hand, component level solutions show complex design parameters resulting in a high level of interaction between the design team.

The traditional phases of the building design process; pre-design, schematic design, and development; don't disappear in the process. The changes are mainly in the way the work is carried out in each phase. The work flows as "iterative loops;". The team members repeatedly review and refine the massive external wall layers in an iterative loop manner at each phase of design (Figure 5.27).

By comparing the construction process of the traditional external wall and the construction process of the integral massive external wall as shown in Figure 5.28, the following can be observed:

- Specialized contractors for implementing the uncommon additional function technologies are required. On the material and element level technologies this is required due to difficulties in mixing, pouring, or curing materials processes. On the component level, the difficulty is in the assembling process. Such consideration during the design process becomes important; otherwise the lack of a specialized contractor will result into a switch to traditional solutions.
- Specialized suppliers become sometimes required, especially for uncommon new materials in the building industry such as PCM and optical fibres. Such consideration also becomes important at the early design stage.
- The Contractor's participation in the design process is seen important in complex product levels such as in component level technologies. This results from the solution complexity during construction, which requires the contractor to share his knowledge, experience and capabilities, influencing the design in the early phases. Ignoring his presence and knowledge sharing in the design phase may result in sacrificing some aspects considered during the design, or even ignoring the whole solution and switching to traditional techniques.

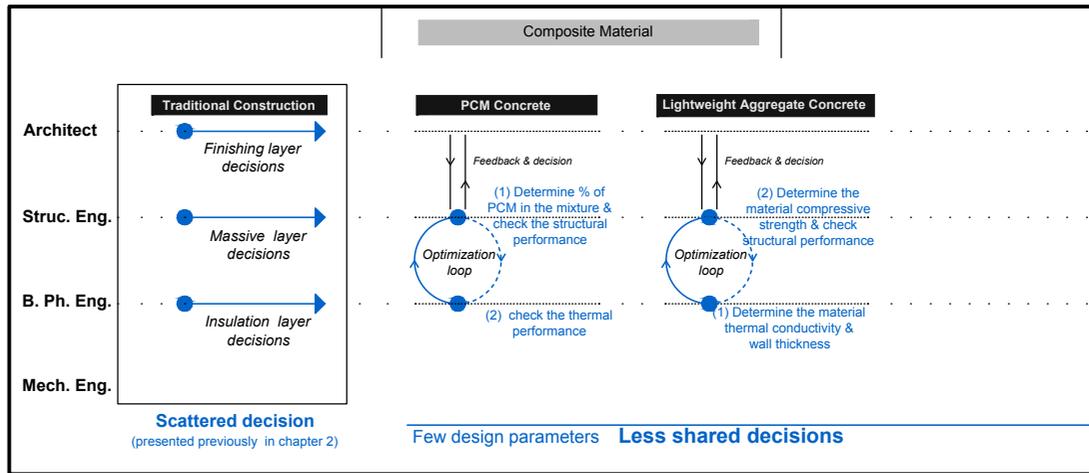


FIGURE 5.27 Design process observations

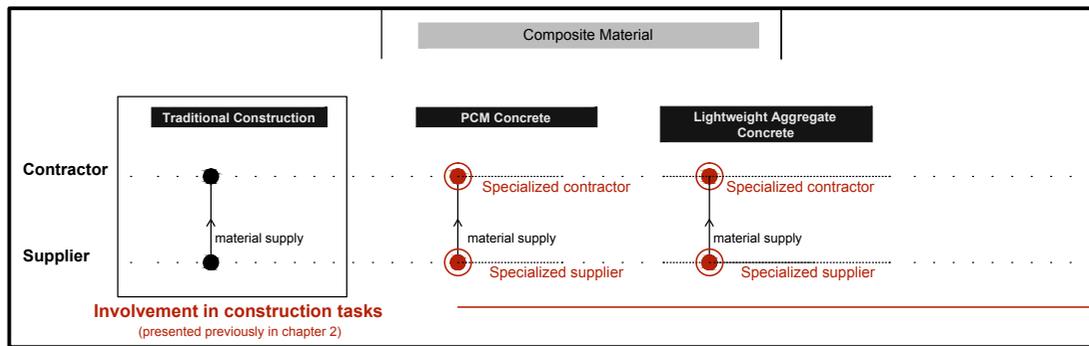
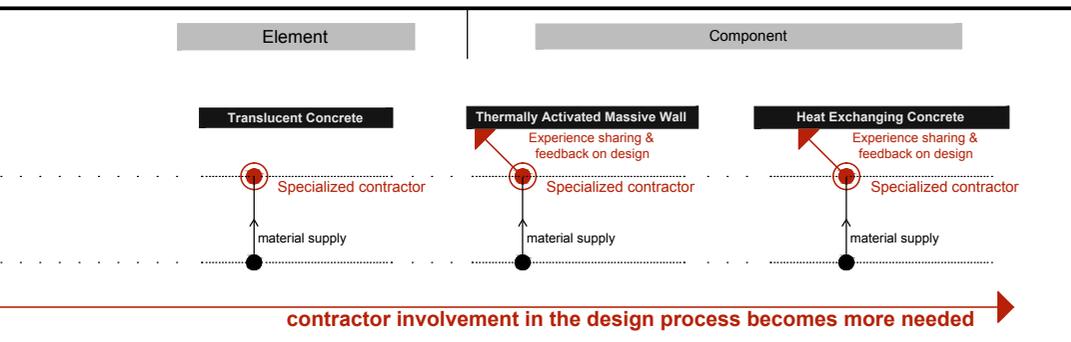
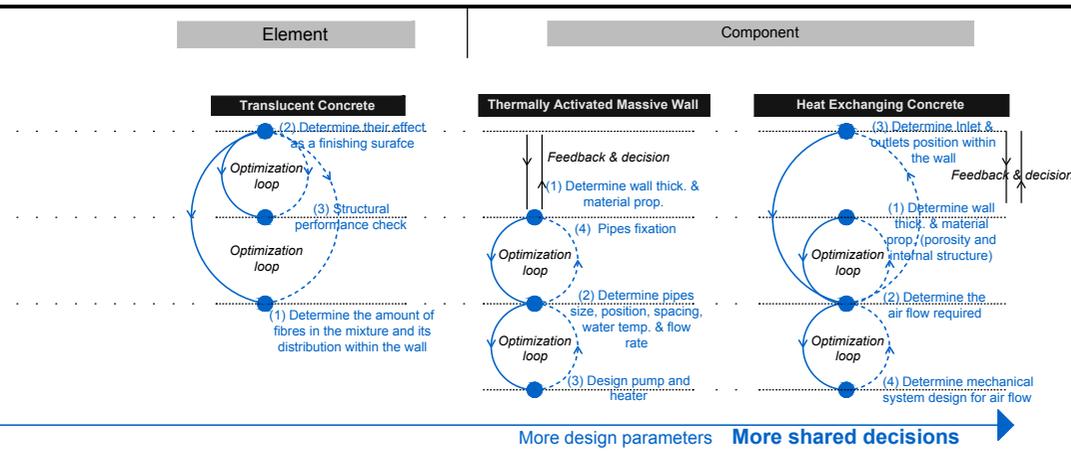


FIGURE 5.28 Construction process observations



## § 5.3 Product-Designed Solution: A Possible Approach

### § 5.3.1 Approach Explanation

The previous section discussed the additional function technologies in the form of project-designed solution, meaning that the technologies and solutions were tailored according to the unique requirements of the project. However, in order to understand the impact of additional function technologies on the process in all its forms, the product-designed approach needs to be considered. In such approach, the external wall has higher dependency on pre-designed solutions that are designed independent from the project. A supplier becomes then more involved in the process. In its extreme case, the integral massive external wall is designed completely independent from the project, and usually through a technology supplier. Figure 5.29 shows the forms and properties of the two extreme systems (Davies & Brady, 2000).

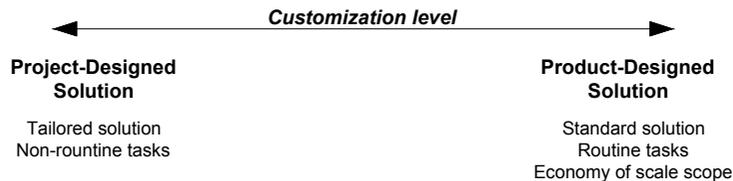


FIGURE 5.29 Forms and properties of the two extreme systems (Davies & Brady, 2000)

## § 5.3.2 Case Studies

The implication of this shift from project-designed to product-designed solution on the design and construction process is explained through case studies. In these cases, unlike the cases of section 5.2, the technologies are provided to the project in the form of products from a supplier, with wall design parameters fixed independent from the project. This affects the design and construction process, giving the supplier a greater in the process as will be seen in coming case studies analysis.

Different market products have been highlighted, however, three case were selected for the analysis. The three cases are believed to be enough for the analysis as they present different product levels according to the available market products. Figure 5.30 shows the different market products with the reasons for the cases selection.

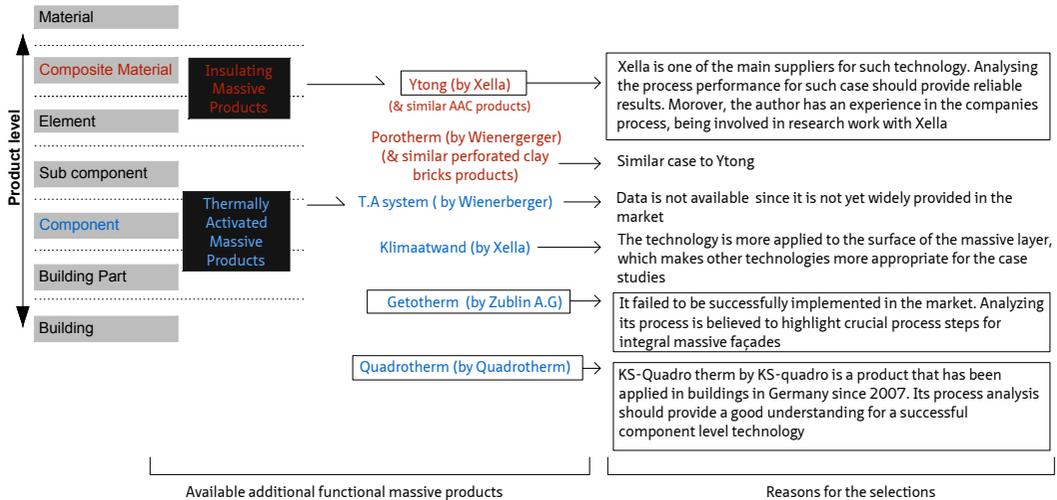


FIGURE 5.30 Reasons for selection of three specific case studies

Accordingly the analyzed case studies are:

- Ytong AAC blocks by Xella
- KS-Quadrotherm (Thermally activated calcium silicate blocks) by KS-quadro
- Geothermshield (Thermally activated structural panels) by Züblin AG.

## YTONG BLOCKS

### About system

Ytong blocks are manufactured from AAC, a technology presented in Section 4.3.2.



FIGURE 5.31 Ytong blocks at a project site

### Technology supplier and technology market position

Xella is one of the world's largest manufacturers of Autoclaved Aerated Concrete and Calcium Silicate units, with 98 plants in 20 countries and sales and marketing organisations in 30 countries. Its AAC is produced in many forms according to its insulation value and strength. However, the Ytong product (Figure 5.31) is the most common product used in massive external wall construction (Xella, 2015).

### External Wall design parameters

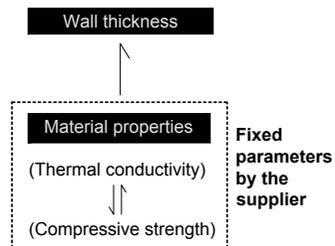


FIGURE 5.32 Ytong design parameters

### Process analysis

The design and construction process of Ytong blocks is outlined in the diagram given in Figure 5.33. Data about the process is gathered from mainly two sources. First is the company's website, which partially explains the process. Second is the author's experience with the company's process, being involved in a research work with Xella.

The following points can be observed:

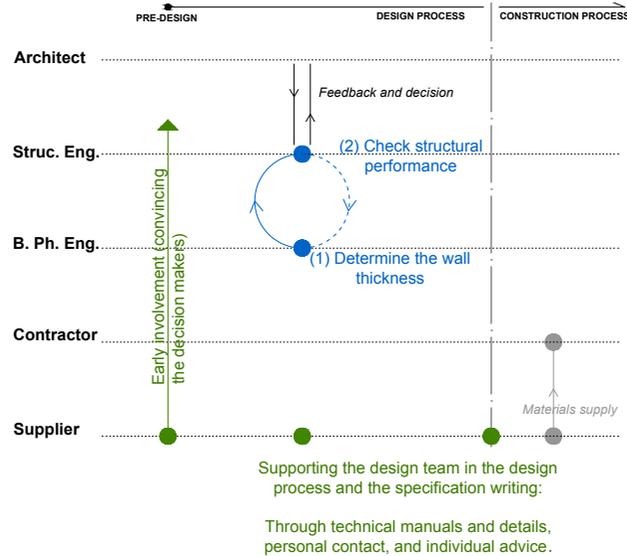


FIGURE 5.33 Design and construction process for project using Ytong blocks

### Project design team tasks

In the process of wall design with Ytong, there is still a shared decision process related to the wall thickness between the Structural Engineer, the Building Physics Engineer and the Architect. However, the parameters related to the material properties (compressive strength and thermal conductivity) are already fixed by the supplier. This results in a simpler shared decision process.

### Supplier tasks

A clear change in the supplier's tasks is his involvement in all product and project stages. In addition to supplying the materials/system in the construction process, his involvement includes:

#### *Pre-design early show-up*

The technology supplier is present in the project in the early design decisions. This is to convince the design team about the advantages of using the Ytong system before a traditional system is selected. Otherwise, it is hard for the design team to go backwards in the process. However, due to the familiarity of the system among architects and decision takers, the system does not require an intense marketing task by the company.

#### *Supporting design team*

The supplier supports the design team during both the external wall design and specification writing. This support takes place through providing technical manuals and details, personal contact, and individual advice.

## KS-QUADRO THERM

### About system

KS-QUADRO THERM is a Thermally Activated Wall system for controlling the temperature of wall surfaces (Figure 5.34). It consists of calcium silicate blocks (known as KS-QUADRO E masonry) and piping modules (known as EVOTURA modules).



FIGURE 5.34 KS-Quadro Therm system

The KS-QUADRO E masonry has a continuous, vertical installation channel system at a distance of 12.5 cm over the entire wall height. In these channels, the piping modules are placed. The EVOTURA piping modules have standard versions with 3, 4 and 5 piping lines with a standard length of 2.40 meters. If required, special lengths can be made available. The spacing of the pipe lines is 25 cm. The height of the module head (flow and return level) is 15 cm (as shown in Figure 5.35) with a recommended ceiling thickness for the system of 18 cm.

### Technology supplier and technology market position

The system is supplied by KS-QUADRO, which is originally a calcium silicate blocks supplier, partnering with EVOTURA, a heating system provider in Germany. The system is being implemented in several projects in Germany since 2007.

### External Wall design parameters

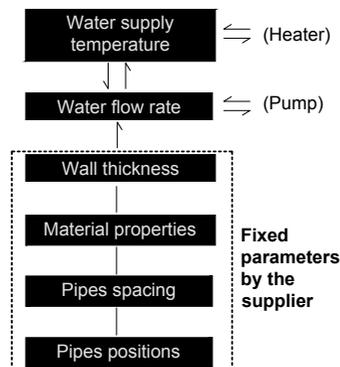


FIGURE 5.35 KS-Quadro Therm design parameters

### Process analysis

The design and construction process of KS-QUADRO THERM system is outlined in a diagram given in Figure 5.36. Data about the process is gathered from mainly two sources. First is the company's website, which partially explains the process. Second is through correspondences between the author and a representative from the company. These correspondences took place after the company was asked by the author about the process to implement KS-QUADRO THERM for a residential row-house building in the Netherlands.

The following points can be observed:

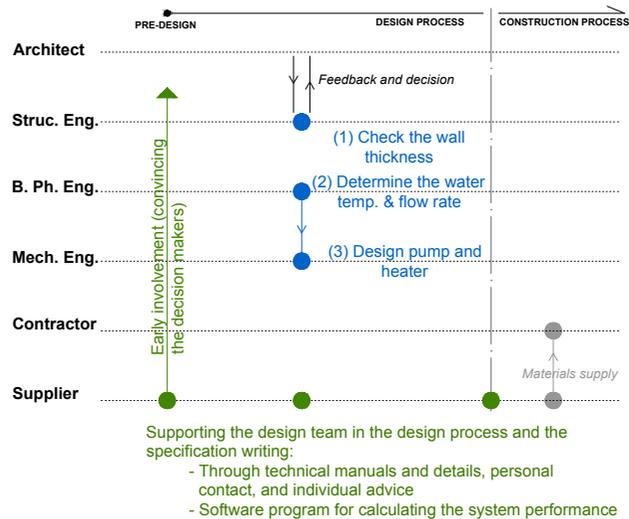


FIGURE 5.36 Design and construction process for KS-QUADRO THERM

### Project design team tasks

In the process of wall design with KS-QUADRO THERM, the decision process is simple as many parameters are fixed. The design tasks are limited to the determination of (1) appropriate wall thickness from the various available blocks by the Structural Engineer, (2) the water temperature and flow rate by the Building Physics Engineer, and (3) the pump and heater system accordingly by the Mechanical Engineer. The massive layer material properties and the pipes diameter, positioning, and spacing are already predetermined by the supplier.

### Supplier tasks

A clear change in the supplier's tasks is his involvement in all product and project stages. This involvement included:

#### *Predesign early show-up*

The technology supplier is present in the project in the early design decisions before a system decision is made, making it hard for the design team to go backwards in the process. Unlike the previous AAC case, the newness of the technology in external walls, together with its complexity (being a component level technology), make the early presence of the company at the early design stage of the project more crucial.

#### *Supporting design team*

Similar to the previous case, the supplier supports the design team during both the external wall design and specification writing. In addition to the technical manuals and details, personal contact, and individual advice; the company provides a special software program for calculating system performance (heating/cooling performance and input energy required). This facilitates the checking tasks for the design team.

## GEOTHERMOSHIELD

### About system

Geothermoshield is a thermally activated product concept based on prefabricated concrete building envelope panels, which have both structural and building service functions. It is primarily designed to provide heating and cooling for the building shell with the main heating/cooling energy source from geothermal energy such as through thermo-active piles, probes, ground collectors and groundwater (Figure 5.37).

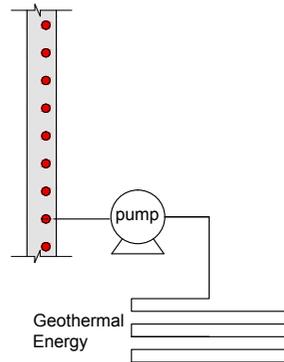


FIGURE 5.37 Geothermoshield concept

The mean inlet temperature for the Geothermoshield is approximately 23°C for heating and 19°C for cooling. In case the necessary inlet flow temperature is not reached, especially when using passive geothermal sources for heating; an additional reversible heat pump implemented in the system adjusts the temperature..

### Technology supplier and technology market position

The product concept was developed by Ed. Züblin AG, a general contractor with in-house engineering having a consulting back office and facilities for producing prefabricated structural elements. However, the concept hasn't been successfully introduced as a product in the market.

### External Wall design parameters

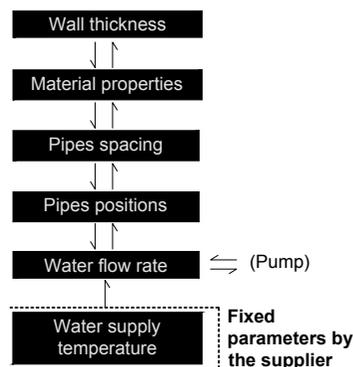


FIGURE 5.38 Geothermoshield design parameters

### Process Analysis

In order to obtain data about the process (since not much data about it is available), correspondence with the company was the most practical data collection method. The approach individual was Dr Ian Quirke, a project manager at Ed. Züblin AG. He was chosen because he is the concept developer. In 2010, he published an article describing the Geothermshield concept (Quirke, Baun, & Hauber, 2010). The discussion was open structured.

Dr Ian Quirke was mainly asked about the reasons, from his point of view, for the failure of Geothermshield being implemented in real projects. His clear answer about the reason of failure gives a good insight about the process:

*"Too complicated. This is better understood when you see things from our viewpoint as a General Contractor working mainly in Germany. We are usually involved in projects at a design stage where it is no longer viable to advance issues of intricate integration of technology, simply because the design team has laid down the basics already and the Client is not going to listen to us. We can (and have successfully) advance such suggestions for key accounts and for projects with early Contractor involvement."*

His answer mainly highlights the importance of early involvement of the system supplier in the design process for the case of additional function technologies, and particularly when it is provided on more complex product levels (Figure 5.39)

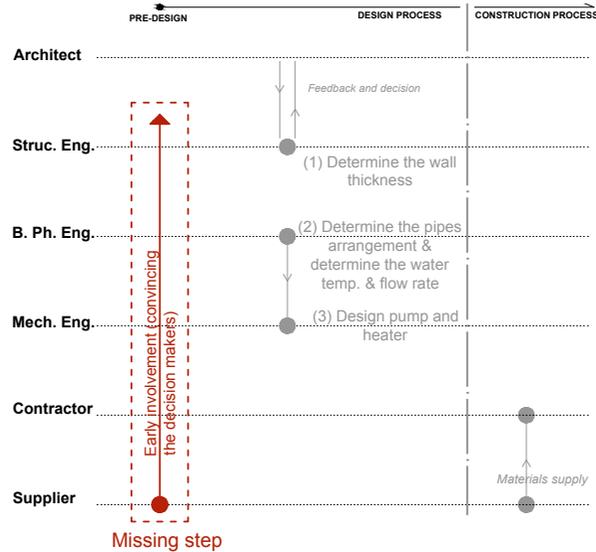


FIGURE 5.39 Design and construction process for Geothermshield

### § 5.3.3 Observations Regarding Product-Based Solutions

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A better understanding of the design process as related to the customization level can be drawn by comparing the design process of the previously analysed product-based solutions with the project-designed solutions previously analysed in Section 5.2.1. Figure 5.40 presents this comparison as related to the design process. The following can be observed:

- In product-designed solutions unlike project-designed solutions, many parameters are fixed independent from the project requirements. For example in Autoclaved Aerated Concrete; parameters as material properties, material compressive strength, and material thermal conductivity are usually determined by the supplier. Suppliers such as Xella provide a wide range of material properties in order to fulfil different project requirements. In the case of KS-Quadro Therm; the massive block properties, the pipes diameter, positioning and spacing are parameters fixed by the supplier. Fixing these parameters result in less shared decisions between the design team and lower level of interaction.

Figure 5.41 presents the observations of the construction process as related to the Product level. The following can be observed:

- In project-based solutions, the supplier is merely involved in the construction process as a material/technology supplier. However, in the product-based additional function solutions, the supplier is involved in all project stages as follows:
  - a In pre-design stage: The technology supplier presence in the project's early design decisions (convincing the decision makers of the technology) is important. However, the intensity of this presence is dependent on both the newness of the technology and its complexity (being on a component level solution and below). New and/or component level technologies are likely to have a more crucial early involvement. This is because new technologies need to be visible, while component level technologies are harder to be incorporated at later design stages.
  - b In design and tendering stage: The technology supplier support is important. This includes support for the project design team during the design and the specification process. The supporting tasks may differ according to the complexity of the solution. Component level technologies (with more parameters) require more complicated support in design task than material level technologies, such as providing a software program for measuring the system performance.
- At component level solutions, which depend on integrating other sub-systems and components into the massive layer, greater dependency on external suppliers to provide those systems becomes required.

It worth mentioning that not many product-based solutions were analyzed as the additional function concept in external walls is relatively new and consequently not many products are available. However, the three selected cases are enough to explain the process changes as related to the customization level and product level.

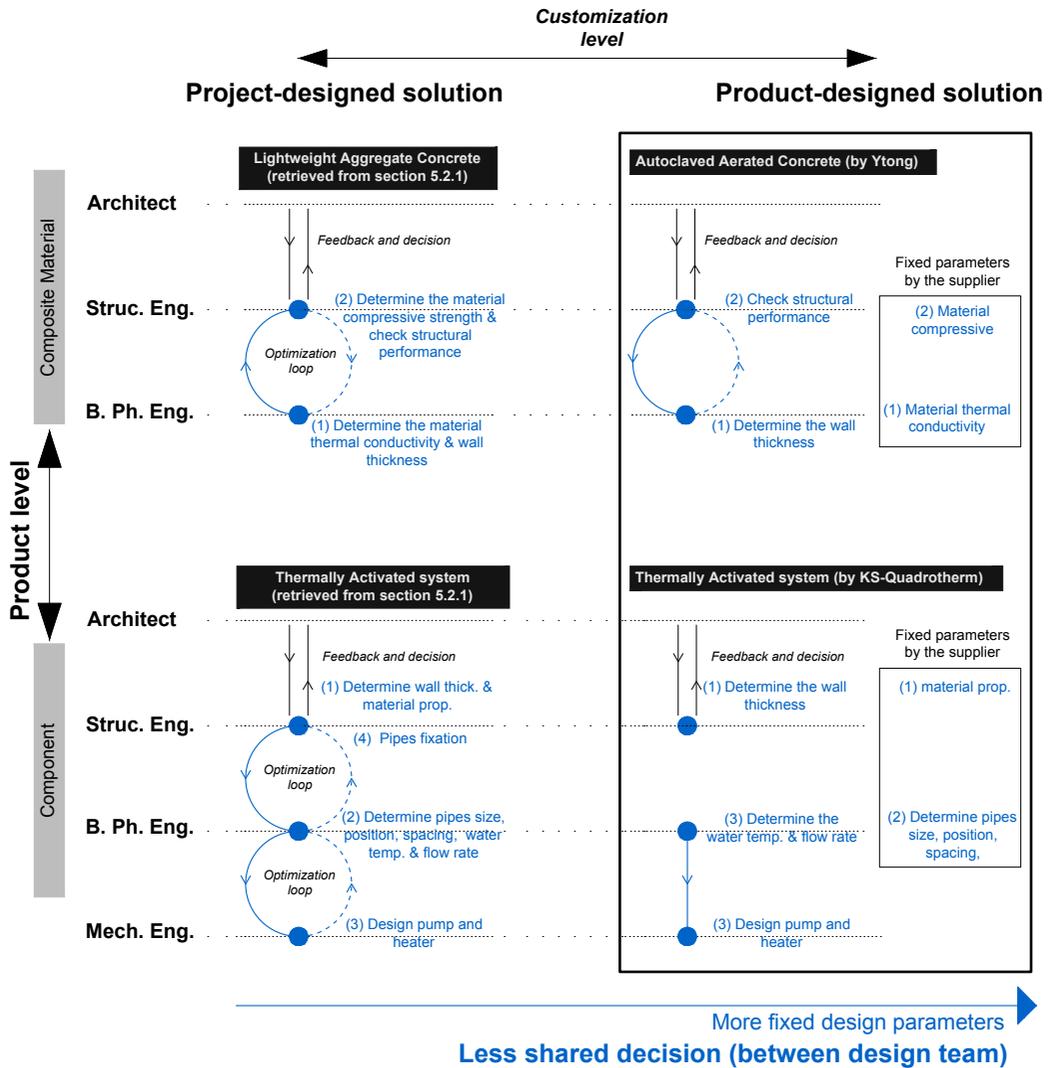


FIGURE 5.40 Design process observations

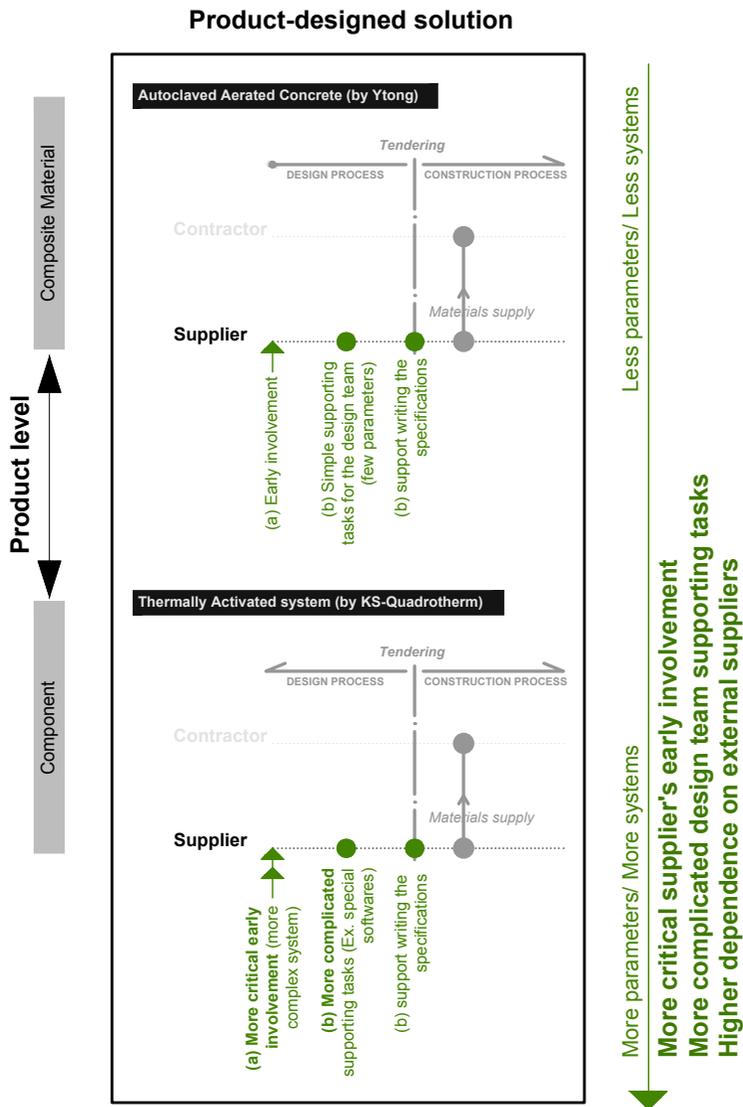


FIGURE 5.41 Construction process observations

## § 5.4 Observations and Guidance Scheme

In order to draw a holistic picture of the massive technologies with additional function process changes, Figure 5.42 links the observations of the project-designed cases of Section 5.2.2 to the observations of the product-designed cases of Section 5.3.3 in one scheme. In this scheme, the following points are considered:

- The customization level is presented on the X axis, and the product level is shown on the y-axis.
- The graph differentiates between solutions provided by the design team (highlighted in blue) and solutions provided by the suppliers (highlighted in red).
- Addition examples other than the ones previously analysed are used in the scheme. This help to better understand the scheme.

Observations from the scheme can best be explained as follows:

- 1 For design team-based additional function solutions:
  - By moving from material solutions to component level solutions, more shared decisions by the design team members are taken as more design parameters are included.
  - By moving from material solutions to component level solutions, the Contractor's involvement in the design stage becomes needed due to the solutions' complexity.
  - By moving from open design parameters to more fixed design parameters, less shared decisions are taken by the design team as more parameters are fixed independent of the project. An example of this case is the Thermally Activated External wall of Zollverein school (which is placed at the right hand side of the Customized Thermally Activated Wall). The presence of water with specific temperature from the coal mine limits the design parameters, which contributes to the reduction of the shared design decisions.
- 2 *For supplier-based additional function solutions:*
  - By moving from material solutions to component solutions, the supplier's involvement in the early design phase becomes more critical as more complex solutions are harder to incorporate at the late design stages.
  - By moving from material solutions to component solutions, the supplier's supporting tasks to the design team becomes harder as solutions becomes more complicated in terms of design.
  - By moving from material solutions to component solutions, more components and sub systems become incorporated in the design. This requires the supplier to depend more on external suppliers.

- By moving from fixed design parameters to more open design parameters where those open parameters are determined by the project design team, more shared decisions are taken by the design team. Three examples of Thermally Activated Wall system can best explain this case. These are the Klimaatwand (by Xella), KS Quadrotherm and Geothermshield systems. Xella has a low degree of customization as the only tailored parameter to the project requirements is the water temperature. In the KS-Quadrotherm, both the water temperature and the wall thickness are tailored according to the project. In the Geothermshield example; the water temperature, the wall thickness, and the pipes positioning are tailored according to the project needs. This reflects on the amount of shared decisions by the design team. The Klimaatwand provides the least amount of shared decisions between the design team, followed by the KS-Quadrotherm, and finally the Geothermshield.
- By moving from fixed design parameters to more open design parameters where those open parameters are determined by the supplier, the supplier's in-house design team requires more frequent collaboration between its members. This depends on the degree of customization and the product level of the additional function solution.

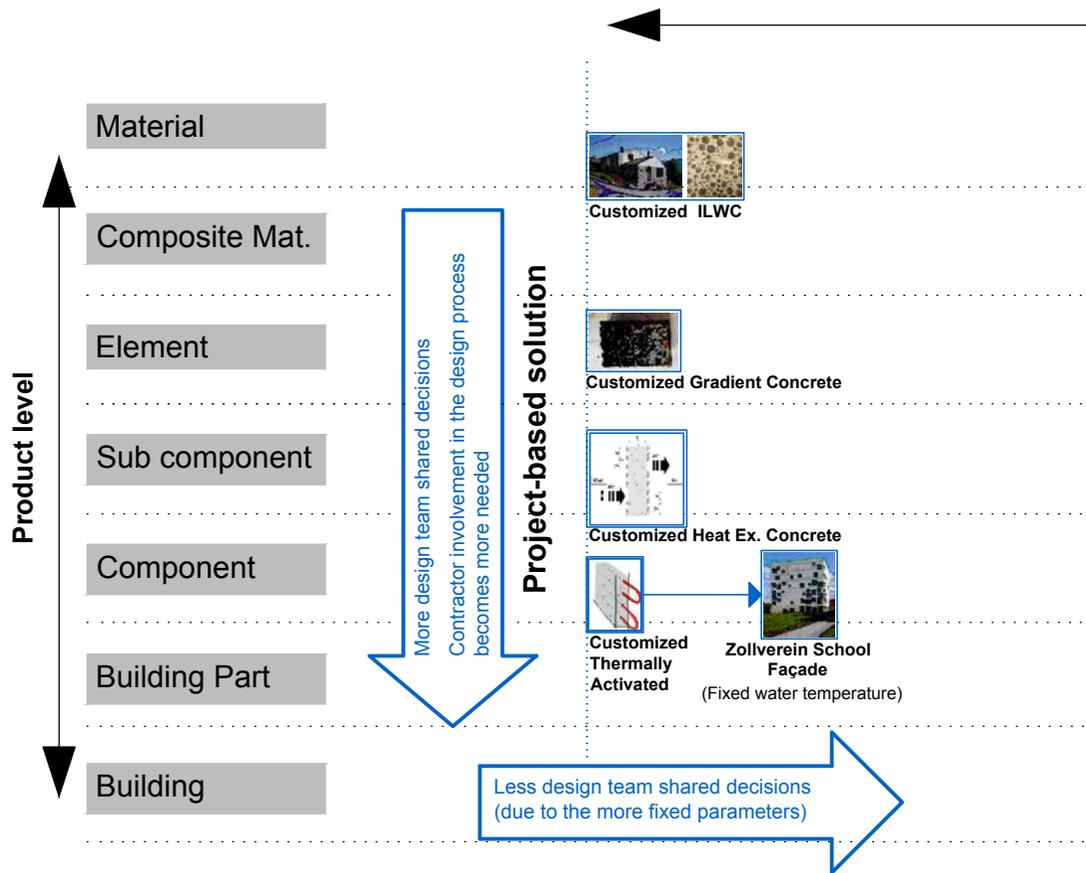


FIGURE 5.42 Observed changes to design and construction process as related to the Product level and Customization level of addition functional massive technology (with examples and explanation)

Customization level



**Porotherm**  
(Perforated clay bricks)

**Ytong (AAC)**



**Geothermshield**

(Water temperature, water flow rate, wall thickness and pipes arrangement are dependent on the project)



**KS-Quadrotherm**

(Water temperature and flow rate are dependent on the project)



**Xella Activated Walls**

(Water temperature is dependent on the project)

**Product-based solution**

More critical supplier's early involvement  
More complicated design team supporting tasks  
Higher dependence on external suppliers

More decisions taken by the supplier's in-house design team

*(in the case the wall design is implemented by the supplier)*

Supplier-based designed cases

Design team based cases

Observations from the supplier cases

Observations from the design team cases



From the observations, the expected changes in the traditional design and construction process can be extracted. This provides the answer to the first part of the research question: *What changes are required to the present traditional design and construction process if massive technologies with additional function are implemented in external walls?*

The following changes are expected:

**1 A different start with a complete design team**

The traditional project setting, in which the architect is simply the form-giver and wall system decider at the early design stage, needs to change. For additional function technologies with more complex parameters, a start with a complete team, which is capable of assessing the different integral technologies before a system selection, is important.

**2 Shared decisions → collaborating design teams**

Design teams need to come together in a more integral way rather than having a scattered nature. This can take place in many forms according to the company's structure and size, and project's nature. In its simple form, this can be through arranging group meetings, interwoven with the overall project schedule. If this is not done at the beginning, it is too easy for the design team to change to the familiar linear design processes

**3 Contractor involvement in early design process → design-build procurement method favored**

The contractor's involvement in the early design stage requires reconsidering the traditional design-bid-build procurement method. This is because the traditional method creates separate responsibilities for design and execution. The contractor becomes known only after the design has been set.

A Design-Build procurement method, where the designer and constructor are the same entity or are on the same team (without tendering stage), will then provide a better environment, particularly for complex product level solutions.

**4 New supplier capabilities (in case technology is provided by supplier)**

**a Supplier's early involvement in design process → changes in market and sales vision**

The shift from the contractor or material specifier, being the supplier's customer, to architect or decision maker, being the supplier customer target, requires a different sales and marketing strategy. This may include changes in the organization, such as acquiring new marketing and sales personnel. The change becomes more crucial for complex product level solutions.

**b Dependency on external suppliers → changes in supply chain organization**

The amount of changes differs from one company to another according to its existing supply chain organization, and from one technology to the other. However, it is likely that these changes are greater at complex technology levels and technologies depending mainly on other sub-systems and sub-components.

**c Acquiring internal supporting team/system**

The supplier supporting tasks require considerations for providing a supporting team that acquires the know-how about the system and the design tasks. In addition, the required tools, facilities and equipment need to be considered. On more complex product levels, where complicated supporting tasks are expected, the internal supporting team/system is expected to be more design knowledgeable.

Based on these recommendations, the following guidance scheme can be generated (Figure 5.43).

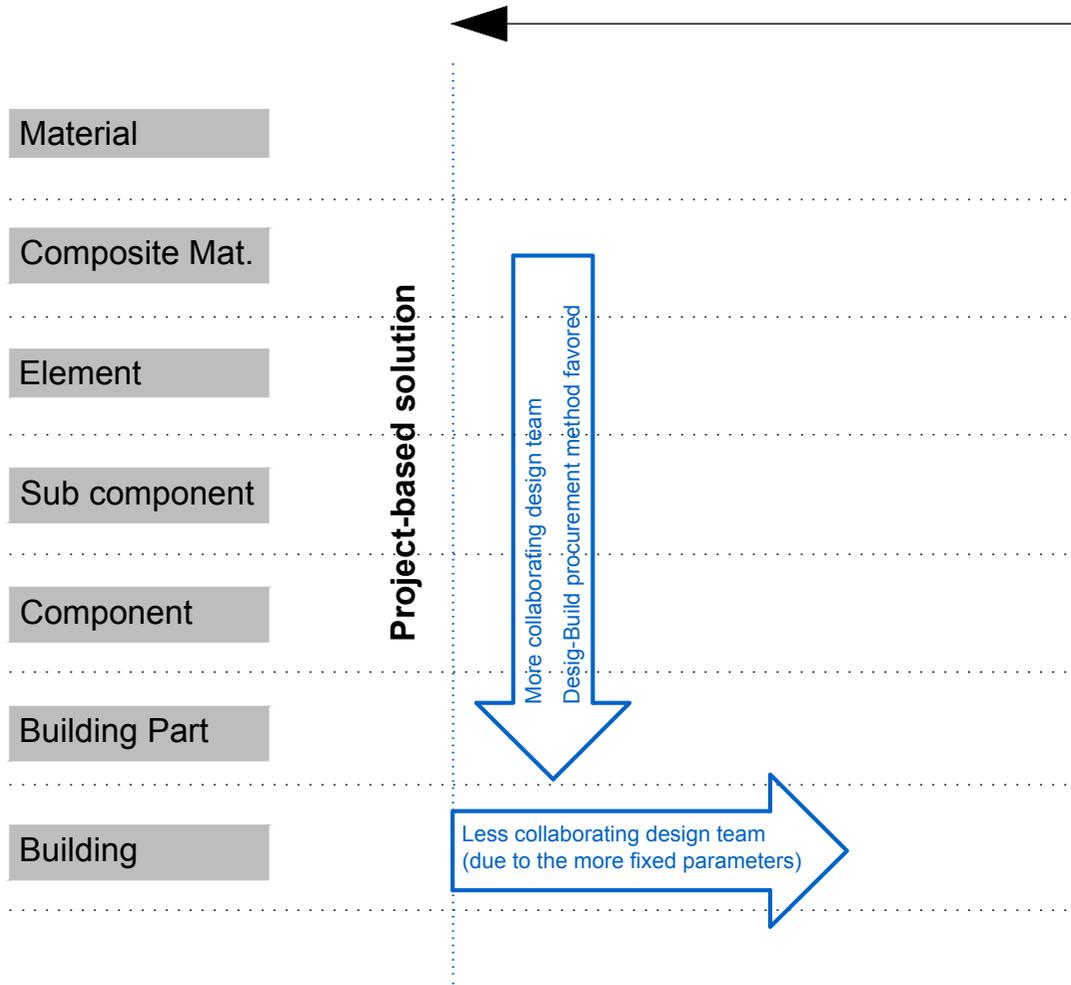


FIGURE 5.43 Recommended changes to design and construction process as related to the Product level and Customization level of addition functional massive technology

Customization level



Product-based solution

More changes in the market and sales vision  
More design knowledgeable supporting team  
More changes in the supply chain organization

More frequent collaboration between  
supplier's in-house design team

*(in the case the wall design is implemented by the supplier)*

Recommended changes for the supplier (supplier solution)

Recommended changes for the design team (design team solution)



The recommendation scheme shows that the process changes depend on the product level in which the technology takes place, the degree of customization of the solution, and whether the system is provided by the supplier or the design team. These three factors can determine the changes required to the design and construction process when massive solutions with additional function are applied in external walls as shown in the scheme. This scheme does not show the clear sharp picture about the process changes, but rather a relative relation between the different forms.

For project decision makers, the scheme shows the impact of selecting a specific additional function technology on the design and construction. For system suppliers, it shows the impact of developing a specific technology on the design and construction process, as well as on the company. The scheme outcome is as follows:

- 1 **For design team-based additional function solutions:**
  - Moving from material solutions to component level solutions requires:
    - a More collaborating design team.
    - b Contractor's involvement in the design stage, which makes the Design-Build procurement method more favoured.
  - Moving from open design parameters to more fixed design parameters requires less collaborating design team.
  
- 2 **For supplier-based additional function solutions:**
  - Moving from material solutions to component solutions requires:
    - a More changes in the market and sales vision
    - b More design knowledgeable supporting team
    - c More changes in the supply chain organization
  - Moving from fixed design parameters to more open design parameters requires more frequent collaboration between the supplier's in-house design team.

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## § 5.5 Conclusions

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This chapter has presented the design and construction process changes required in the traditional design and process when massive technologies with additional function are implemented in external wall. Different massive technologies with additional function were analysed after being implemented in external walls. The case studies ranged from already existing additional functions technologies, such as AAC, to new concepts, such as Heat Exchanging Concrete. The following conclusions can then be generated:

- With the addition of functions to the massive component, other external wall performances could be affected. For example, adding an insulation function to concrete reduces its structural strength. The functional success of a technology depends on a balance between different criteria that differ from one project to another.
- Integral massive external wall technologies can occur at different product levels. They range from material integral solutions, to element integral solutions, to component integral solutions.
- The product level and the customization level in project-based solutions and product-based solutions were used to identify the process changes for different case studies.
- A guidance scheme for different stakeholders was generated showing the expected process changes as related to the product level and customization level. For the design team solutions, the position can determine the collaboration level between the design team and the type of procurement method. For the supplier solution, this position can determine the level of change in the company's market and sales vision, the level of knowledge of the supporting team, and the level of changes in the supply chain organization.
- For the design team based solutions, moving from material solutions to component level solutions requires two changes. First, it requires a more collaborating design team. Second, it requires the contractor's involvement in the design stage, which makes the Design-Build procurement method more favoured. However, moving from open design parameters to more fixed design parameters requires less collaborating design team.
- For supplier based solution, moving from material solutions to component level solution requires three changes from the supplier's side. First, it requires more changes in the market and sales vision. Second, it requires more design knowledgeable supporting team. Finally, it requires more changes in the supply chain organization. Moving from fixed design parameters to more open design parameters requires more frequent collaboration between the supplier's in-house design team.

Each project has its own context that can make one form of technology more favourable than another. For example in cases where collaboration between project teams is hard to achieve, product-based solutions will then be favoured. The developed guidance scheme works as guidance for such decisions.

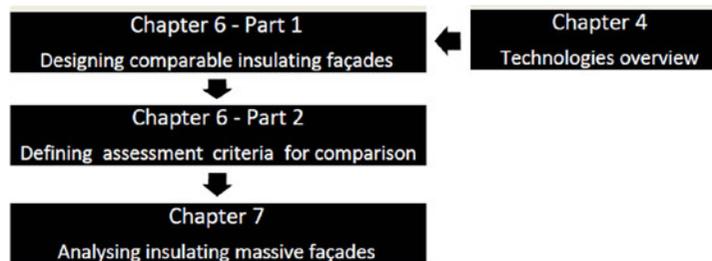


# 6 Design for Insulating Massive External Walls in the Netherlands and Egypt

## § 6.1 Introduction

In the previous chapters, several massive technologies with additional function were presented. These technologies covered many functions such as insulation, heating, thermal storage, and light transmittance. However, deriving a general conclusion regarding whether additional function technologies are better than traditional solutions is not easy. Each technology provides a different function but could affect other functions. In addition, each project is different requiring a different set of performances.

The coming chapters investigate whether additional function technologies in external walls are better than traditional external walls. However, the study focuses on the insulating technologies, previously presented in Chapter 4, and in the context of the Netherlands and Egypt. The following scheme shows the structure of the related chapters.



This chapter focuses on designing comparable insulating massive external walls for each context, the Netherlands and Egypt, and on setting the criteria for the comparison. It aims to provide an answer to the question of *how we can compare additional insulating massive external wall technologies with the traditional massive external walls in Netherlands and Egypt*.

The chapter is divided into four main sections. In the first section, the reasons for focusing on additional function insulating massive technologies are outlined. In the second section, which focuses on external wall design, a typical building case is defined for each context. This is followed by a discussion regarding the building rules and regulations related to the external walls in each context. Accordingly, comparable external wall designs for the Netherlands and Egypt are defined. In the third section, the assessment criteria for comparing the designs are set and explained. Finally, conclusions regarding the contents of this chapter are drawn.

## § 6.2 Reasons for Focusing on Additional Insulating Massive Technologies

The selection of insulation as an additional function in the coming part of the research is for the three following reasons:

### 1 Insulation is an important function for both the Netherlands and Egypt

For both contexts, the topic of insulating external wall and building envelopes is generally of great importance. However, this importance is seen differently in each context. In the Netherlands, the external wall insulation is mandatory. The external wall has to fulfil a specific R-value of 4.5 m<sup>2</sup>k/W. In Egypt, the situation is different. External wall insulation is not mandatory and no regulations mention minimum requirements for its insulation performance. However, the insulation issue has become recently alarming.

Egypt's reliance on mechanical equipment in residential buildings for cooling has sharply increased. The last 20 years witness a rapid growth of sale figures of fans and air-conditioners. The number of air-conditioning units exceeded 54,000 units per year between the years 1996 and 2006, while it reached an average of 766,000 units per year between the years 2006 and 2010 (Attia et al., 2012). This increasingly accelerated reliance on mechanical acclimatisation all over the country resulted in peaking energy consumption rates. In August 2014, the electricity demand hit a record of 27,700 megawatts, which is 20% more than the power stations could produce (Kingsley, 2014).

As a result, Egypt is now suffering from a worrisome energy crisis that the country witnessed in decades, with parts of the country having six power cuts a day for up to two hours at a time. The energy problem in Egypt then highlights the importance of discussing insulation as an important function in building envelope.

## 2 Other technologies require further separate studies.

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Other additional functional technologies are more complex and require further technology developments and subsequent separate studies as outlined below.

- In order to assess the functional performance of a new technology in relation to a specific function, both the new wall technology and the traditional wall have to be comparable and equivalent in all other performances. Presently, most of the studied technologies are still concepts, with still unknown performances. Further research is needed to determine their performances.
- Smart solutions require special simulation programs to design and generate results. At the same time, due to the newness of the technologies, no data is available from existing projects.

## 3 Wide range of massive insulating technologies

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As illustrated in Chapter 4, there is a wide range of insulating massive technologies. Some of them already exist such as Autoclaved Aerated Concrete, while others are currently being developed like Aerogel Concrete. Moreover, each technology has various mixtures providing different levels of insulation and structural performances. This creates a wide pool of possibilities and, consequently, provides a more general conclusion regarding the comparison between additional function technologies and traditional solutions.

## § 6.3 Comparable External Wall Designs

### § 6.3.1 Defining Typical Building Case

Depending on how the building is defined, different external walls are accordingly shaped. Defining a repetitive typical case becomes then necessary in order to design comparable external wall solutions in a realistic and reliable manner. In Table 6.1, the typical boundary conditions for each context are defined, with explanation for the reasons for their selection. To reach this representative case, the following points are considered:

- Building typology
- Number of floors
- New or renovated building
- Construction typology
- Structural loads
- External wall structural typology
- Typical erection method

	THE NETHERLANDS	EGYPT																
BUILDING TYPOLOGY	Residential (Row houses)	Residential (Apartments)																
Biggest segment	<p>In the Netherlands, residential buildings account for almost 70% of the total building stock (Marini et al., 2014).</p> <p>Both Row-housing and apartment buildings are popular housing typologies in the Netherlands. However, row house remains as the most common house typology and is a cultural icon for many Dutch residents. The following chart shows the percentages of building types in the Netherlands (Carrascal, Fausti, Beentjes, Clarke, &amp; Steel, 2014).</p> <table border="1"> <caption>Building Typologies in the Netherlands</caption> <thead> <tr> <th>Typology</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Row houses</td> <td>53%</td> </tr> <tr> <td>Apartments</td> <td>33%</td> </tr> <tr> <td>Detached houses</td> <td>14%</td> </tr> </tbody> </table>	Typology	Percentage	Row houses	53%	Apartments	33%	Detached houses	14%	<p>Egyptian building stock comprises about 12 million buildings. About 7.2 million are residential buildings, i.e. 60% of the building stock. These are mostly apartment blocks (Hanna, 2013). The following chart shows the percentages of the building typologies in Egypt (Gamal, 2014).</p> <p>There are about 19.8 million residential apartments, and are expected to reach about 23 million in 2030 (Hanna, 2013).</p> <table border="1"> <caption>Building Typologies in Egypt</caption> <thead> <tr> <th>Typology</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Apartments</td> <td>88%</td> </tr> <tr> <td>Rural houses or villas</td> <td>8%</td> </tr> <tr> <td>Shelters</td> <td>4%</td> </tr> </tbody> </table>	Typology	Percentage	Apartments	88%	Rural houses or villas	8%	Shelters	4%
Typology	Percentage																	
Row houses	53%																	
Apartments	33%																	
Detached houses	14%																	
Typology	Percentage																	
Apartments	88%																	
Rural houses or villas	8%																	
Shelters	4%																	

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	THE NETHERLANDS	EGYPT																																																
BUILDING TYPOLOGY	Residential (Row houses)	Residential (Apartments)																																																
High energy consumption	<p>In 2010, the total consumption of energy in the Netherlands was about 53 million tonnes of oil equivalent. The building sector was responsible for 21 % of the total primary energy consumption. The following chart shows the energy distribution among the different sectors in the Netherlands (Eurostat, 2014).</p> <table border="1"> <caption>Energy Distribution in the Netherlands (2010)</caption> <thead> <tr> <th>Sector</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Building sector</td> <td>21%</td> </tr> <tr> <td>Industry</td> <td>27%</td> </tr> <tr> <td>Transport</td> <td>28%</td> </tr> <tr> <td>Agriculture</td> <td>6%</td> </tr> <tr> <td>Services</td> <td>18%</td> </tr> </tbody> </table> <p>With a more focus on the Dutch residential sector; heating is the major contributor to the energy consumption with about 60% of the total energy consumption. The following chart shows the energy distribution in Dutch household (Laustsen, 2008).</p> <table border="1"> <caption>Energy Distribution in Dutch Household</caption> <thead> <tr> <th>Category</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Heating</td> <td>60%</td> </tr> <tr> <td>Heating water</td> <td>21%</td> </tr> <tr> <td>Appliances</td> <td>11%</td> </tr> <tr> <td>Light</td> <td>2%</td> </tr> <tr> <td>Cooking</td> <td>1%</td> </tr> </tbody> </table>	Sector	Percentage	Building sector	21%	Industry	27%	Transport	28%	Agriculture	6%	Services	18%	Category	Percentage	Heating	60%	Heating water	21%	Appliances	11%	Light	2%	Cooking	1%	<p>In 2009, the total consumption of energy in Egypt was about 72 million tonnes of oil equivalent. The building sector was responsible for 32% of the total primary energy consumption as shown in the following chart (Gamal, 2014).</p> <table border="1"> <caption>Energy Distribution in Egypt (2009)</caption> <thead> <tr> <th>Sector</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Building sector</td> <td>32%</td> </tr> <tr> <td>Industry</td> <td>35%</td> </tr> <tr> <td>Transport</td> <td>28%</td> </tr> <tr> <td>Agriculture</td> <td>5%</td> </tr> </tbody> </table> <p>With more focus on the Egyptian residential sector; cooling is the major contributor to energy consumption with about 65% of the total energy consumption. The intensity of solar radiation and the clarity of the sky are the main reasons for the extreme levels of encountered heat resulting in the high cooling loads (Sheta, Sharples, &amp; Fotios, 2012). The following chart shows the energy distribution in Egyptian household (Attia et al., 2012; Gamal, 2014).</p> <table border="1"> <caption>Energy Distribution in Egyptian Household</caption> <thead> <tr> <th>Category</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Cooling</td> <td>65%</td> </tr> <tr> <td>Heating</td> <td>9%</td> </tr> <tr> <td>DHW</td> <td>6%</td> </tr> <tr> <td>Plug loads</td> <td>12%</td> </tr> <tr> <td>Lighting</td> <td>5%</td> </tr> <tr> <td>Cooking</td> <td>3%</td> </tr> </tbody> </table>	Sector	Percentage	Building sector	32%	Industry	35%	Transport	28%	Agriculture	5%	Category	Percentage	Cooling	65%	Heating	9%	DHW	6%	Plug loads	12%	Lighting	5%	Cooking	3%
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Lighting	5%																																																	
Cooking	3%																																																	

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	THE NETHERLANDS	EGYPT
NEW OR RENOVATED	<b>New</b>	
	This research is more applicable to the newly constructed buildings. This is because the research is investigating the massive layer part of the external wall, which does not usually change in the renovated construction (due to its long lifespan). Thus the focus in this research is on newly constructed buildings.	
NUMBER OF FLOORS	<b>3 Floors</b>	<b>4 Floors</b>
	In the Netherlands, row houses are usually low rise buildings with an average of three storeys.	In Egypt, usually the number of floors for the newly constructed apartment buildings varies according the street width. The general rule is that the maximum building height is 1.5 times the street width. With an average of street width in residential areas of 7.7 m, this normally results in a 4-floor apartment buildings (Gamal, 2014)
CONSTRUCTION TYPOLOGY	<b>Concrete Construction</b>	
	In the Netherlands, the structural systems for buildings consist mainly of reinforced concrete frames and walls, load-bearing masonry, or a combination of both. Timber structures are not commonly used, while steel is used for special building typologies such as industrial buildings, railway stations, and high-rise office buildings (Santos, 2006).	In Egypt, the reinforced concrete skeleton structures are almost the only construction typology used in the residential sector, particularly in the form of beam and column skeleton. Wood is not commercially available (it is mainly used in furniture construction), while steel is expensive and is only used in office and high-rise buildings. Moreover, Egypt is expected to be one of the top five global exporters of cement in the next few years (Darwish, 2007).
EXTERNAL WALL STRUCTURAL TYPOLOGY	<b>Load-bearing</b>	<b>Non-load-bearing</b>
	In the Netherlands, both load bearing and non-load bearing external walls can be found in new houses depending on the design. However, load bearing external walls is selected in this research as the typical case.	In Egypt, walls and external walls of new houses are always non-load bearing elements. They are merely used as infill elements due to the dependency on the column and beam system.
MASSIVE WALL ERECTION METHOD	<b>Unreinforced Masonry</b>	
	Walls can be classified according their erection methods as either precast (masonry blocks) or onsite casting. As already mentioned in Chapter 2, the traditional massive external walls in both the Netherlands and Egypt are usually unreinforced masonry construction. Based on Santos (Santos, 2006) and the author's experience as an architect in Egypt, manual lifting of blocks stays the most common method for erecting the masonry traditional walls in both contexts. For this reason, only unreinforced masonry walls are considered in the comparison between external wall designs.	

TABLE 6.1 The typical boundary conditions for the Netherlands and Egypt

## § 6.3.2 Determining Building Rules and Regulations for Each Context

Most countries have their own building rules and regulations. These rules and regulations are mostly provided and developed by governmental building institutes. In order to build external walls that are comparable with the current traditional ones, it is important to comply with the building codes and regulations for each context. The rules and regulations that have to be followed when designing a building or an external wall are extensive. However, Table 6.2 summarizes the important relevant rules and regulations, which directly affect the design and construction of external walls, and particularly its solid masonry part.

	RULES & REGULATIONS	THE NETHERLANDS	EGYPT
Safety	<b>Fire resistance rating</b> Duration for which a passive fire protection system can withstand a standard fire resistance test without collapsing/failure.	<b>60 mins</b> (with a temperature of 900°C) <i>(NEN 6068/C1 nl)</i>	<b>60 mins</b> (with a temperature of 900°C) <i>(Egyptian Code for Fire Fighting: Part 1: Edition 4: 2007)</i>
	<b>Flame-Spread rating</b> It is used to describe the surface burning characteristics of building materials Flame-Spread Classification (Flame-Spread Rating or Index) Class I (or A) 0 - 25 Class II (or B) 26 - 75 Class III (or C) 76 - 200	<b>Non Combustible</b> <b>Class (B) 26 - 75</b> <i>(NEN-EN 13501-1)</i>	<b>Non Combustible</b> <b>Class (B) 26 - 75</b> <i>(Egyptian Code for Fire Fighting: Part 1: Edition 4: 2007)</i>

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	RULES & REGULATIONS	THE NETHERLANDS	EGYPT
Health	<b>Sound transmission loss</b> It is the effectiveness of a wall, floor, door or other barrier in restricting the sound passage. The unit of measurement of sound transmission loss is the decibel (dB) (at frequency between 100 Hz and 3150 Hz).	<b>20(dB)</b> (NPR 5079:1999 nl)	(Does not exist)
	<b>Protection against external moisture</b>	External surfaces are required to be water resistant. (NEN 2778:2014 nl)	(Does not exist)
	<b>Protection against condensation problems</b> In practice, the “vapour diffusion thickness”, also called “Sd-value” [m], is used. It indicates the thickness of a static layer of air that has the same water vapour resistance as the building material of thickness t [m] If $S_d \leq 0.5\text{m}$ then the wall is a diffusion-open requiring a vapour barrier If $S_d > 0.5\text{m}$ then wall is diffusion-blocking and does not require vapour barrier If $S_d \geq 1500\text{m}$ then the wall is a diffusion-proof strand does not require vapour barrier	Appropriate water vapour control strategy	(Does not exist)
Energy	<b>Thermal insulation</b> The process of insulating against transmission of heat	<b>R = 4.5m<sup>2</sup>k/w</b> (the capacity of wall to resist heat flow) (NEN 7120 + C2: 2012 / C5: 2014 nl)	(Does not exist)
Masonry construction	Minimum material compressive strength	Dependent on the wall design of the masonry wall (mainly wall thickness and loads applied )  <i>EN 1996-1-1 (2005) (English): Eurocode 6: Design of masonry structures - Part 1-1</i>	<b>Fired Clay Bricks</b> - Solid 3.5 MPa - Perforated 2 MPa <b>Concrete Block</b> - Solid 2 MPa - Perforated 1.6 MPa <b>Aerated Concrete Blocks</b> 2.5 MPa <b>Sand-lime Bricks</b> 4 N/mm <sup>2</sup> (EPC 204 – 2005)
	Minimum external wall thickness	Dependent on the structural, building physics, and fire and sound calculations	<b>20 cm</b> (EPC 204 – 2005)

TABLE 6.2 Summary of the important relevant rules and regulations affect the design and construction of solid masonry external walls

The data in the above table has been gathered from two main sources:

- 1 [www.bouwbesluitonline.nl](http://www.bouwbesluitonline.nl), which is an online source for the Dutch building codes.
- 2 Housing and Building National Research Centre (HBNRC), which is a governmental research institute concerned with building and construction in Egypt. HBNRC is fully responsible for issuing codes and specifications related to the construction industry in Egypt.

## Discussion

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### The Netherlands

The requirements posed on external wall have increased significantly through the past decades. The oil crisis initiated considerations for energy consumptions in buildings, and the first energy regulations for buildings were issued. Moreover, an increasing number of codes dealing with environmental pollution, product and user safety came into being. The building industry was obliged to set and enforce new standards, which mainly focused on building physical aspects (Klein, 2013). These requirements and standards are consequently being developed.

### Egypt

In Egypt, the situation is different than that in the Netherlands. First, many aspects for different external wall performances are not mentioned in the building code as indicated in the previous table. Moreover, the inability of the government to control the building construction is clear. Despite the presence of some laws and regulations governing housing construction, the absence of government enforcement of these laws and standards led to the spread of illegal constructions. This explains the wide spread of external external walls having a 12-cm thick brick construction, which is almost half the minimum required thickness (Figure 6.1).



**FIGURE 6.1** A 12-cm thick external walls found in many current constructions

### *About the lack of energy regulations in Egypt*

In 2000, there was a motivation to issue the Egyptian Energy Standards for Residential Buildings. They were presented by the Housing and Building National Research Centre in 2006. They aimed to achieve a better performance and thermal comfort for the occupiers. However, these standards have not, until now, entered the framework of implementation.

A possible explanation for this might be that there is no valid knowledge of the appropriate technologies and building materials in construction standards, which can be used to achieve the goal of sustainable buildings in Egypt. Furthermore, energy standards should be simplified and presented as sustainable design guidelines for each community, so that they can be followed by architects, designers and engineers. This has not been done (F. Liu, Meyer, & Hogan, 2010; Sheta et al., 2012) .

### *About the lack of sound regulations*

In 2010, the government stated that the Egyptian Code for designing and implementing works of acoustics and noise control in buildings was being prepared by the Housing and Building National Research Centre. It aimed to regulate design of buildings in Egypt and lay the bases for the conditions and means controlling noise of interior and surrounding buildings (MSEA, 2015). However, so far until now, it was not put into the framework of implementation.

### *About the lack of external moisture and condensation problems in the regulations in Egypt*

The Egyptian building codes and regulations do not mention the requirements for protection against external moisture for external walls. This may be due to the dryness and few rainwater received in Egypt. Egypt receives fewer than 8 mm of precipitation annually in most areas compared to an average of 765 mm in the Netherlands (World Weather, 2015a, 2015b).

As for the unawareness of the condensation problems in regulations, this can be due to the relative low humidity level in the Egyptian climate. Egypt has an average relative humidity of 50% compared to 85% in the Netherlands (World Weather, 2015a, 2015b). Moreover, in Egypt windows are always used for ventilation in both summer and winter. This reduces the risk of having different water vapour content between the inside and the outside, which mainly leads to vapour transmission through walls.

The previous discussion shows how the building regulations affecting the external wall differ in Egypt and the Netherlands. One reason behind this difference is the different climate they possess. Another reason is the lack of awareness of the importance of such

regulations in Egypt, by both the government and the people. However, gaining this awareness is important to overcome Egypt's energy problem and enhance the building quality in Egypt in general.

### § 6.3.3 Comparable Insulating Massive External Wall Designs for Each Context

As presented in Chapter 4, the insulating technologies include:

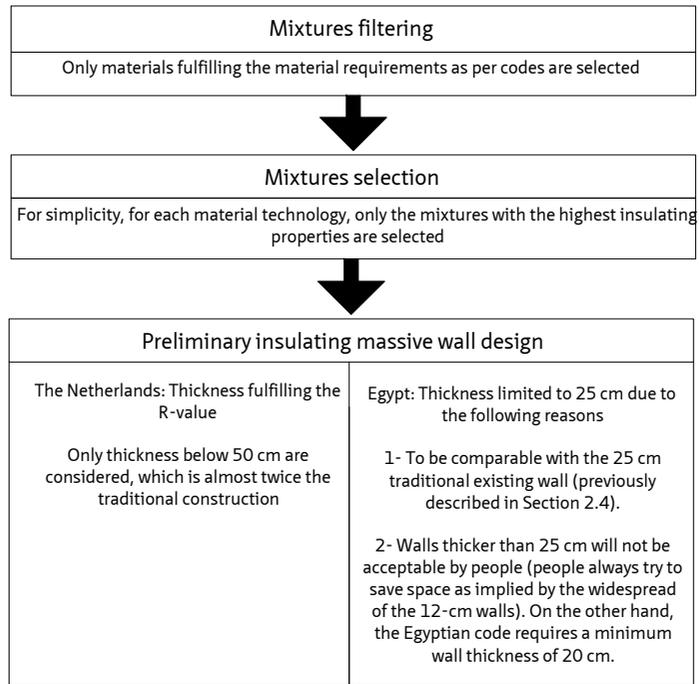
- Expanded Clay Concrete mixture
- Expanded Glass Concrete mixture
- Aerogel Concrete mixture
- Aerated Concrete products
- Perforated Clay Bricks products

Each technology included the mixtures presented in Table 6.3.

	EXPANDED CLAY CONCRETE	EXPANDED GLASS CONCRETE MIXTURE	AEROGEL CON- CRETE MIXTURE	AERATED CONCRETE PRODUCTS	PERFORATED CLAY BRICKS PROD- UCTS	
					Unfilled with insulation	Filled with insu- lation
	Gatmann's House mixture	30% Expanded Glass - 70% Concrete	60% Aerogel - 40% Concrete	AAC (C5/800)	Porotherm 30	Poroton - T8 -MW
(more insulating) <-----	Infra Lightweight Concrete	53% Expanded Glass - 47% Concrete	UHPC + Aerogel	AAC (C5/650)	Poptherm PL-I	
		70% Expanded Glass - 30% Concrete	70% Aerogel - 10% Air - 20% Concrete ( <i>insulation unknown</i> )	AAC (C2/400)		
		70% Expanded Glass - 10% Air - 20% Concrete	75% Aerogel - 10% Air - 15% Cement ( <i>insulation unknown</i> )	AAC (C2/300)		
		70% Expanded Glass - 20% Air - 10% Concrete	70% Aerogel - 24% Air - 6% Cement			
		70% Expanded Glass - 24% Air - 6% Cement				

TABLE 6.3 The selected technologies and their mixtures

In order to reach comparable external wall designs in respect to the typical building rules and regulations for each context, the following design steps are considered:



From the mixture properties presented in Chapter 4, the rules and regulations presented in Section 6.3.2, and selecting the highest insulating mixtures; the following mixtures are preliminarily selected for each context as shown in Table 6.4 and 6.5.

## The Netherlands

	EXPANDED GLASS CONCRETE	AEROGEL CONCRETE	AUTOCLAVED AERATED CONCRETE	PERFROATED CLAY BRICKS	
				Unfilled with insulation	Filled with insulation
Mixture	70% Expanded Glass - 24% Air - 6% Cement	70% Aerogel - 24% Air - 6% Cement	AAC (C2/300)	Poptherm PL-I	Poroton - T8 - MW
Properties	Density: 468 kg/m <sup>3</sup> Compressive strength: 2.5 N/mm <sup>2</sup> Thermal conductivity: 0.09 W/m.K	Density: 372 kg/m <sup>3</sup> Compressive strength: 0.4 N/mm <sup>2</sup> Thermal conductivity: 0.03 W/m.K	Density: 300 kg/m <sup>3</sup> Compressive strength: 1.6 N/mm <sup>2</sup> Thermal conductivity: 0.07 W/m.K	Density: 626 kg/m <sup>3</sup> Compressive strength: 1.8 N/mm <sup>2</sup> Thermal conductivity: 0.12 W/m.K	Density: 652 kg/m <sup>3</sup> Compressive strength: 1.8 N/mm <sup>2</sup> Thermal conductivity: 0.08 W/m.K

TABLE 6.4 The selected mixtures for the Dutch case

## Egypt

	EXPANDED CLAY CONCRETE	EXPANDED GLASS CONCRETE	AEROGEL CONCRETE	AUTOCLAVED AERATED CONCRETE	PERFROATED CLAY BRICKS	
					Unfilled with insulation	Filled with insulation
Mixture	Infra Light-weight Concrete	70% Expanded Glass - 24% Air - 6% Cement	UHPC + Aerogel	AAC (C2/400)	Porotherm 30	Poroton - T8 - MW
Properties	Density: 760 kg/m <sup>3</sup> Compressive strength: 7.4 N/mm <sup>2</sup> Thermal conductivity: 0.18 W/m.K	Density: 468 kg/m <sup>3</sup> Compressive strength: 2.5 N/mm <sup>2</sup> Thermal conductivity: 0.09 W/m.K	Density: 450 kg/m <sup>3</sup> Compressive strength: 3 N/mm <sup>2</sup> Thermal conductivity: 0.08 W/m.K	Density: 400 kg/m <sup>3</sup> Compressive strength: 3.4 N/mm <sup>2</sup> Thermal conductivity: 0.1 W/m.K	Density: 800 kg/m <sup>3</sup> Compressive strength: 10 N/mm <sup>2</sup> Thermal conductivity: 0.18 W/m.K	Density: 652 kg/m <sup>3</sup> Compressive strength: 1.8 N/mm <sup>2</sup> Thermal conductivity: 0.08 W/m.K

TABLE 6.5 The selected mixtures for the Egyptian case

By applying the selected mixtures to the external walls as per the previously mentioned thicknesses, the insulating wall designs are generated. Only in the case of gradient wall construction, unlimited wall compositions can be achieved. However, for the sake of simplicity, the gradient external wall will be limited to the Aerogel Concrete technology, which possesses the highest insulating mixtures. It will be limited to three materials as shown in Figure 6.2.

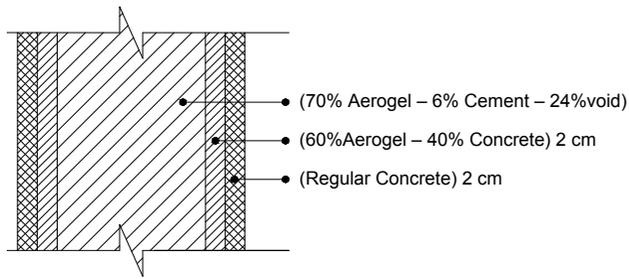


FIGURE 6.2 Aerogel gradient wall

The following external wall designs are generated according to the selected mixtures and thicknesses (Figure 6.3 and 6.4)

### The Netherlands

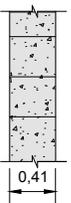
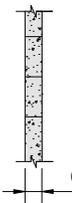
EXPAND GLASS CONCRETE	AEROGEL CONCRETE	AERATED CONCRETE	PERFORATED CLAY BRICKS		GRADIENT CONCRETE
70%E.G.- 6%Cement - 24%Void	70%A.- 6%Cement - 24%Void	AAC C2(300)	PL-I (unfilled)	Poroton-T8-MW (filled)	Gradient Concrete
					
R-value = 4.5 m <sup>2</sup> k/w					

FIGURE 6.3 Dutch external wall designs according to the selected mixtures

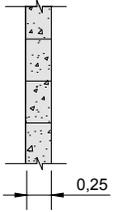
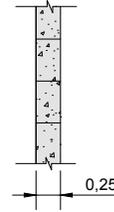
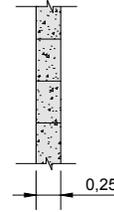
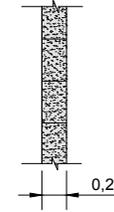
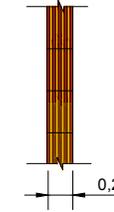
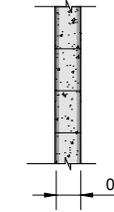
EXPAND CLAY CONCRETE	EXPAND GLASS CONCRETE	AEROGEL CONCRETE	AERATED CONCRETE	PERFORATED CLAY BRICKS		GRADIENT CONCRETE
Infra Lightweight Concrete	70%E.G.- 6%Cement - 24%Void	UHPC + Aerogel	AAC C2(400)	Porotherm 30 (unfilled)	Poroton-T8-MW (filled)	Gradient Concrete
						

FIGURE 6.4 Egyptian external wall designs according to the selected mixtures

In Figure 6.5 and 6.6 the structural loads and fulfilments of the national codes are checked for the Netherlands and Egypt. The structural calculations used in checking are included in Appendix 3. For the newly developed materials with unknown performances, a reference material with a close composition is used as a guidance.



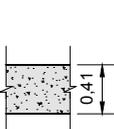
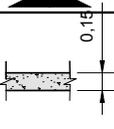
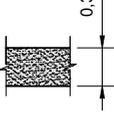
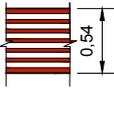
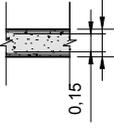
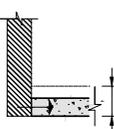
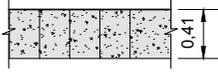
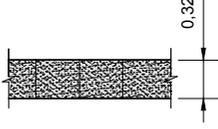
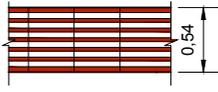
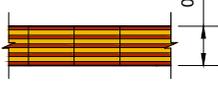
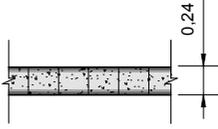
	EXPAND GLASS CONCRETE	AEROGEL CONCRETE	AERATED CONCRETE	PERFORATED CLAY BRICKS	GRADIENT CONCRETE
Insulating Design (R-value = 4.5 m <sup>2</sup> kw)	70%E.G.- 6%Cement - 24%Void 	70%A - 6%Cement - 24%Void 	AAC C2(300) 	PL-I (unfilled) 	Cone material: 70%Aerogel - 6%Cement - 24%Void 
Vertical loads	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)
Horizontal loads	(Checked in Appendix 4)	Require thickness = 25cm (Appendix 4) However, since the wall structure became close to the Gradient Concrete case, for the sake of variation a different Aerogel mixture is considered (UHPC+ Aerogel) 	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)
Water vapor control	In order for the wall to be a vapor blocking structure, Sd should be greater than 0.5 ( Sd= $\mu \cdot t$ , where $\mu$ is vapor permeability coefficient and t is the wall thickness) $\mu$ of the material is unknown (reference material) Since the two materials have a close composition, it is most likely that the $\mu$ of both material are close, and therefore the wall structure is a vapor blocking <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 5px auto;"><b>Reference material</b> Reapor product Is an acoustic panel. 80% Expanded Glass aggregate + 20%Air Density, 270 kg/m3 <math>\mu = 4</math> (Reapor, 2015)</div>	$\mu$ (vapor permeability coefficient) is unknown In order for the wall to be a vapor blocking structure where Sd = $\mu \cdot t > 0.5$ $\mu$ needs to be > 1.3	Sd = $\mu \cdot t = 3 \times 0.32 = 0.96 (> 0.5)$ Therefore it is a vapor blocking construction	Sd = $\mu \cdot t = 5 \times 0.54 = 2.7 (> 0.5)$ Therefore it is a vapor blocking construction	For the outer ordinary concrete layer Sd = $\mu \cdot t = 90 \times 0.04 = 3.6 (> 0.5)$ Therefore it is a vapor blocking construction
Fire (Flame-spread rating)	Flame-spread rating of the material is unknown. However, all its ingredients ( expanded glass & cement) are classified as Non-combustible A1. (Liaver, 2015)	Flame-spread rating of the material is unknown. However, all the mixture ingredients (Aerogel, cement and sand) are classified as Non-combustible A1 (Lumira, 2015).	Non-combustible A1 (Xelia, 2015)	Non-combustible A1 (Wienerberger, 2015)	Similar to the UHPC+Aerogel

FIGURE 6.5 The structural loads and national codes check for the Duch external walls

Fire (Holding strength in fire)	Sound Insulation	Final wall design
<p>Since all its ingredients are non-combustible and it has relatively thick wall, most likely will be provide more than 60 mins fire rating</p>	<p>Sound transmission loss of the construction is unknown. (reference material)</p> <p>Since: - Both have almost the same materials - Reapor is originally used as a sound insulation panel - The wall is almost 10 times thicker than Reapor. Therefore, the wall most likely provide an high sound transmission loss</p>	 <p><b>EXPAND GLASS CONCRETE</b></p>
<p>Reference material Aerogel Concrete (50mm) 70% Aerogel + 20% Concrete + 10% Air 2 hrs fire rating (Raiké, 2008)</p> <p>Reference material Aerogel Concrete (50mm) 75% Aerogel + 15% Cement + 10% Air 41dB (Raiké, 2008)</p> <p>Reference material Reapor product</p>	<p>The wall fire rating is unknown (reference material) Since the two materials have a close composition, and the UHPC+Aerogel is of thicker construction, it is most likely than UHPC+Aerogel will have more than 2hr fire rating</p> <p>Sound transmission loss of the construction is unknown (reference material) Since the two materials have a close composition, and the UHPC+Aerogel is of thicker construction, it is most likely than UHPC+Aerogel will have sound transmission loss &gt; 20dB</p>	 <p><b>AEROGEL CONCRETE</b></p>
<p>10 cm YTONG could stand against fire for at least 4 hours. (Xella, 2015)</p>	<p>30 cm YTONG provide a sound transmission loss of 41dB (Xella, 2015)</p>	 <p><b>AERATED CONCRETE</b></p>
<p>The 36.5 cm thick wall has 90-180 mins fire rating (Wienerberger, 2015)</p>	<p>The 52 cm thick wall provide a sound transmission loss of 48dB (Wienerberger, 2015)</p>	 <p><b>PERFORATED CLAY BRICK (unfilled)</b></p>
<p>The 36.5 cm thick wall has 90-180 mins fire rating (Wienerberger, 2015)</p>	<p>The 52 cm thick wall provide a sound transmission loss of 48dB (Wienerberger, 2015). The 36cm wall will likely provide more than required 20dB.</p>	 <p><b>PERFORATED CLAY BRICK (filled)</b></p>
<p>Similar to the UHPC+Aerogel</p>	<p>Similar to the UHPC+Aerogel</p>	 <p><b>GRADIENT CONCRETE</b></p>

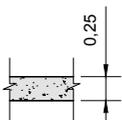
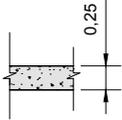
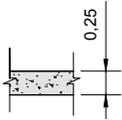
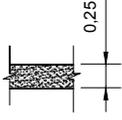
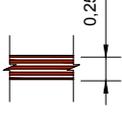
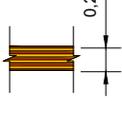
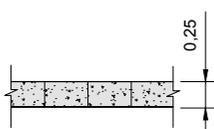
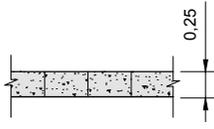
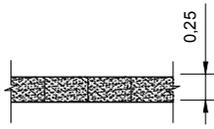
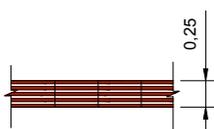
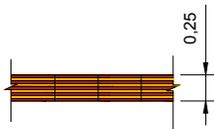
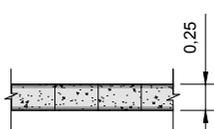
	EXPAND CLAY CONCRETE	EXPAND GLASS CONCRETE	AEROGEL CONCRETE	AERATED CONCRETE	PERFORATED CLAY BRICKS	GRADIENT
	Infra Lightweight Concrete	70%E.G.- 6%Cement - 24%void	UHPC + Aerogel	AAC C2(400)	Porotherm 30 (unfilled) Poroton-T8-MW (filled)	Gradient Concrete
Insulating Design						
Vertical loads (calculations in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)
Horizontal loads (calculations in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)	(Checked in Appendix 4)
Water vapor Control	Not mentioned in the Egyptian code or applied in practice , and that is because the weather in Egypt is dry, with low humidity levels					
Fire (Flame-spread rating)	Flame-spread rating of the material is unknown. However, all its ingredients ( expanded clay, cement and sand) are classified as Non-combustible A1. (Llaver, 2015)	Flame-spread rating of the material is unknown. However, all the mixture ingredients ( expanded glass & cement ) are classified as Non-combustible A1. (Llaver, 2015)	Flame-spread rating of the material is unknown. However, all the mixture ingredients ( aerogel, cement and sand) are classified as Non-combustible A1 (Lumira, 2015).	Non-combustible A1 (Xella, 2015)	Non-combustible A1 (Wienerberger, 2015)	Similar to the UHPC+Aerogel

FIGURE 6.6 The structural loads and national codes check for the Egyptian external walls

<p>Fire (Holding strength in fire)</p>	<p>Since all its ingredients are non-combustible and it has relatively thick wall, most likely will be provide more than 60 mins fire rating</p>	<p>Since all its ingredients are non-combustible and it has relatively thick wall, most likely will be provide more than 60 mins fire rating</p>	<p>The wall fire rating is unknown (reference material)</p> <p>Since the two materials have a close composition, and the UHPC+Aerogel is of thicker construction, it is most likely than UHPC+Aerogel will have more than 2hr fire rating</p>	<p>10 cm YTONG could stand against fire for at least 4 hours. (Xella, 2015)</p> <p>Reference material Aerogel Concrete (50mm) 70% Aerogel + 20%Concrete +10%Air 2 hrs fire rating (Ratke, 2008)</p>	<p>The 25 cm thick wall has 90 mins fire rating. (Wienerberger, 2015)</p>	<p>The 36.5 cm thick wall has 90-180 mins fire rating. The 25cm wall will likely provide more than 60 mins fire rating. (Wienerberger, 2015)</p>	<p>Similar to the UHPC+Aerogel</p>
<p>Sound insulation requirements are not mentioned in the Egyptian code, However, the wall sound performance is as follows</p>							
<p>Sound Insulation</p>	<p>Sound transmission loss of the construction is unknown. However by referring to the Reapor material (as in Expanded Glass Concrete of the Dutch case), the 25cm should then provide an acceptable sound insulation.</p>	<p>Sound transmission loss of the construction is unknown. However by referring to the Reapor product (as in Expanded Glass Concrete of the Dutch case), the 25cm should then provide an acceptable sound insulation.</p>	<p>Sound transmission loss of the construction is unknown. However by referring to the reference material (75% Aerogel + 15% Cement + 10% Air) as in the Aerogel Concrete Dutch case), the 25cm wall should then provide an acceptable sound insulation.</p>	<p>30 cm YTONG provide a sound transmission loss of 41dB (Xella, 2015). The 25cm wall should then provide an acceptable sound insulation.</p>	<p>The 37 cm thick wall provide a sound transmission loss of 48dB (Wienerberger, 2015). The 25cm wall should then provide an acceptable sound insulation.</p>	<p>The 52 cm thick wall provide a sound transmission loss of 48dB (Wienerberger, 2015). The 25cm wall will likely provide more than required 20dB.</p>	<p>Similar to the UHPC+Aerogel</p>
<p>Final wall design</p>	 <p>EXPAND CLAY CONCRETE</p>	 <p>EXPAND GLASS CONCRETE</p>	 <p>AEROGEL CONCRETE</p>	 <p>AERATED CONCRETE</p>	 <p>PERFORATED CLAY BRICK (unfilled)</p>	 <p>PERFORATED CLAY BRICK (filled)</p>	 <p>GRADIENT CONCRETE</p>

## § 6.4 Defining Assessment Criteria For comparison

Many literature studies have focused on defining the criteria for measuring the success of a construction. Their definitions about the criteria varied in the level of details that should be reached. However; time, cost, and quality were the three basic criteria discussed almost in every literature about this topic (Atkinson, 1999; Belassi & Tukel, 1996; Chan & Chan, 2004; Hatush & Skitmore, 1997; D. Walker, 1996; D. H. Walker, 1995). Atkinson (Atkinson, 1999) called these three criteria the “iron triangle” (Figure 6.7).

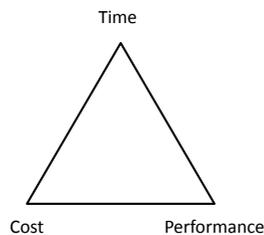


FIGURE 6.7 The Iron Triangle

The external wall, being a part of the building, can follow the same criteria. In the following paragraphs, these criteria will be briefly explained in the context of massive external walls construction.

### 1 Time in massive external walls

Time is a key factors influencing the project success. It refers to the duration for completing the project or a construction (Chan & Chan, 2004).

Time control is always one of the basic goals of all involved project parties. From the initial concept, throughout all project phases, the owner is interested in reducing the time for delivering the project. This is because for the owner, the earlier the project is completed, the earlier the building will start operating and the earlier the profit will start. In addition, delays in construction projects are usually expensive, as the cost of staff involved in the project is time dependent. Moreover, there is an on-going inflation in wages and material prices.

Time is important to external wall construction, as it is for the whole project. However for massive external walls, the labour productivity becomes mainly what determines the time. Unlike curtain walls, which require a sophisticated design and relatively short

construction time, massive external walls are labour intensive. They are relatively simple to design, however, they require long construction time when compared to curtain walls. Construction speed for massive external walls becomes mostly dependent on labour productivity and efficiency on construction site.

The labour productivity depends on the type of tasks performed. Each work task requires different levels of labour input per unit of output. The basic tasks for massive external walls construction include:

- 1 Bricklaying (in case of masonry construction)
- 2 Concreting (in case of onsite casted walls)
- 3 Insulation placing
- 4 Finishing layer

The labour productivity is expressed in terms of man-hour/m<sup>2</sup>

## 2 Cost in massive external walls

---

Cost is another important measure. Cost is defined as the degree in which the completion of a project is within the estimated budget (Chan & Chan, 2004). Historically, cost is considered the most important factor by clients. Most clients seek value for money, which usually means spending as little as possible (Hatush & Skitmore, 1997). The traditional “Design-Bid-Build” tendering system is actually based on this concept, which makes the cost the main criterion used for selecting the contractor.

‘Project cost’ should not only be determined by the tender sum. It should be determined by the overall cost from the early project design to its completion. This may include cost resulting from changes during the construction and cost resulting from legal actions such as issuing building permits (Chan & Chan, 2004).

Generally, the term ‘Cost’ is interpreted in varying ways according to different people. For example, a contractor views the cost as the material cost, labour cost, transport and equipment cost. On the other hand, a client views the cost as, in addition to the previous, the contractor’s profit margin, productivity, overheads, and the subsequent operation and maintenance costs.

A external wall can be sometimes an expensive building part. In case of advanced curtain wall for example, it can be even the most expensive element in the building (Klein, 2013). However, commonly used massive external walls are considered cheap when compared to curtain walls. This will be discussed in details in Chapter 7. In this study for the sake of simplicity, the term cost will refer to material and labour cost. This is expressed in terms of Price/m<sup>2</sup>.

### 3 Quality

---

As explained generally by Chan (Chan & Chan, 2004), quality can best be measured by the degree of conformance to all technical requirements and fulfilling the construction objectives. According to this definition, it becomes essential to retrieve again Klein's functional tree (also known as objective tree), which was presented in Chapter 3. Klein's objective tree, in addition to showing the external wall functions, covers the whole set of performances that can be used to assess external walls performing the same set of functions. Figure 6.8 shows the performances of assessment in Klein's objective tree. These performances include the following:

#### A Wall thickness

The thickness is an important factor that contributes to the success of the external wall construction. Thinner walls are favoured as they provide more internal space. *Wall thickness is expressed in terms of length unit (m).*

#### B Operational energy

Operational energy is the energy used in buildings during their operational phase. However, for solid external walls, controlling the thermo-physical characteristics of the building envelope (insulation and thermal storage) becomes the external wall's main contribution in the reduction of operational energy, and particularly the heating and cooling energy. *Operational energy is expressed in terms of energy units (kWh or MJ).*

#### C Embodied energy

Embodied energy is an accounting method, which aims to find the total sum of the energy necessary for an entire product life-cycle. This assesses the relevance and extent of energy into raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and/or decomposition (Hildebrand, 2012).

Massive materials have different ranges of embodied energy. Generally, modern building materials are known to have a major impact on the environment throughout their life cycle (and particularly in their production process). Concrete for example requires high energy in manufacturing its ingredients, particularly cement. To produce cement, limestone and other clay-like materials are heated in a kiln at 1400°C (Venta & Eng, 1998). Bricks require a firing process. When bricks are fired in a kiln or clamp, a ceramic bond should be formed. Depending on the type of clay, this happens at temperatures between 900 and 1,200°C (Elias-Ozkan, Summers, Surmeli, & Yannas, 2006). *Embodied energy is expressed in terms of energy units (kWh or MJ).*

#### D Carbon dioxide emission

Carbon dioxide is the main greenhouse gas produced through human activities. The primary human activity that produces Carbon dioxide is the combustion of fossil fuels such as coal, natural gas, and oil. Massive Materials are generally known for their high carbon dioxide emission during production (Elias-Ozkan, Summers, Surmeli, & Yannas, 2006). *Carbon dioxide emission is expressed in terms of KgCO<sub>2</sub>*

#### E Reuse and recycling

The issue of recyclability is becoming of high concern in the building industry in general, and consequently in external walls. Massive structures generally have good potentials for being recycled. In the Netherlands for example, the total demolition construction waster in 1996 was 12.5 million, in which concrete/brick fraction contributed to almost 90% of this quantity (Durmisevic, 2006). According to the Dutch building standard, 20% of recycled concrete can be used as aggregate for new concrete (not for high-quality concrete), while 80% can be downcycled and used as road base (Durmisevic, 2006).

Still there is no defined way to measure recyclability and reuse of building components. However, in this research two aspects will be used to determine the reuse/recyclability potential of the external wall:

- 1 The possibilities for being disassembled (according to the connection type)
- 2 The amount of energy used for the material to be recycled or reused. *This is expressed in terms of energy units (kWh or MJ)*

#### F Lifetime and durability

The issue of the material lifetime and durability is an important factor when considering different external wall typologies and materials. Massive construction is generally known for its high durability and low maintenance. However, periodic inspections and maintenance can extend the life of the structure even more. This can best be expressed by an estimation of the number of years to repair or replace the existing structure; i.e. *it is expressed in terms of years.*

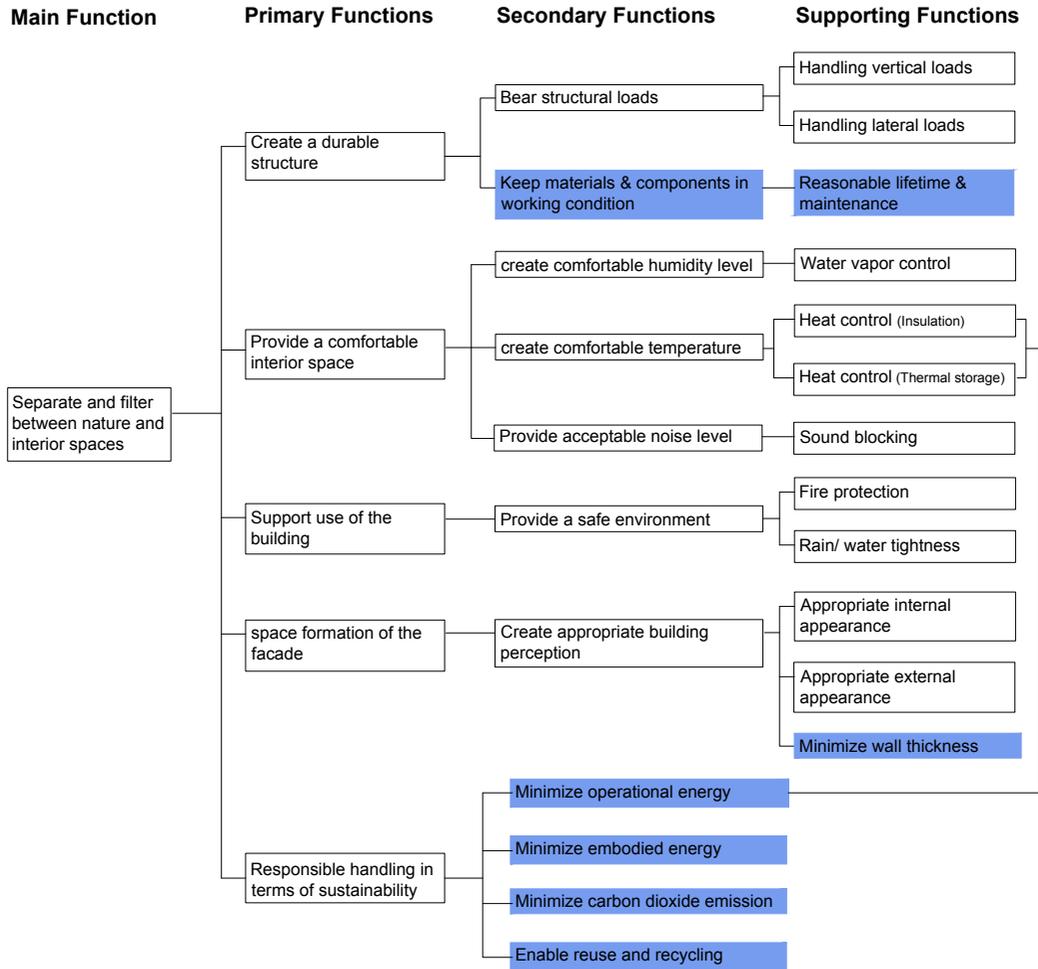


FIGURE 6.8 The performances of assessment highlighted in Klein's objective tree. These performances were not considered in the external wall design, however, they can be used to compare the different external walls.

## § 6.5 Summary

In this chapter, comparable insulating massive external walls were designed for the Netherlands and Egypt. First, the typical building in each context was defined. In Egypt, a 4-floor apartment building, of concrete construction and with non-load

bearing external walls, is typical. In the Netherlands, 3-floor row houses, of concrete construction with load-bearing external wall, are typical. This was followed by an overview regarding the regulations, which could affect the external wall design, in each context. Due to the differences between the two contexts concerning both the selected typical building and the governing rules and regulations, each context had different external wall designs.

Accordingly, five different additional insulating massive external walls were designed for the Netherlands. The external wall designs varied in thicknesses, mainly due to the requirements of minimum R-value in the Dutch regulations. As for Egypt, six different insulating massive external walls were designed. However, all Egyptian external walls had a constant thickness of 25 cm, which is similar to the traditional external wall since there are no thermal requirements in Egyptian codes.

Then the criteria for wall assessment were defined based on literature about measuring the success of construction projects together with Klein's objective tree. Construction time, cost, wall thickness, operational energy, embodied energy, carbon dioxide emission, recyclability and reuse potential are noted to be the most appropriate criteria to be used in assessing the different external wall designs.



# 7 Insulating Massive External Walls Assessment and Results

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## § 7.1 Introduction

---

In this chapter, the designed external walls for the two contexts will be assessed according to the criteria set in the previous chapters. This allows answering the second main question: *will massive technologies with additional function provide a more successful construction compared to the traditional massive external wall construction in the Netherlands and Egypt (with a closer view on insulating function)?*

In order to reach a scientific answer, this chapter is divided into four main sections. In the first section, the analysis of the Dutch external walls as related to each criterion is presented. This illustrates how different designs in the Netherlands function as related to specific performances. In the second section, the same is carried out for the Egyptian designed external walls. In the third section, a scoring system for each context is set. This allows comparing the different performances together, and deriving an answer to the question under consideration. In the same section, the results are presented. In the final section, the conclusions regarding the contents of this chapter are drawn.

## § 7.2 Massive External Wall Performances: the Netherlands

In this part the traditional layered external wall of the Netherlands is compared with the additional insulating designed masonry external walls. The additional insulating external walls include both new technologies such as Aerogel Concrete, and already existing technologies such as the Autoclaved Aerated Concrete external walls. Figure 7.1 shows the different external wall designs and the performance parameters used for comparison.

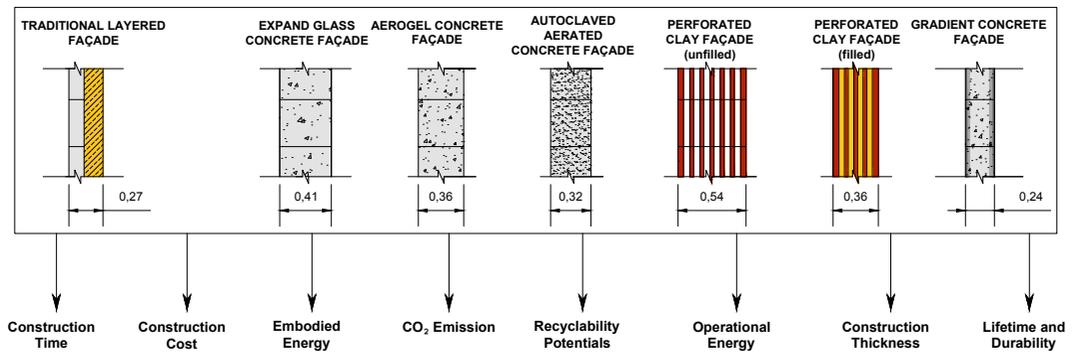


FIGURE 7.1 Different Dutch external wall designs and performance parameters used for comparison

## § 7.2.1 Construction Time

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As previously explained in Chapter 6, only unreinforced masonry technologies are considered in the comparisons. Accordingly the following calculations and assumptions are considered:

### *Methods for Calculating Bricklaying Productivity*

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As studied by Sander (Sanders & Thomas, 1991), the effort required, in terms of work hours, to place 1 square meter of masonry depends mainly on two aspects: the weight of the unit and its face area. Other aspects such as the mortar used, the amount of cutting due to design details, and the weather are also other factors affecting the productivity, but not as effective as the block weight and area (Sanders & Thomas, 1991). A separate study by Kolkoski, author of *Masonry Estimating*, provided a graph relating unit weight to production rate (Schierhorn, 1993). The analysis is based on a real project, which utilized common bricklaying tasks (Figure 7.2).

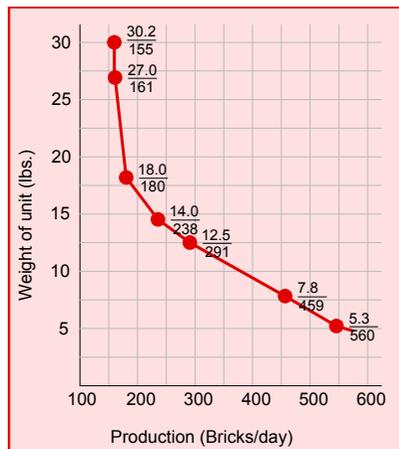


FIGURE 7.2 Graph relating unit weight to production rate (Bricks/day) based on a real project (Schierhorn, 1993)

### *Methods for Calculating Insulating Productivity*

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Not many researches have discussed insulation placing productivity. However, in a detailed research project under the title 'Evaluating an Exterior Insulation and Finish System for Deep Energy Retrofits', a detailed man-hour productivity for external wall insulation was conducted. The two-floor house incorporates a traditional insulation

system (Dentz & Podorson, 2014). The productivity rate is noted to be 0.55 hr/m<sup>2</sup>. This includes: setting up two-story scaffold around entire house, making the windows trims, and cutting the edges. This project is used as a reference project for the insulating productivity.

### Assumption

All blocks have a constant weight of 12 kg, which is the weight of the commonly used calcium silicate block having dimensions of 297 mm x 198 mm x 120 mm and a density of 1750 kg/m<sup>3</sup>.

Based on the previous calculating methods and assumption, Table 7.1 and Figure 7.3 present the construction time for the different designs.

Wall Thickness (m)	Density $\rho$ (kg/m <sup>3</sup> )	Block weight (Kg)	Block area (m <sup>2</sup> ) = Weight / ( $\rho \times T$ )	Blocks per day (from Figure 7.2)	Bricklaying (m <sup>2</sup> per day) = Block area x Blocks per day	Bricklaying (m <sup>2</sup> per hr) = (m <sup>2</sup> per day) / 8	Bricklaying (hr per m <sup>2</sup> ) = 1/(m <sup>2</sup> per hr)	Insulation (hr per m <sup>2</sup> )	Total (hr per m <sup>2</sup> )	
TRADITIONAL MASSIVE EXTERNAL WALL	0.12	1750	12	0.06	161	9.20	1.15	0.87	0.6	1.5
EXPANDED GLASS CONCRETE EXTERNAL WALL	0.41	468	12	0.06	161	10.08	1.26	0.79	-	0.8
AEROGEL CONCRETE EXTERNAL WALL	0.36	450	12	0.07	161	11.93	1.49	0.67	-	0.7
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	0.32	300	12	0.13	161	20.44	2.56	0.39	-	0.4
PERFORATED CLAY EXTERNAL WALL (UNFILLED)	0.54	626	12	0.04	161	5.72	0.71	1.40	-	1.4

>>>

PERFORATED CLAY EXTERNAL WALL (FILLED)	0.36	652	12	0.05	161	8.23	1.03	0.97	-	1.0
GRADIENT CONCRETE EXTERNAL WALL	0.24	792,5	12	0.06	161	10.16	1.27	0.79	-	0.8

TABLE 7.1 Construction time for different Dutch external wall designs

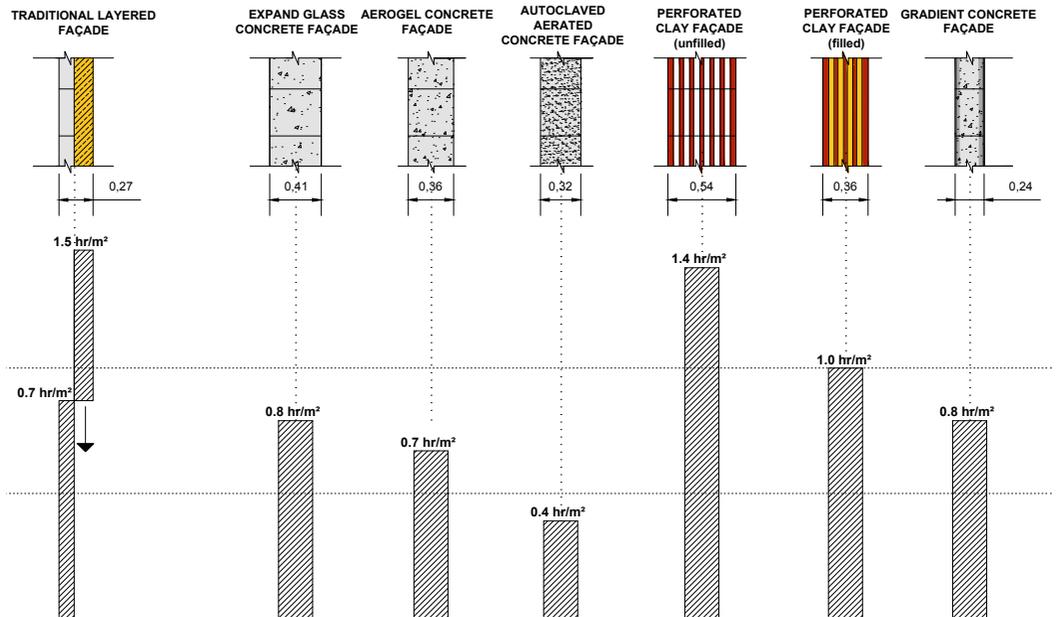


FIGURE 7.3 Construction time for different Dutch external wall designs

### Observations

- The graph presents the construction time for erecting external walls using different masonry blocks. All blocks utilized different materials, which accordingly required different thicknesses to fulfil the minimum R-value. With a constant block weight, the area for each block varied.

- Aerated Concrete has the highest productivity rate (requiring about 75% less time than the traditional external wall). On the other hand, both the traditional external wall and the Perforated Cay Brick external wall have the lowest productivity rate.
- Although in the traditional external wall construction, the bricklaying and insulation fixing occur sequentially; in large-scale construction, the construction time may be reduced. This is because for large-scale surface areas, there can be a degree of overlap between the bricklaying task and the insulation placing task, depending on the project task scheduling (as shown by the arrow in Figure 7.3).

## § 7.2.2 Construction Cost

---

The construction cost for the different designed masonry external walls is presented in both Table 7.4 and Figure 7.4. The following inputs and assumptions are considered:

### *Material cost*

---

Unlike common construction pricing, which is mentioned in the yearly official price indicators (known as Bouwkostenwijzer in the Netherlands), the uncommon construction pricing is not mentioned. Consequently, the prices used in this section are based on the average market prices from different suppliers. All prices noted are based on large quantities (for covering the construction of a project consisting of 4 row houses), including transportation (to Delft city). The average suppliers' prices are shown in Tables 7.2 and 7.3 (as per November, 2014).

### *Labour cost*

---

As per the Collective Labour Agreement in the Netherlands 2009-2014, the wage for skilled workers in a construction site job ranges from 9.76 to 15.74 Euros per hour (as at July, 2014), with an average of 12,75 Euros per hour (ABU, 2012).

MARKET BASIC MATERIAL PRICES	PRICE/KG (EUROS)
<b>Concrete Ingredients</b>	
Cement 25 kg	0.27
Ready Mixed Concrete	0.25
<b>Aggregates</b>	
Expanded Glass (Liaver)	0.49
Aerogel	35.00
<b>Other Materials</b>	
Aer Solid (air entraining - Sika)	9.00

TABLE 7.2 Average material prices by suppliers (as sold in kg)

MARKET ELEMENT PRICES	PRICE/M <sup>3</sup> (EUROS)
Calcium Silicate Blocks	304
Insulation (Rockwool)	44
Autoclaved Aerated Concrete (AAC C2/300)	272
Perforated Clay Brick (PL-I) (unfilled)	219
Perforated Clay Brick (Poroton-T8-MW) (filled)	373

TABLE 7.3 Average element prices by suppliers (as sold in m<sup>3</sup>)

	Mixture composition/m <sup>3</sup>	Wall thickness (m)	Materials/ products cost				
			Price of calcium silicate blocks/m <sup>2</sup> (Euros) =Thickness x Price of C.S per m <sup>3</sup>	Price of insulation/m <sup>2</sup> (Euros) =Thickness x price of ins. per m <sup>3</sup>	Price of cement/m <sup>2</sup> (Euros) =Thickness x Weight of cem. per m <sup>3</sup> x price of cem. per kg	Price of agg./m <sup>2</sup> (Euros) =Thickness x Weight of aggregates per m <sup>3</sup> x price of agg. per kg	
TRADITIONAL MASSIVE EXTERNAL WALL	0.12 m Calcium Silicate blocks - 0.15m Rock-wool ins.	0.12 + 0.15	36.53	6.62	-	-	
EXPANDED GLASS CONCRETE EXTERNAL WALL	Cement (120kg) - Exp.Glass Agg. (180Kg) - Water (120Kg) - Air entraining (Aer Solid) (48Kg) (Heinz et al., 2011)	0.41	-	-	13.28	36.27	
AEROGEL CONCRETE EXTERNAL WALL	Contains > 60% Aerogel (72kg)	0.36	-	-	-	> 907	
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	-	0.32	-	-	-	-	
PERFORATED CLAY EXTERNAL WALL (UN-FILLED)	-	0.54	-	-	-	-	
PERFORATED CLAY EXTERNAL WALL (FILLED)	-	0.36	-	-	-	-	
GRADIENT CONCRETE	70% Aerogels - 6% Cement - 24% Void	Cement (120Kg) - Aerogel Agg. (84Kg) - Water (60Kg) - Air ent. (48Kg) (Heinz et al., 2011)	0.15	-	-	4.86	441.00
	60% Aerogel - 40% Concrete	Cement (459kg) - Aerogel (72kg) (Gao et al., 2014)	0.04	-	-	4.96	100.80
	Concrete	Ready mixed concrete (1976 kg).	0.04	-	-	19,76	-
	Total			-	-	29.58	541.80

TABLE 7.4 Construction cost for different Dutch external wall designs

	Price of air entraining/ m <sup>2</sup> (Euros) =Thickness x Weight of air ent.per m <sup>3</sup> x price of air ent. per kg	Price of perforated bricks (or AAC)/m <sup>2</sup> =Thickness x price of perf. bricks (or AAC) per m <sup>3</sup>	Total materials/ products cost (Euros)	Labour cost			Total cost/m <sup>2</sup> (Euros)
				Const. time (hour) (as per section 7.2.1)	Average labour wage (Euros/ hour)	Total labour cost (Euros) = Const. time x average labour wage	
	-	-	43.15	1.5	12.75	18.7	62
	177.12	-	226.67	0.8	12.75	10.1	237
	-	-	>907	0.7	12.75	8.6	>916
	-	87.17	87.17	0.4	12.75	5.0	92
	-	118.46	118.46	1.4	12.75	17.8	136
	-	134.22	134.22	1.0	12.75	12.4	147
	64.80	-	510.66				
	-	-	105.76				
	-	-	19.76				
	64.80	-	636.18	0.8	12.75	10.0	646

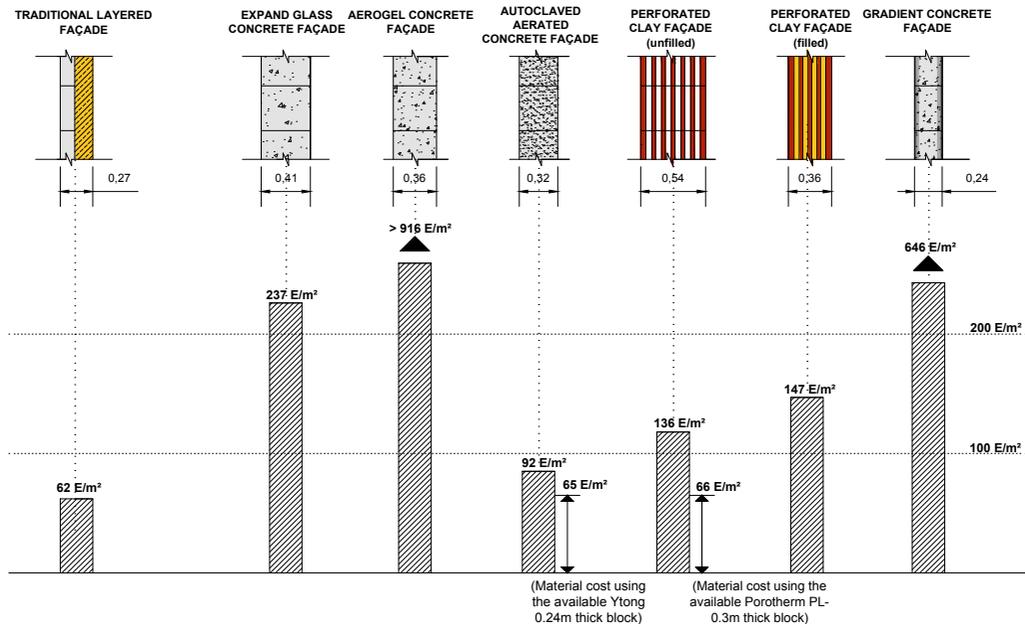


FIGURE 7.4 Construction cost for different Dutch external wall designs

### Observations

- Significant cost differences between the traditional external wall and the additional insulating technologies can be noticed. This is mainly because, in order for massive technologies with additional function to fulfil the minimum insulation R-Values, larger thicknesses and consequently more material quantities are required. The Aerated Concrete external wall has the lowest cost among other additional insulating wall technologies; whereas Aerogel Concrete external wall has the highest cost (due to the high price of Aerogel) reaching more than 15 times the price of the traditional external wall.
- Although the price of Expanded Glass is not expensive, the high price of the air entraining agent used, with relatively large quantities, is the main reason for its high cost. It contributes to almost 75% of the total cost.
- Construction cost in Table 7.4, particularly for new materials (Aerogel Concrete, Expanded Glass Concrete, Gradient Concrete) gives guiding figures rather than sharp figures. First, these prices can be subjected to increase if the technologies are provided as a readymade blocks by a supplier (as Autoclaved Aerated Concrete blocks or

Perforated Clay Bricks), as overheads will be added. Second the mass production will be another aspect affecting the prices, as it will most likely push the price down.

### § 7.2.3 Embodied Energy

The embodied energy for the different designed masonry external walls is presented in Table 7.7 and Figure 7.5. The following input values are considered:

- Tables 7.5 and 7.6 show the embodied energy coefficient used in the calculations. The values used for the embodied energy were taken from the Inventory of Carbon and Energy Database (ICE) Version 1.6a created by the University of Bath (Cradle to gate) (Hammond & Jones, 2008). However, the Embodied Energy of the following materials was obtained from other sources as they are uncommon and not found in the database:
  - Expanded Glass aggregate, from the report prepared by Denison (Denison & Halligan, 2010).
  - Aerogel embodied energy, from the research work carried out by Dowson (Dowson, Grogan, Birks, Harrison, & Craig, 2012). However, the results should be dealt with as conservative estimates. This is because the Aerogel was produced in a laboratory and not developed for mass manufacture or refined to reduce its environmental impact. In addition, the samples used were small and the obtained values were up scaled without considering major changes to the equipment used or manufacturing steps.

MATERIALS EMBODIED ENERGY	MJ/KG	SOURCE
<b>Concrete Ingredients</b>		
Cement	4.60	(Hammond & Jones, 2008)
Ready Mixed Concrete	0.95	(Hammond & Jones, 2008)
<b>Aggregates</b>		
Expanded Glass (Liaver)	27.00	(Denison & Halligan, 2010)
Aerogel	67.83	(Dowson et al., 2012)

TABLE 7.5 Embodied energy coefficient (EEC) of materials

ELEMENTS EMBODIED ENERGY	MJ/KG	SOURCE
Calcium Silicate Blocks	0.85	(Hammond & Jones, 2008)
Insulation (Rockwool)	16.8	(Hammond & Jones, 2008)
Autoclaved Aerated Concrete	3.5	(Hammond & Jones, 2008)
Perforated Clay Bricks	3	(Hammond & Jones, 2008)

TABLE 7.6 Embodied energy coefficient (EEC) of products

	Wall composition & density per m <sup>3</sup>	Wall Thickness (m)	E.E. of Calcium silicate/ m <sup>2</sup> (MJ/m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x E.E.C. of C.S	E.E. of insulation/ m <sup>2</sup> (MJ/m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x E.E.C. of ins.	
TRADITIONAL MASSIVE EXTERNAL WALL	Calcium silicate block (1750kg) - Rockwool insulation (45kg)	0.12 + 0.15	179	113	
EXPANDED GLASS CONCRETE EXTERNAL WALL	Cement (120kg) – Expanded Glass Aggregates (180Kg) - Water (120Kg) – Air entraining (Aer Solid) (48Kg) (Heinz et al., 2011)	0.41	-	-	
AEROGEL CONCRETE EXTERNAL WALL	mixture contains > 60% Aerogel (72kg)	0.36	-	-	
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	AAC (300kg)	0.32	-	-	
PERFORATED CLAY EXTERNAL WALL (UN-FILLED)	Perforated clay brick (626kg)	0.54	-	-	
PERFORATED CLAY EXTERNAL WALL (FILLED)	Perforated clay brick (626kg) + Rockwool insulation (26kg)	0.36	-	163	
GRADIENT CONCRETE EXTERNAL WALL	70% Aerogels - 6% Cement - 24% Void	Cement (120Kg) - Aerogel Aggregates (84Kg) - Water (60Kg) - Air entraining (Aer Solid) (48Kg) (Heinz et al., 2011)	0.15		
	60% Aerogel - 40% Concrete	Cement (459kg) - Aerogel (72kg) (Gao et al., 2014)	0.04		
	Concrete	Ready mixed concrete (1976 kg) (Heinz et al., 2011)	0.04		
	Total				

TABLE 7.7 Embodied energy for different Dutch external wall designs

	E.E. of cement/ m <sup>2</sup> (MJ/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x E.E.C. of cement	E.E. of aggregates/ m <sup>2</sup> (MJ/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x E.E.C. of aggregates	E.E. of air entraining/ m <sup>2</sup> (MJ/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x E.E.C. of air entraining	E.E of perforated bricks (or AAC)/ m <sup>2</sup> (MJ/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x E.E.C. of perfo- rated b.	Total E.E./m <sup>2</sup> (MJ/m <sup>2</sup> )
	-	-	-		292
	226	1993	Not available		>2216
	-	1758	-		> 1758
	-	-	-		336
	-	-	-	1014	1014
	-	-	-	676	839
	83	855	Not available		937
	84	195	-		280
	75	-	-		75
	242	1050			>1292

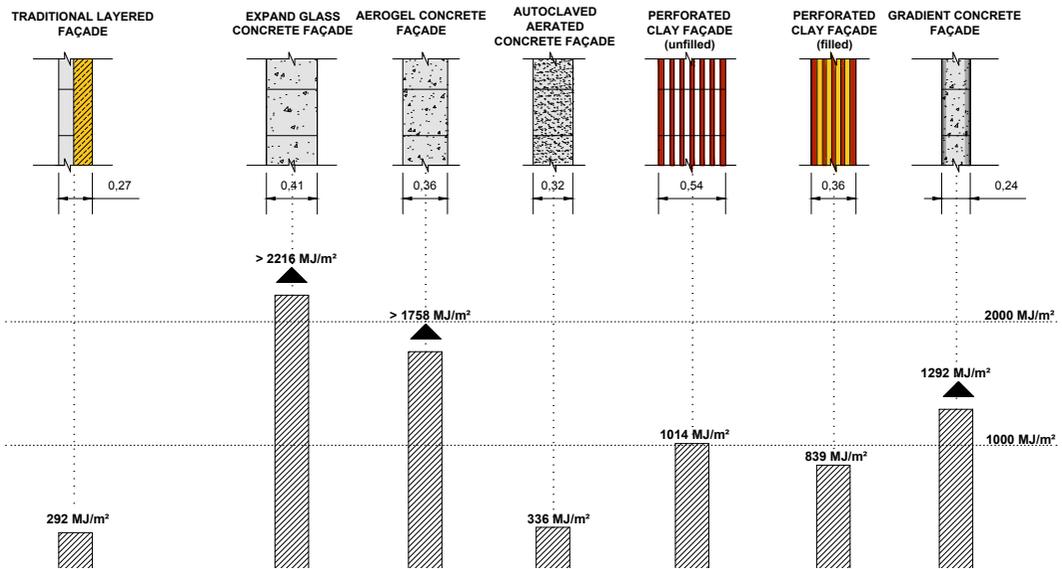


FIGURE 7.5 Embodied energy for different Dutch external wall designs

## Observations

- The traditional external wall has the lowest embodied energy compared to all additional insulating massive constructions. The massive layer in the traditional external wall contributes to about 60% of the total embodied energy ( $178 \text{ MJ/m}^2$ ), whereas the insulation layer contributes to about 40% of the total embodied energy ( $113 \text{ MJ/m}^2$ ).
- Aerated Concrete construction has the lowest embodied energy among all additional insulating massive constructions, whereas Expanded Glass Concrete construction has the highest embodied energy. This is because the embodied energy of Expanded Glass is relatively high and it is used in the mixture with large quantities. It contributes to almost 90% of the total embodied energy calculated.

## § 7.2.4 Carbon Dioxide Emission

The carbon dioxide emission for the different designed masonry external walls is presented in Table 7.10 and Figure 7.6. The following input values are considered:

Tables 7.8 and 7.9 show the carbon dioxide emission used in the calculations. The values used for were taken from the Inventory of Carbon and Energy Database (ICE) Version 1.6a created by the University of Bath (Cradle to gate) (Hammond & Jones, 2008). However, the carbon dioxide emission of the following materials was obtained from other sources because they are uncommon and not found in the database:

- Expanded glass aggregate, from the Environmental product declaration of Glasopor expanded glass (Glasopor, 2015).
- Aerogel carbon dioxide emission, from the research work carried out by Dowson (Dowson, Grogan, Birks, Harrison, & Craig, 2012). However, the results should be dealt with as conservative estimates. This is because the aerogel was produced in a laboratory and not developed for mass manufacture or refined to reduce its environmental impact. In addition, the samples used were small and the obtained values were up scaled without considering major changes to the equipment used or manufacturing steps.

MATERIALS CO2 EMISSION	KG.CO2/KG	SOURCE
<b>Concrete Ingredients</b>		
Cement	0.83	(Hammond & Jones, 2008)
Ready Mixed Concrete	0.13	(Hammond & Jones, 2008)
<b>Aggregates</b>		
Expanded Glass	0.27	(Glasopor, 2015)
Aerogel	4.3	(Dowson et al., 2012)

TABLE 7.8 Carbon dioxide emission of materials

ELEMENTS CO2 EMISSION	KG.CO2/KG	SOURCE
Calcium Silicate Blocks	0.13	Estimated as concrete
Insulation (Rockwool)	1.05	(Hammond & Jones, 2008)
Autoclaved Aerated Concrete	0.33	(Hammond & Jones, 2008)
Perforated Clay Bricks	0.22	(Hammond & Jones, 2008)

TABLE 7.9 Carbon dioxide emission of products

	Wall composition & density per m <sup>3</sup>	Wall Thickness (m)	CO2 emission of Calcium silicate/m <sup>2</sup> (KgCO <sub>2</sub> / m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x CO2 emission of C.S	CO2 emission of insulation/ m <sup>2</sup> (KgCO <sub>2</sub> / m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x CO2 emission of insulation	
TRADITIONAL MASSIVE EXTERNAL WALL	Calcium silicate block (1750kg) - Rockwool insulation (45kg)	0.12 + 0.15	27	7	
EXPANDED GLASS CONCRETE EXTERNAL WALL	Cement (120kg) – Expanded Glass Aggregates (180Kg) - Water (120Kg) – Air entraining (Aer Solid) (48Kg) (Heinz et al., 2011)	0.41	-	-	
AEROGEL CONCRETE EXTERNAL WALL	mixture contains > 60% Aerogel (72kg)	0.36	-	-	
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	AAC (300kg)	0.32	-	-	
PERFORATED CLAY EXTERNAL WALL (UN-FILLED)	Perforated clay brick (626kg)	0.54	-	-	
PERFORATED CLAY EXTERNAL WALL (FILLED)	Perforated clay brick (626kg) + Rockwool insulation (26kg)	0.36	-	10	
GRADIENT CONCRETE EXTERNAL WALL	70% Aerogels - 6% Cement - 24% Void	Cement (120Kg) - Aerogel Aggregates (84Kg) - Water (60Kg) - Air entraining (Aer Solid) (48Kg) (Heinz et al., 2011)	0.15		
	60% Aerogel - 40% Concrete	Cement (459kg) - Aerogel (72kg) (Gao et al., 2014)	0.04		
	Concrete	Ready mixed concrete (1976 kg) (Heinz et al., 2011)	0.04		
	Total				

TABLE 7.10 Carbon dioxide emission for different Dutch external wall designs

	CO2 emission of cement/ m <sup>2</sup> (KgCO <sub>2</sub> / m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x CO2 emission of cement	CO2 emission of aggregates/ m <sup>2</sup> (KgCO <sub>2</sub> / m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x CO2 emission of aggregates	CO2 emission of air entraining/ m <sup>2</sup> (KgCO <sub>2</sub> / m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x CO2 emission of air entraining	CO2 emission of perforated bricks (or AAC)/ m <sup>2</sup> (KgCO <sub>2</sub> / m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x CO2 emission of perforated b.	Total CO2 emission/m <sup>2</sup> (KgCO <sub>2</sub> / m <sup>2</sup> )
	-	-	-		34
	41	20	Not available		>61
	-	111	-		> 111
	-	-	-	32	32
	-	-	-	74	74
	-	-	-	50	60
	15	54	Not available		69
	15	12	-		28
	10	-	-		10
	40	67			>107

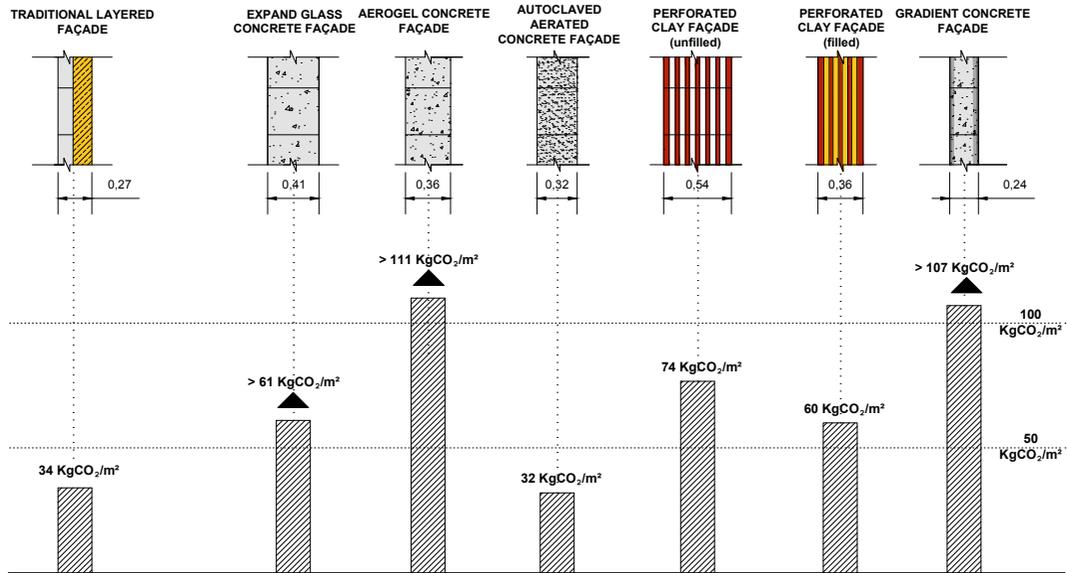


FIGURE 7.6 Carbon dioxide emission for different Dutch external wall designs

### Observations

- Aerated Concrete external wall has the lowest carbon dioxide emission compared to all additional insulating massive constructions, whereas the traditional external wall comes in the second position. The calcium silicate blocks contributes to about 80% of the total carbon dioxide emission of the traditional external wall (27 KgCO<sub>2</sub>/m<sup>2</sup>), whereas the insulation layer contributes to about 20% (7 KgCO<sub>2</sub>/m<sup>2</sup>).
- Aerogel Concrete construction has the highest carbon dioxide emission. This is because the carbon dioxide emission of aerogel is relatively high.

## § 7.2.5 Recyclability

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The recyclability potentials for the different designed masonry external walls are presented in Table 7.12 and Figure 7.7. The following calculations and assumptions are considered:

- As mentioned in Chapter 6, the common form of reusing the massive material is to down-cycle it to recycled aggregates. The energy used in the down-cycling process, particularly in the crushing process of massive materials to form recycled aggregates, was noted by the Environmental Protection to be 0.04 MJ/kg (Environmental Protection Agency, 2014).
- For rockwool insulation, the only form noted by the author for reusing/recycling rockwool insulation is to recycle it in forming new rockwool insulation. Research work carried out by Schmidt studied the energy used in the recycling process of wool insulation (excluding disassembly energy). It is mentioned to be 16.13 MJ/kg (Schmidt, Jensen, Clausen, Kamstrup, & Postlethwaite, 2004). This is considered high since the embodied energy for virgin rockwool insulation as provided by the Inventory of Carbon and Energy Database (ICE) is 16.8 MJ/kg. Table 7.11 presents the energy used in the recycling/reuse tasks.

ENERGY IN RECYLCING/REUSE	MJ/KG
Crushing into recycled aggregates	0.04
Recycling rockwool Insulation	16.13

TABLE 7.11 Energy used in recycling/reuse tasks

	Disassembly process	Wall composition & density per m <sup>3</sup>	Wall thickness (m)	Energy for recycling the massive layer (MJ/m <sup>3</sup> ) = Thickness x density x E.E in recycling	Energy for recycling the insulation layer = Thickness x density x E.E in recycling	Total energy for recycling (MJ/m <sup>2</sup> )
TRADITIONAL MASSIVE EXTERNAL WALL	Requires disassembly process	Calcium silicate (1750kg) + Insulation (45kg)	0.12 m (C.S.) - 0.15m (Ins.)	8	109	117
EXPANDED GLASS CONCRETE EXTERNAL WALL	Does not require disassembly process	Exp. Glass Concrete (468kg)	0,41	8	-	8
AEROGEL CONCRETE EXTERNAL WALL	Does not require disassembly process	Aerogel Concrete (450kg)	0,36	6	-	6
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	Does not require disassembly process	AAC (300kg)	0,32	4	-	4
PERFORATED CLAY EXTERNAL WALL (UN-FILLED)	Does not require disassembly process	Fired clay (626kg)	0,54	6	-	14
PERFORATED CLAY EXTERNAL WALL (FILLED)	Requires complicated disassembly process	Fired Clay (626kg) - Insulation (27kg)	0,36	9	157	166
GRADIENT CONCRETE EXTERNAL WALL	Does not require disassembly process	Gradient Concrete (793kg)	0,24		-	8

TABLE 7.12 Recyclability potentials for different Dutch external walls

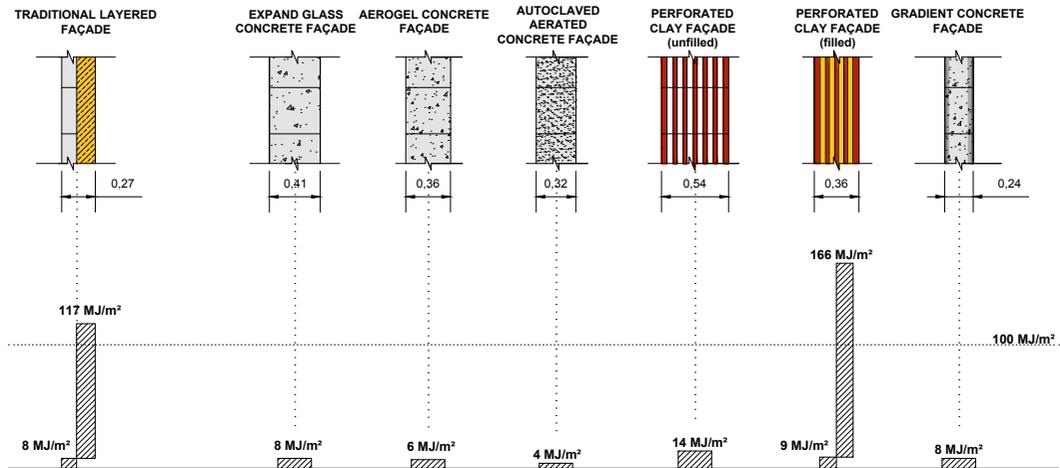


FIGURE 7.7 Recyclability potentials for different Dutch external wall designs

### Observations

- All additional insulating massive constructions provide a high recyclability potential due to the elimination of the separating process and the low energy required for the crushing process. Among the monolithic additional insulating technologies, the Autoclaved Aerated Concrete external wall requires the least energy for down cycling, whereas the Perforated Clay Brick external wall requires the highest energy for down cycling.
- The Perforated Clay Bricks filled with insulation have the lowest potential for recyclability for two reasons. First, it is composed of two materials, the bricks and the insulation, which are interwoven together in one element. This makes their disassemble process very complicated unlike the other additional insulating massive constructions, where the external wall is monolithic requiring no disassembly process. Second, the insulation material requires relatively high energy to be recycled.
- The traditional external wall has the second lowest potential for recyclability. Its two layers are permanently fixed together (either by adhesive or ties), which are not meant for being disassembled. Also the recycling its insulation requires high energy.

## § 7.2.6 Operational Energy

The effect of the thermo-physical characteristics of the external walls on the operational energy and particularly heating energy is shown in Figure 7.8.

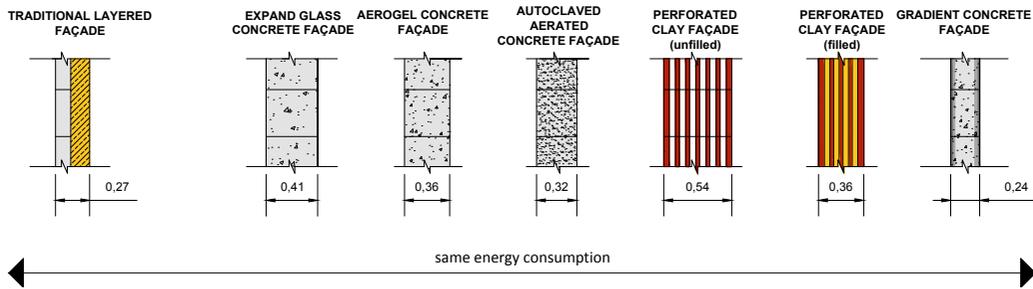


FIGURE 7.8 Operational energy for different Dutch external wall designs

### Observation

- The effect of the different masonry external walls on the operational energy can be considered the same (Figure 7.8) with energy consumption less than 117 kWh/m<sup>2</sup> / year (BSRIA, 2014). This is because:
  - All constructions have the same R-value (4.5 m<sup>2</sup>k/w), which is relatively high.
  - With higher insulating buildings, the thermal mass becomes less effective (from the interview that took place with Martin Tenpierrik, mentioned in Section 5.2.1).

## § 7.2.7 Construction Thickness

Thick external walls are usually less acceptable because they result in a reduction in inner spaces. Moreover, they require more time and cost for construction as shown in previous sections. A comparable scale for assessing the effect of different thicknesses will be provided in Section 7.4. However, construction thickness of the different technologies can be seen in Figure 7.9.

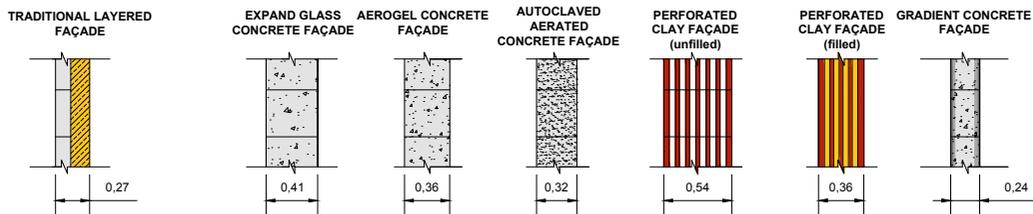


FIGURE 7.9 Thickness for different Dutch external wall designs

### Observation

- The only masonry external wall that provides a thickness less than the traditional external wall is the Gradient Concrete. This is because Aerogel is a very good thermal insulator. On the other hand Perforated Clay Bricks provided the thickest external wall construction with a thickness twice of the traditional external wall.

## § 7.2.8 Lifetime and Durability

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The performance of the different masonry external walls regarding lifetime and durability is presented in Figure 7.10. Table 7.13 shows estimation of the number of years to repair or replace the different materials. Numbers are mostly based on the work done by Manfred Hegger (Hegger, Auch-Schwelk, & Mattias Fuchs, 2006) otherwise the different source is mentioned. For some materials data that are not available, a reasonable guess is made as shown below.

MATERIAL	DURABILITY (YEARS)
Calcium Silicate Blocks	60 - 80
Clay Brick	> 80
Concrete	> 80
Lightweight Aggregate Concrete	> 50 (Assumption)
AAC	> 50 (Assumption)
Rockwool Insulation	30 (Trachte & Massart, 2011)
Perforated Clay Brick (unfilled)	>80
Perforated Clay Brick (filled)	>40 (Assumption) Because the Perforated Clay Bricks incorporates insulation which is well protected by the brick ribs, it can last more than the layered insulation

TABLE 7.13 Lifetime and durability duration for different materials

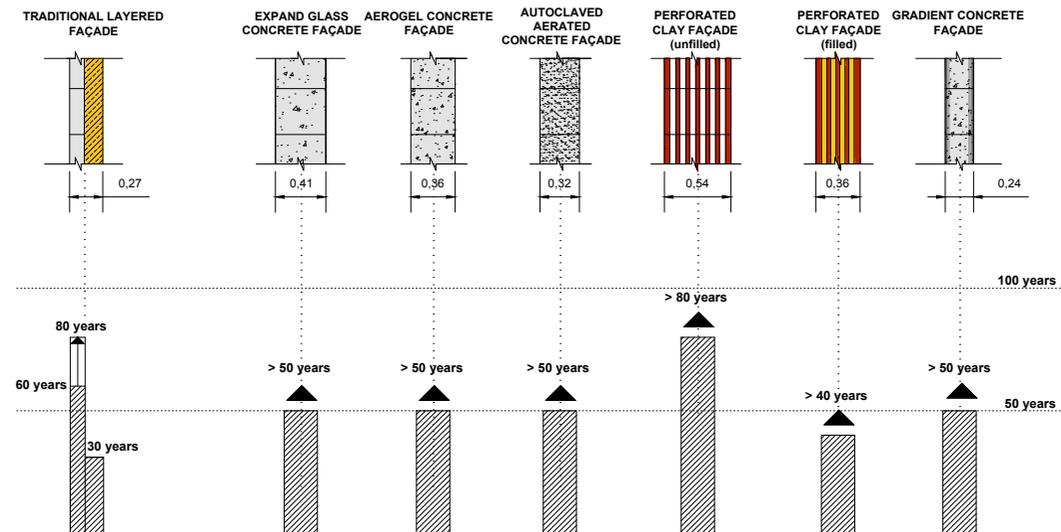


FIGURE 7.10 Lifetime and durability for different Dutch external wall designs

### Observation

- Based on the available literature, the traditional layered construction has the least lifespan. This is due to the relatively short lifespan of the rockwool insulation, which requires a replacement after 30 years. On the other hand, the Perforated Clay Brick has the highest lifespan of more than 80 years.

## § 7.3 Massive External Wall Performances: Egypt

In this section, the traditional monolithic external wall of Egypt is compared to the additional insulating designed masonry external walls. As previously explained, the Egyptian traditional external wall does not provide an insulating function as insulation requirements are not mentioned in building rules and regulations. However, when comparing the performances of additional insulating massive technologies in external walls in Egypt, it becomes important to consider a layered construction in the comparison. Adding a layered external wall to the comparison will indicate in which form insulation function can be better: in an integral form or a layered form.

The following aspects provide a guideline for designing the layered external wall:

- Based on the design criteria for the Egyptian external wall, given in Chapter 6, and in order for the external walls to be comparable, a thickness of 25 cm for the external walls is maintained.
- The Egyptian building rules and regulations require a minimum masonry external wall thickness of 20 cm (Section 6.3.2).
- In the Egyptian market, the only available insulation material is the glass wool insulation. It is usually sold with a thickness of 1 or 2 inches (2.5 or 5 cm).

Accordingly, Figure 7.11 shows schematically the layered external wall design for the Egyptian context.

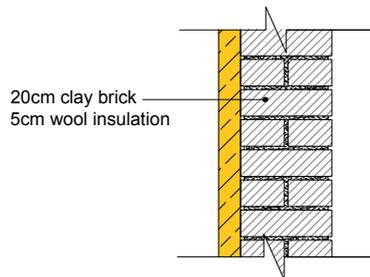


FIGURE 7.11 Layered external wall design for Egyptian context

Figure 7.12 shows the different external wall designs and the performance parameters used for comparison.

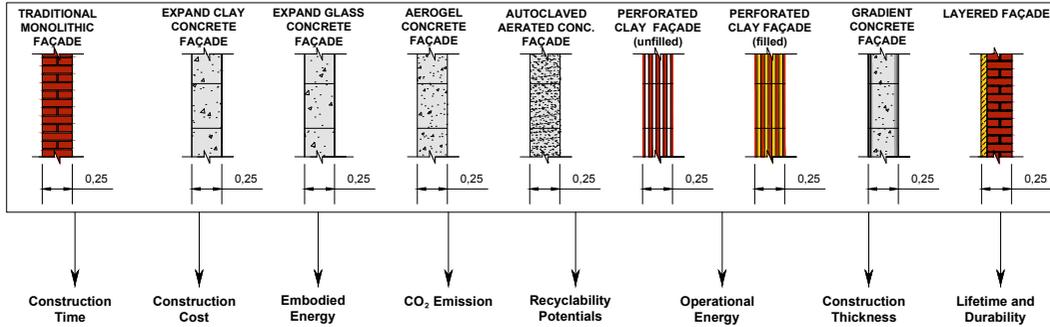


FIGURE 7.12 Different Egyptian external wall designs and performance parameters used for comparison

### § 7.3.1 Construction Time

The construction time for the different designed masonry external walls is presented in Table 7.14 and Figure 7.13. The method for calculating the bricklaying productivity rate is similar to that of the Dutch case.

#### Assumption

All blocks have a constant weight of 2.2 kg, which is the weight of the commonly used clay brick having dimensions of 250 mm x 120 mm x 60 mm and a density of 1200 kg/m<sup>3</sup>

	Wall Thickness (m)	Density $\rho$ (kg/m <sup>3</sup> )	Block weight (Kg)	Block area (m <sup>2</sup> ) =Weight/( $\rho \times T$ )	Blocks per day (from Figure 7.2)	
TRADITIONAL MASSIVE EXTERNAL WALL	0.25	1200	2.2	0.007	600	
EXPANDED CLAY CONCRETE EXTERNAL WALL	0.25	760	2.2	0.012	600	
EXPANDED GLASS CONCRETE EXTERNAL WALL	0.25	468	2.2	0.019	600	
AEROGEL CONCRETE EXTERNAL WALL	0.25	450	2.2	0.020	600	
AUTOCURED AERATED CONCRETE EXTERNAL WALL	0.25	400	2.2	0.022	600	
PERFORATED CLAY BRICK EXTERNAL WALL (UNFILLED)	0.25	800	2.2	0.011	600	
PERFORATED CLAY BRICK EXTERNAL WALL (FILLED)	0.25	652	3.2	0.013	600	
GRADIENT CONCRETE EXTERNAL WALL	0.25	792.5	2.2	0.011	600	
LAYERED EXTERNAL WALL	0.2 (Brick) + 0.05 (Ins.)	1200	2.2	0.018	600	

TABLE 7.14 Construction time for different Egyptian external wall designs

	Bricklaying (m <sup>2</sup> per day) = Block area x Blocks per day	Bricklaying (m <sup>2</sup> per hr) = (m <sup>2</sup> per day)/ 8	Bricklaying (hr per m <sup>2</sup> ) = 1/(m <sup>2</sup> per hr)	Insulation (hr per m <sup>2</sup> )	Total (hr per m <sup>2</sup> )
	4.40	0.55	1.82	-	1.8
	6.95	0.87	1.15	-	1.2
	11.28	1.41	0.71	-	0.7
	11.73	1.47	0.68	-	0.7
	13.20	1.65	0.61	-	0.6
	6.60	0.83	1.21	-	1.2
	8.10	1.01	0.99	-	1.0
	6.66	0.83	1.20		1.2
	5.50	0.69	1.45	0.6	2.1

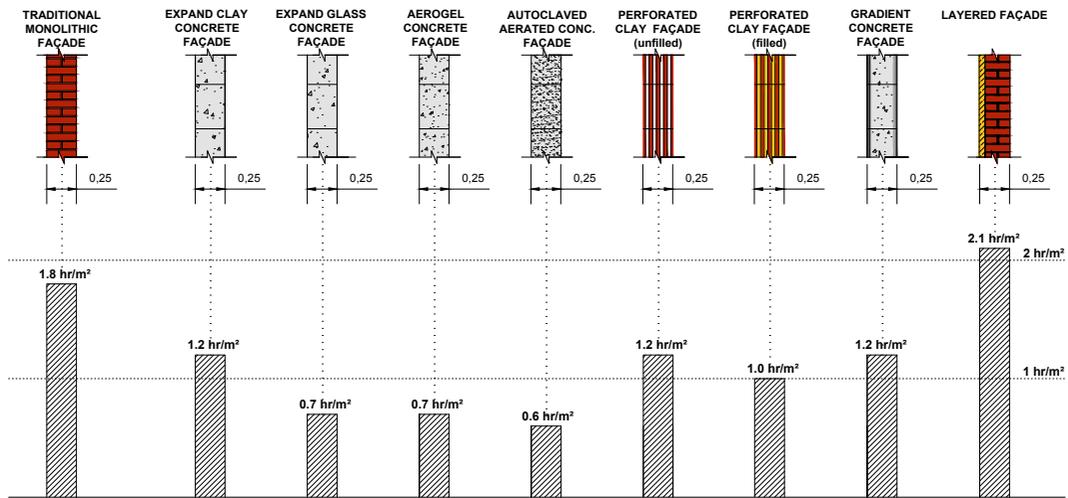


FIGURE 7.13 Construction time for different Egyptian external wall designs

### Observations

- Due to the constant thickness of the different constructions, the construction time for monolithic construction becomes dependent on the material densities. Autoclaved Aerated Concrete, which possesses the lowest densities, provides the highest productivity rate.
- The layered construction has the lowest productivity rate. This is because the bricks are of high density requiring more time in construction than other constructions. In addition, it requires an additional time step for placing the insulation.

## § 7.3.2 Construction Cost

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The construction cost for the different designed masonry external walls is presented in Table 7.17 and Figure 7.14. The following inputs and assumptions are considered.

### *Materials cost*

---

In Egypt, there is no official price indicator document that can be referred to. Consequently, the prices used in this section are based on the average market prices from different suppliers. All prices noted are based on large quantities (for covering the construction of a medium size apartment building consisting of 4 floors), including transportation (to Cairo). The prices are shown in Tables 7.15 and 7.16 (as per November, 2014).

### *Assumptions*

---

All additional function technologies (except for expanded clay technologies) are new to the Egyptian market. This makes price prediction for most construction technologies hard. For some technologies, a “reasonable prediction” is made.

- Expanded Glass: The manufacturing process of expanded glass is close to expanded clay as they both use rotating kiln with high temperature. Since expanded clay is available in Egypt, then it can be assumed that expanded glass can be locally produced. By applying the same price difference between expanded clay and expanded glass in the Netherlands, the Egyptian expanded glass can be estimated to be 1.56 EGP/kg.
- Autoclaved Aerated Concrete/Perforated Clay Bricks: Both Autoclaved Aerated Concrete and Perforated Clay Bricks are not available in the Egyptian market. However, their raw materials are available in Egypt (sand and lime for Autoclaved Aerated Concrete, and clay and insulation for Perforated Clay Bricks). Therefore, they can be locally produced. It is expected that for Autoclaved Aerated Concrete and unfilled Perforated Clay Bricks, 1 m<sup>2</sup> (25 cm thick wall) can range from 100 EGP to 150 EGP (triple the price of the traditional construction). As for filled Perforated Clay Bricks 1 m<sup>2</sup> (25 cm thick) can range from 150 EGP to 200 EGP.

### Labour cost

---

The average wage for skilled masons in a construction site job is 160 EGP per day (as of January 2014), with an average of 20 EGP per hour (based on the author's experience as an Architect in Egypt). Since insulation is uncommon, it will be assumed that the wage for insulation labour is the same.

MARKET BASIC MATERIAL PRICES	PRICE/KG (EGP)
<b>Concrete Ingredients</b>	
Cement	0.65
Ready Mixed Concrete	0.23
<b>Aggregates</b>	
Expanded Clay	0.35
Expanded Glass	1.56 (Assumption)
Aerogel	Expected to be high (as it is already expensive & will be imported)
<b>Other materials</b>	
Aer Solid (air entraining - Sika)	Expected to be high (as it is already expensive & will be imported)
Locally produced air entraining agent	0.08

TABLE 7.15 Average material prices by suppliers (as sold in kg)

MARKET ELEMENT PRICES	PRICE/M <sup>3</sup> (EGP)
Traditional Clay Brick	183
Autoclaved Aerated Concrete (AAC C2/400)	400-600 (Assumption)
Perforated Clay Bricks (unfilled)	400-600 (Assumption)
Perforated Clay Bricks (filled)	600-800 (Assumption)
Glass Wool Insulation	500

TABLE 7.16 Average element prices by suppliers (as sold in m<sup>3</sup>)



		Mixture composition/m <sup>3</sup>	Wall thickness (m)	Materials/ products cost				
				Price of bricks/m <sup>2</sup> (EGP) =thickness x price of bricks per m <sup>3</sup>	Price of insulation/m <sup>2</sup> (EGP) =thickness x price of ins. Per m <sup>3</sup>	Price of cement/m <sup>2</sup> (EGP) =thickness x price of cement per m <sup>3</sup>	Price of aggregates/m <sup>2</sup> (EGP) =thickness x price of agg. per m <sup>3</sup>	
TRADITIONAL MASSIVE EXTERNAL WALL		Clay bricks (1200kg)	0.25	45,83	-	-	-	
EXPANDED CLAY CONCRETE EXTERNAL WALL		Cement (330kg) - Sand (158kg) - Liapor (195kg) - Water (165kg) - Air ent. agent (2kg) (Zareef, 2010)	0.25	-	-	54.81	17.06	
EXPANDED GLASS CONCRETE EXTERNAL WALL		Cement (120kg) - Liaver (180kg) - Water (120kg) - Air ent. (Aer solid) (48kg) (Heinz et al., 2011)	0.25	-	-	19.50	70.16	
AEROGEL CONCRETE EXTERNAL WALL		Mixture contains > 60% Aerogel (72kg)	0.25	-	-	Not available	Not available	
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL		-	0.25	-	-	-	-	
PERFORATED CLAY BRICK F. (UNFILLED)		-	0.25	-	-	-	-	
PERFORATED CLAY BRICK F. (FILLED)		-	0.25	-	-	-	-	
GRADIENT CONCRETE EXTERNAL WALL	70% Aerogels - 6% Cement - 24% Void	Cement (120kg) - Aerogel (84kg) - Water (60kg) - Air ent. (48kg) (Heinz et al., 2011)	0.17	-	-	13.26	Not available	
	60% Aerogel - 40% Concrete	Cement (459kg) - Aerogel (72kg) (Gao et al., 2014)	0.04	-	-	11.93	Not available	
	Concrete	Concrete (2000 kg)	0.04	-	-	-	-	
	Total		0.25					
LAYERED EXTERNAL WALL		0.2 M Clay bricks - 0.05M Insulation	0.20 + 0.05	36.67	25.00	-	-	

TABLE 7.17 Construction cost for different Egyptian external wall designs

	Price of air entraining agent/m <sup>2</sup> (EGP) =thickness x price of air ent. per m <sup>3</sup>	Price of perforated bricks (or aac)/ m <sup>2</sup> (EGP) =thickness x price of air ent. per m <sup>3</sup>	Total materials/ products cost (EGP)	Labour cost			Total cost (EGP)
				Const. time (hour) (as per section 7.3.1)	Average labour wage (egp/ hour)	Total labour cost (EGP) = Const. time x average labour wage	
	-	-	46	1.8	21	37.80	84
	0.16	-	72.03	1.2	21	25.20	97
	Not available	-	Not available but expected to be too expensive	0.7	21	14.70	Not available but expected to be too expensive
	-	-	Not available but expected to be too expensive	0.7	21	14.70	Not available but expected to be too expensive
	-	100 - 150	100 - 150	0.6	21	12.60	112 - 162
	-	100 - 150	100 - 150	1.2	21	25.20	125 - 175
	-	150 - 200	150-200	1.0	21	21.00	171- 221
	Not available	-					
	-	-					
	-	-					
			Not available but expected to be too expensive	1.2	21	25.20	Not available but expected to be too expensive
	-	-	62	2.1	24	50.40	112

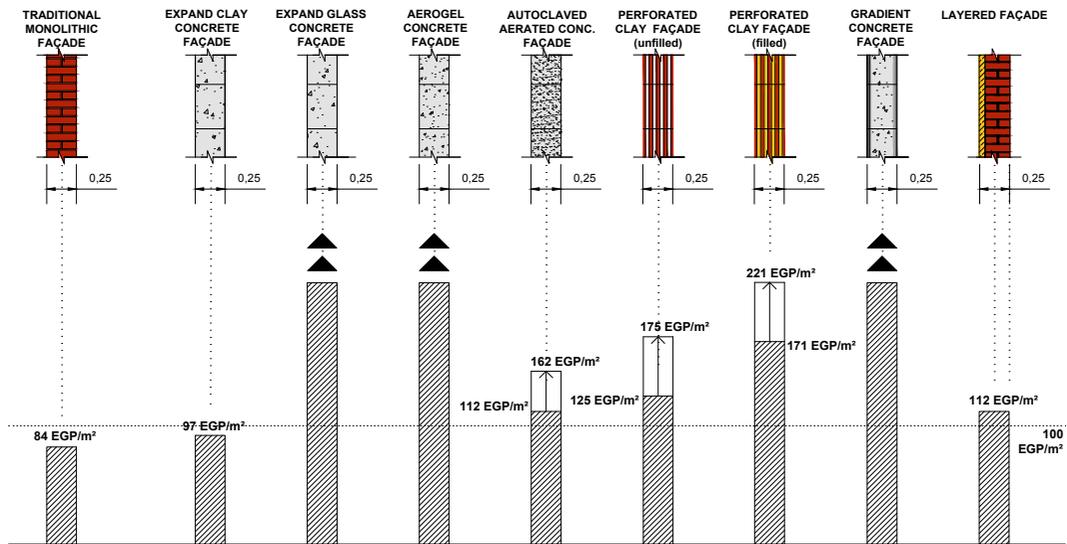


FIGURE 7.14 Construction cost for different Egyptian external wall designs

### Observations

- The traditional external wall has the lowest cost among all constructions. Its material cost comprises about 55% of the total cost, whereas its labour cost comprises about 45% of the total cost.
- Expanded Clay Concrete external wall has the lowest price among additional massive technologies. Its material comprises about 75% of the total cost whereas its labour cost comprises about 25% of the total cost. On the other hand, Aerogel Concrete external wall is expected to be the most expensive.
- Labour cost is reduced in additional insulating technologies. This is because with constant block weight, lower-density materials result in larger block surface; therefore, faster construction and lower labour cost.

### § 7.3.3 Embodied Energy

---

The embodied energy for the different designed masonry external walls is presented in the Table 7.18 and Figure 7.15 (using the same sources as those for the Dutch case in Section 7.2.3).

		Wall composition & density per m <sup>3</sup>	Wall Thickness (m)	E.E. of Bricks (MJ/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x E.E.C. of bricks	E.E. of insulation (MJ/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x E.E.C. of insulation	
		Fired Clay (1200kg)	0,25	900	-	
		Cement (330Kg) - Sand (158Kg) - Liapor (195Kg) - Water (165KG) - Air entraining agent (2Kg) (Zareef, 2010)	0,25	-	-	
		Cement (120kg) - Liaver (180Kg) - Water (120Kg) - Air entrain- ing Agent (Sika) (48Kg) (Heinz et al., 2011)	0,25	-	-	
		mixture contains > 60% Aerogel (72kg)	0,25	-	-	
		AAC (400 kg)	0,25	-	-	
		Perforated Clay Bricks (800 kg)	0,25	-	-	
		Perforated clay brick (626kg) + Rockwool insulation (26kg)	0,25	-	0	
GRADIENT CONCRETE	70% Aerogels - 6% Cement - 24% Void	Cement (120Kg) - Aerogel (84Kg) - Water (60Kg) - Air entraining Agent (Sika) (48Kg) (Heinz et al., 2011)	0,17			
	60% Aerogel - 40% Concrete	Cement (459kg) - Aerogel (72kg) (Gao et al., 2014)	0,04			
	Concrete	Concrete (2000 kg)	0,04			
	Total		0,25	-	-	
		Clay bricks (1200kg) + Insulation (45kg)	0,20 + 0,05	720	38	

TABLE 7.18 Embodied Energy for different Egyptian external wall

	E.E. of cement (MJ/m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x E.E.C. of cement	E.E. of aggregates/m <sup>2</sup> (MJ/m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x E.E.C. of aggregates	E.E. of air entraining/m <sup>2</sup> (MJ/m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x E.E.C. of air entraining	E.E of perforated bricks (or AAC) (MJ/m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x E.E.C. of perforated bricks (or AAC)	Total E.E (MJ/m <sup>2</sup> )
	-	-	-	-	900
	380	1316	not available	-	>1695
	138	1215	not available	-	>1353
	unknown	1221	-	-	> 1220
	-	-	-	-	350
	-	-	-	-	600
	-	-	-	470	579
	94	969	not available		1062
	84	195	-		280
	75	-	-		75
	253	1164	not available	-	>1643
	-	-	-	-	758

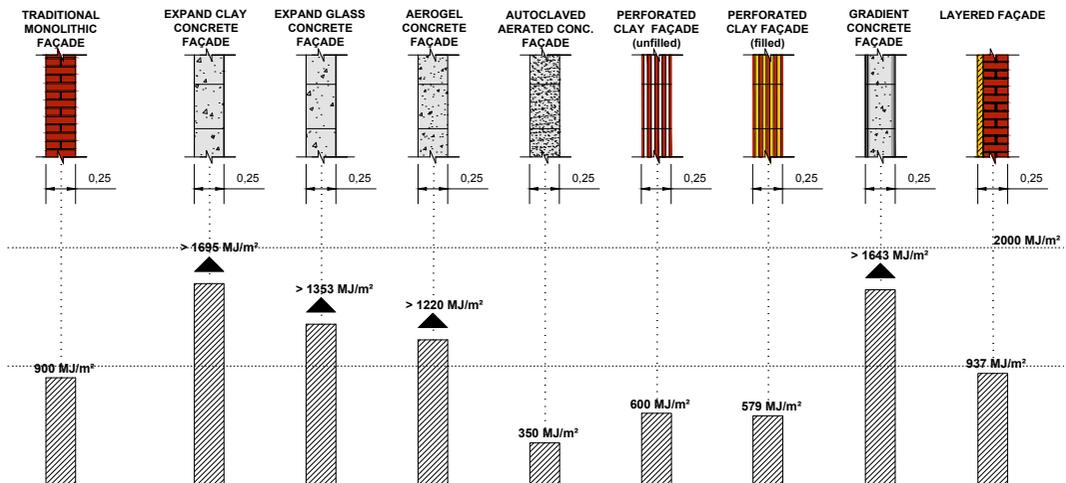


FIGURE 7.15 Embodied Energy for different Egyptian external wall designs

### Observations

- The Aerated Concrete construction has the lowest embodied energy (almost 70% less than the traditional construction) due to its low density.
- The embodied energy coefficient for the clay brick and the Autoclaved Aerated Concrete are close. However, the traditional monolithic external wall and the layered external wall have high embodied energy (almost 3 times the embodied energy of the Autoclaved Aerated Concrete). This is due to the high density of the clay brick compared to the Autoclaved Aerated Concrete.
- Although the exact embodied energies for light weight aggregate concretes are not known, their embodied energies are expected to be very high due to the high embodied energy incorporated with the production of the aggregates.

### § 7.3.4 Carbon Dioxide Emission

---

The carbon dioxide emission for the different designed masonry external walls is presented in the Table 7.19 and Figure 7.16 (using the same sources as those for the Dutch case in Section 7.2.4).

	Wall composition & density per m <sup>3</sup>	Wall Thickness (m)	CO2 emission of Bricks (Kg.CO2/m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x CO2 emission of bricks	CO2 emission of insulation (Kg.CO2/m <sup>2</sup> ) = Thickness x Weight per m <sup>3</sup> x CO2 emission of insulation	
TRADITIONAL MASSIVE EXTERNAL WALL	Fired Clay (1200kg)	0,25	66	-	
EXPANDED CLAY CONCRETE EXTERNAL WALL	Cement (330Kg) - Sand (158Kg) - Liapor (195Kg) - Water (165Kg) - Air entraining agent (2Kg) (Zareef, 2010)	0,25	-	-	
EXPANDED GLASS CONCRETE EXTERNAL WALL	Cement (120kg) - Liaver (180Kg) - Water (120Kg) - Air entrain- ing Agent (Sika) (48Kg) (Heinz et al., 2011)	0,25	-	-	
AEROGEL CONCRETE EXTERNAL WALL	mixture contains > 60% Aerogel (72kg)	0,25	-	-	
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	AAC (400 kg)	0,25	-	-	
PERORATED CLAY BRICK EXTERNAL WALL (UN-FILLED)	Perforated Clay Bricks (800 kg)	0,25	-	-	
PERORATED CLAY BRICK EXTERNAL WALL (FILLED)	Perforated clay brick (626kg) + Rockwool insulation (26kg)	0,25	-	7	
GRADIENT CONCRETE	70% Aerogels - 6% Cement - 24% Void	Cement (120Kg) - Aerogel (84Kg) - Water (60Kg) - Air entraining Agent (Sika) (48Kg) (Heinz et al., 2011)	0,17		
	60% Aerogel - 40% Concrete	Cement (459kg) - Aerogel (72kg) (Gao et al., 2014)	0,04		
	Concrete	Concrete (2000 kg)	0,04		
	Total		0,25	-	-
LAYERED EXTERNAL WALL	Clay bricks (1200kg) + Insulation (45kg)	0,20 + 0,05	53	2	

TABLE 7.19 Carbon dioxide emission for different Egyptian external wall designs

	CO2 emission of cement (Kg.CO2/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x CO2 emission of cement	CO2 emission of aggregates/m <sup>2</sup> (Kg.CO2/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x CO2 emission of aggregates	CO2 emission of air entraining/m <sup>2</sup> (Kg.CO2/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x CO2 emission of air entraining	CO2 emission of perforated bricks (or AAC) (Kg.CO2/m <sup>2</sup> ) =Thickness x Weight per m <sup>3</sup> x CO2 emission of perforated bricks (or AAC)	Total CO2 emission (Kg.CO2/m <sup>2</sup> )
	-	-	-	-	66
	68	13	not available	-	>81
	25	12	not available	-	>37
	unknown	77	-	-	>77
	-	-	-	-	33
	-	-	-	-	44
	-	-	-	34	41
	17	61	not available	-	78
	15	12	-	-	28
	75	-	-	-	75
	107	74	not available	-	>181
	-	-	-	-	55

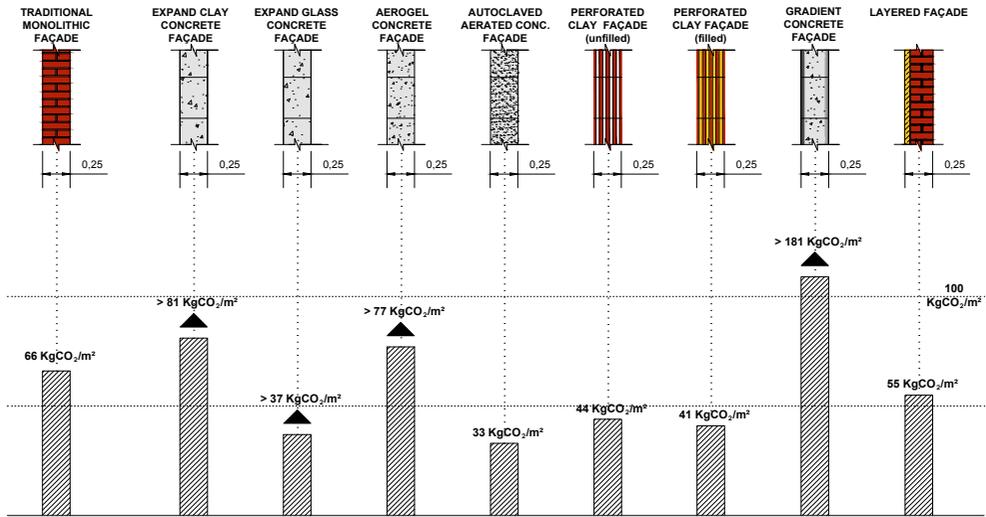


FIGURE 7.16 Carbon Dioxide Emission for different Egyptian external wall designs

### Observations

- The Aerated Concrete construction has the lowest carbon dioxide emission (almost half of the traditional construction) due to its low density.
- The Gradient Concrete wall shows the highest carbon dioxide emission due to the high carbon dioxide emission of aerogel aggregates.

### § 7.3.5 Recyclability

The recyclability potentials for the different designed masonry external walls is presented in Table 7.20 and Figure 7.17 (using same sources as those of the Dutch case in Section 7.2.5)

	Disassembly process	Wall composition & density per m <sup>3</sup>	Wall thickness (m)	Energy for recycling the massive layer (MJ/m <sup>3</sup> ) = Thickness x density x E.E in recycling	Energy for recycling the insulation layer = Thickness x density x E.E in recycling	Total energy for recycling (MJ/m <sup>2</sup> )
TRADITIONAL MASSIVE EXTERNAL WALL	Does not require disassembly process	Fired Clay (1200kg)	0,25	12	-	12
EXPANDED CLAY CONCRETE EXTERNAL WALL	Does not require disassembly process	Exp. Clay Concrete (760kg)	0,25	8	-	8
EXPANDED GLASS CONCRETE EXTERNAL WALL	Does not require disassembly process	Exp. Glass Concrete (468kg)	0,25	5	-	5
AEROGEL CONCRETE EXTERNAL WALL	Does not require disassembly process	Aerogel Concrete (450kg)	0,25	5	-	5
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	Does not require disassembly process	AAC (400kg)	0,25	4	-	4
PERFORATED CLAY BRICK EXTERNAL WALL (UNFILLED)	Does not require disassembly process	Fired Clay (800kg)	0,25	8	-	8
PERFORATED CLAY BRICK EXTERNAL WALL (FILLED)	Requires complicated disassembly process	Fired Clay (626kg) + Insulation (27kg)	0,25	6	110	116
GRADIENT CONCRETE EXTERNAL WALL	Does not require disassembly process	Gradient Concrete (793kg)	0,25	8	-	8
LAYERED EXTERNAL WALL	Requires disassembly process	Fired Clay (1200kg) + Insulation (45kg)	0,20 (Brick) + 0,05 (Ins.)	10	37	46

TABLE 7.20 Recyclability potentials for different Egyptian external wall designs

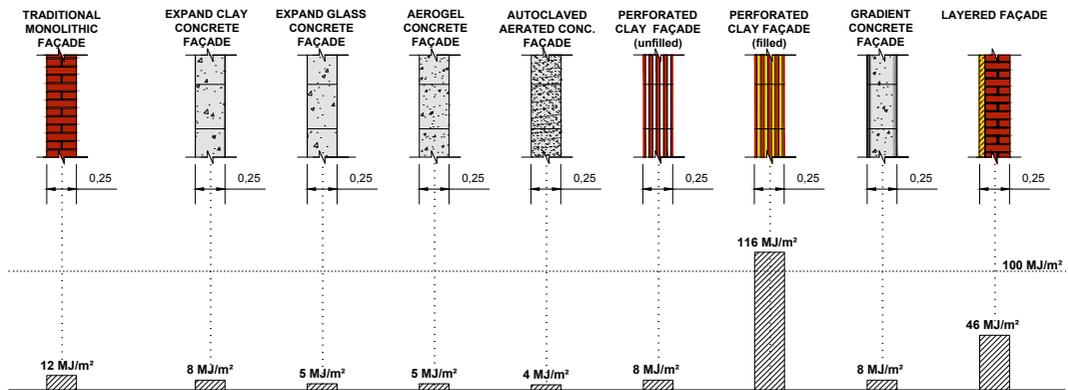


FIGURE 7.17 Recyclability potentials for different Egyptian external wall designs

### Observations

- Similar to the Dutch case, all external wall constructions, except for the layered external wall and filled Perforated Clay Bricks, have relatively good recyclability potentials. This is because they do not require a disassembly process, unlike the layered external wall and filled Perforated Clay Bricks. Moreover the energy used for crushing the massive construction is relatively low. Autoclaved Aerated Concrete has the highest potential for recyclability as it has the lowest density.
- The filled Perforated Clay Bricks show the lowest potential for recyclability because the disassembly process between the Clay Bricks and the insulation can be complicated. Moreover recycling its insulation requires high energy.

### § 7.3.6 Operational Energy

To measure the effect of the different external wall technologies on the operational energy performance, the energy performance for cooling and heating loads were simulated. The program TRNSYS was used for the simulation. A typical medium size apartment building with its predefined parameters from Chapter 6 was used. A typical 2-cm plaster finish internal and external finish was added to the wall construction. The following results were generated (simulation details are found in Appendix 5). The operational energy for the different external wall designs is presented in Table 7.21 and Figure 7.18.

	Total heating demand (KWh/m <sup>2</sup> /year)	Peak total heating demand (W/m <sup>2</sup> )	Total cooling demand (KWh/m <sup>2</sup> /year)	Peak total cooling demand (W/m <sup>2</sup> )
TRADITIONAL MASSIVE CONSTRUCTION	44.11	70.43	62.29	100.00
EXPANDED CLAY CONCRETE EXTERNAL WALL	27.27	59.59	50.49	95.45
EXPANDED GLASS CONCRETE EXTERNAL WALL	25.53	57.91	48.54	93.57
AEROGEL CONCRETE EXTERNAL WALL	24.85	57.7	48.28	94.3
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	25.64	58.25	48.82	94.30
PERFORATED CLAY BRICK EXTERNAL WALL (UNFILLED)	27.81	60.78	51.49	97.35
PERFORATED CLAY BRICK EXTERNAL WALL (FILLED)	25.51	57.65	48.13	93.71
GRADIENT CONCRETE	24.11	56.86	47.19	92.71
LAYERED INSULATING CONSTRUCTION	26.20	58.46	49.19	94.16

TABLE 7.21 Operational energy for different Egyptian external wall designs

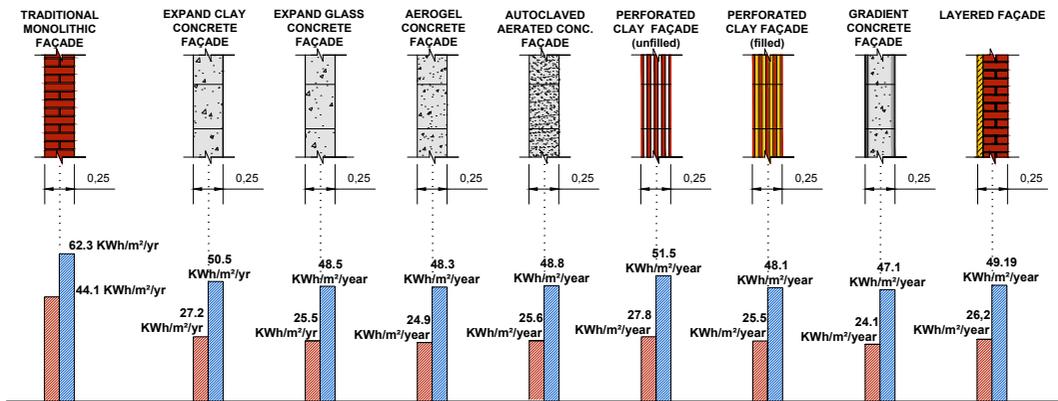


FIGURE 7.18 Operational energy for different Egyptian external wall designs

### Observations

- For all additional insulating constructions, a reduction in cooling and heating loads is noticed (An average reduction of 32% for heating loads, and 23% for cooling loads).
- The additional insulating constructions vary in their U-value and thermal mass. However, they have a very close effect on the Operational Energy (for both heating and cooling loads).
- The values are calculated based on merely insulating just the external wall. The roof is not taken into consideration. It is expected that a holistic approach (containing the roof as an insulated component) will even provide a better performance for operational energy reduction.

### § 7.3.7 Construction Thickness

All external walls are designed to have a thickness of 25 cm as explained in Chapter 6. This is to be comparable with the traditional external wall, which has a thickness of 25 cm. External walls thicker than 25 cm will not likely be accepted by people, whereas external walls with thickness less than 20 cm are not allowed by the Egyptian code for masonry construction (EPC 204 – 2005).

### § 7.3.8 Lifetime and Durability

The performance of the different masonry external walls regarding lifetime and durability is presented in Figure 7.19 (using the same sources as those of the Dutch case in Section 7.2.8).

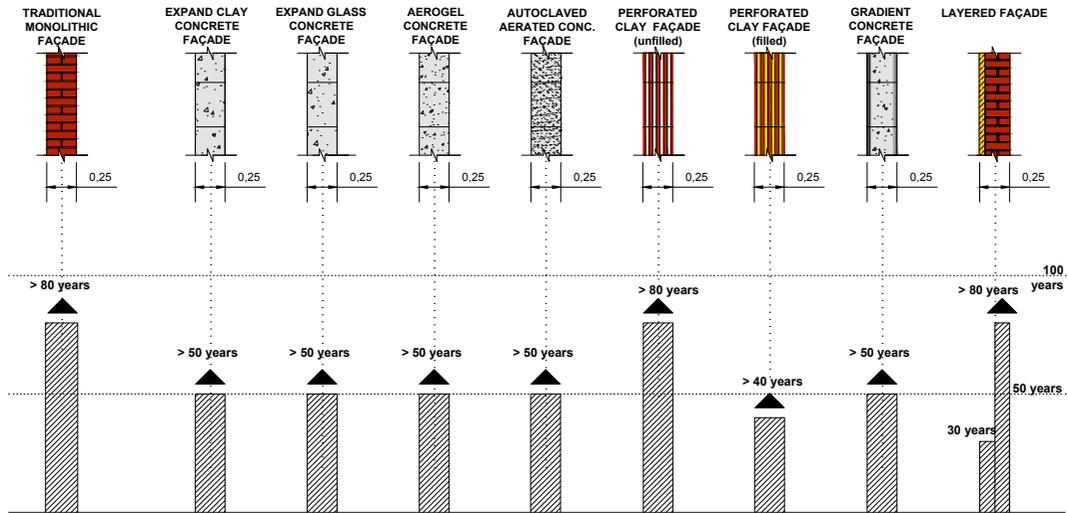


FIGURE 7.19 Lifetime and durability for different Egyptian external wall designs

#### Observation

- The layered construction has the least lifespan. This is due to the relatively short lifespan of the wool insulation. On the other hand, the traditional monolithic brick construction and the Perforated Clay Bricks construction have the highest lifespan of more than 80 years.

## § 7.4 Scoring System and Results

In the previous sections, the external walls were analysed based on separate performances. In this section, a numerical scoring system, which allows the comparison of all performances together, is used to derive comprehensive conclusions. The scoring system is based on:

### 1 Relative importance (weight) of each performance

It is necessary to consider the relative weight, which should be given for each performance. More points should be assigned to the performances of more importance. To determine this relative importance, a short questionnaire was given to five Dutch architects and five Egyptian architects. These architects were involved in medium-sized residential projects. The questionnaire basically requested from the architects to place the relative weight for the different performances, first, according to the real market situation, then according to their future expectations. Architects were selected for this questionnaire because they are the main decision makers when it comes to selecting the external wall system. A sample of the questionnaire form is included in Appendix 6. Figures 7.20 and 7.21 present the results of the questionnaire.

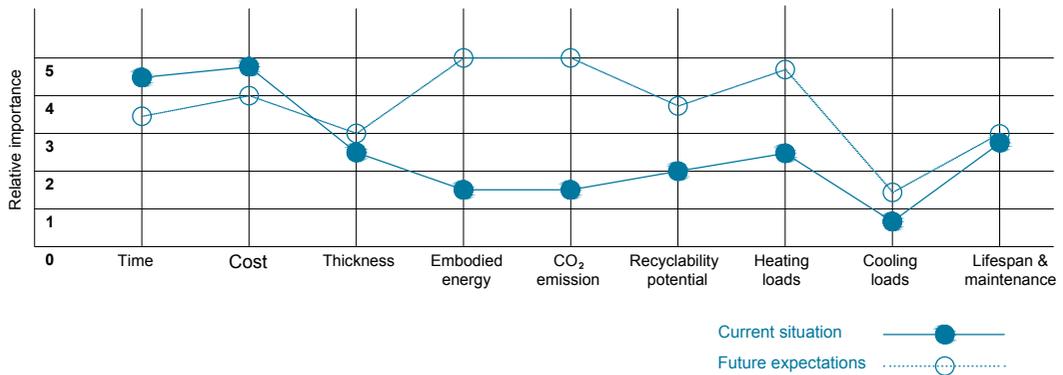


FIGURE 7.20 Relative importance of each performance in the Dutch context

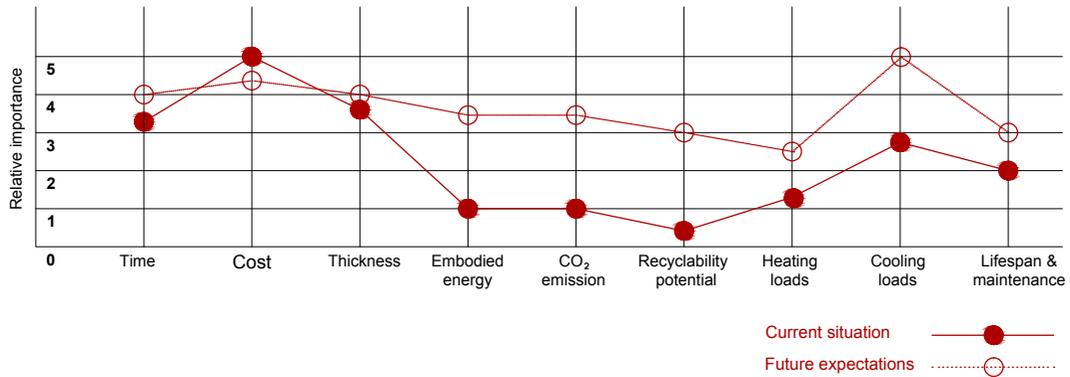


FIGURE 7.21 Relative importance of each performance in the Egyptian context

The results of the questionnaire show that reduction in the construction time, cost, external wall thickness and durability are the most important factors used currently in the Netherlands. Embodied energy, carbon dioxide emission, recyclability potentials and operational energy are also important but with less relative weight. In the future, this changes. Embodied energy, carbon dioxide emission, recyclability potentials, and operational energy will become of more importance.

In Egypt, the situation is similar. The reduction in construction time, cost and external wall thickness are the most important factors considered currently in Egypt. However in the future, the embodied energy, carbon dioxide emission and recyclability potentials will gain importance, but the time and cost reduction will still be more important. In addition, the operational energy, particularly related to cooling, is expected to be of high importance.

## 2 Grading system for each performance

A scoring system from 0 to 6 is set for each performance. The scoring number represents a range of performances (as shown below). Having 7 grades is believed to result into an appropriate precise result. This grading is based on the author's experience as an architect in Egypt, and researcher in the field of building envelopes in the Netherlands. Figures 7.22 and 7.23 present the grading system for each performance in the Dutch and Egyptian context and show the performance of the traditional external wall construction.

By applying the determined grading and relative weight, the following results can be drawn as shown in Tables 7.22 to 7.25.

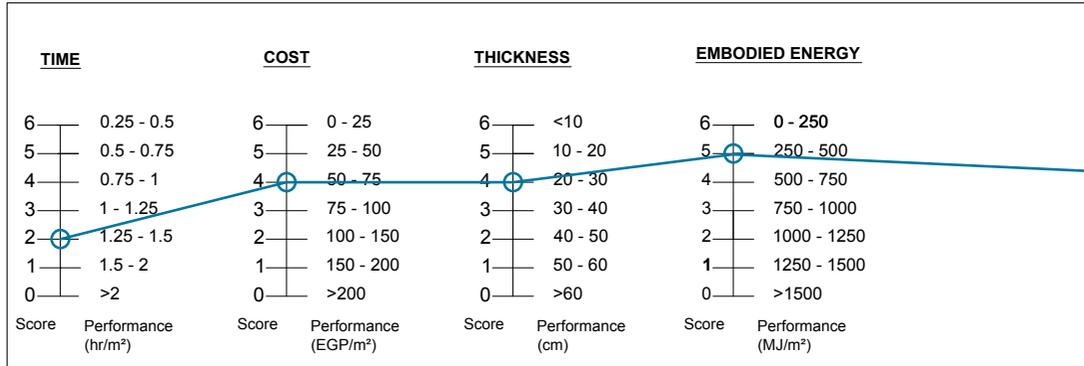


FIGURE 7.22 Grading for each performance in the Dutch context

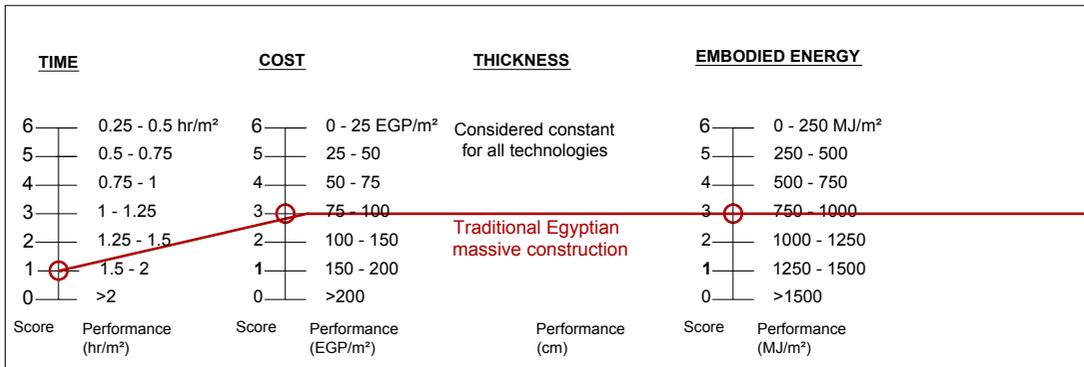
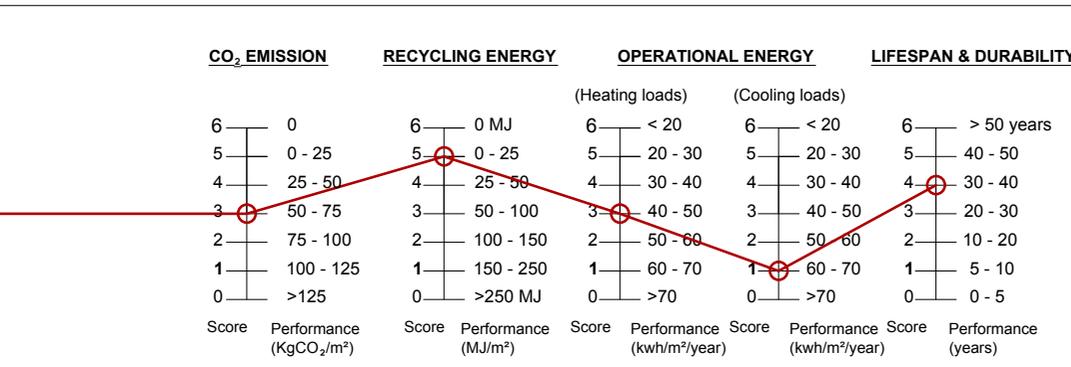
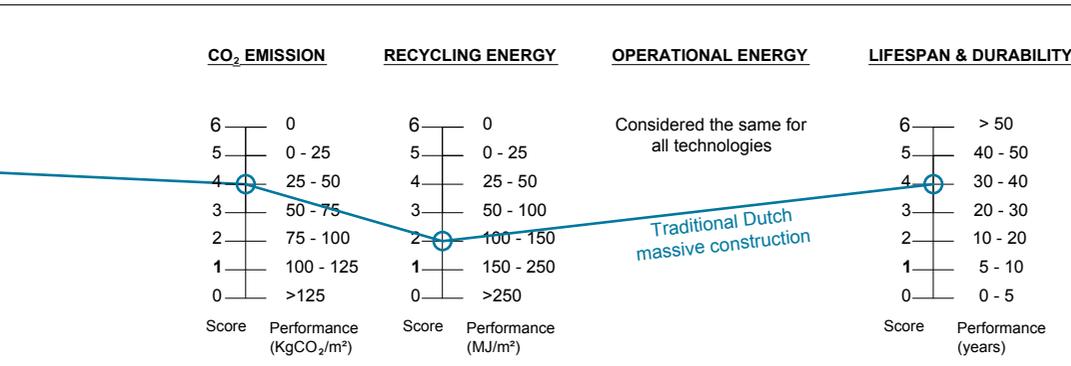


FIGURE 7.23 Grading for each performance in the Egyptian context



THE NETHERLANDS (CURRENT CONSIDERATIONS)								
		TRADITIONAL EXTERNAL WALL		EXPANDED GLASS CONCRETE EXTERNAL WALL		AEROGEL CONCRETE EXTERNAL WALL		
				70% Expanded Class - 6% Cement - 24% Void		UHPC+Aerogel		
CRITERIA	Relative weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	
TIME	4.5	2	9	4	18	5	22.5	
COST	4.8	4	19	0	0	0	0	
THICKNESS	2.5	4	10	2	5	3	7.5	
OP. ENERGY (HEATING)	-	-	-	-	-	-	-	
OP. ENERGY (COOLING)	-	-	-	-	-	-	-	
EMBODIED E.	1.5	5	7.5	0	0	0	0	
CO2 EMISS.	1.5	4	6	3	4.5	0	0	
RECYCLING P.	2	2	4	5	10	5	10	
LIFESPAN & DURABILITY	3	4	12	6	18	6	18	
<b>TOTAL</b>			67.5		55.5		58	

TABLE 7.22 Performance of Dutch external wall designs with current considerations

THE NETHERLANDS (FUTURE CONSIDERATIONS)								
		TRADITIONAL EXTERNAL WALL		EXPANDED GLASS CONCRETE EXTERNAL WALL		AEROGEL CONCRETE EXTERNAL WALL		
				70% Expanded Glass - 6% Cement - 24% Void		UHPC+Aerogel		
CRITERIA	Relative Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	
TIME	3.5	2	7	4	14	5	17.5	
COS	4	4	16	0	0	0	0	
THICKNESS	3	4	12	2	6	3	9	
OP. ENERGY (HEATING)	-	-	-	-	-	-	-	
OP. ENERGY (COOLING)	-	-	-	-	-	-	-	
EMBODIED E.	5	5	25	0	0	0	0	
CO2 EMISS.	5	4	20	3	15	0	0	
RECYCLING P.	3.3	2	6.5	5	16.3	5	16.3	
LIFESPAN & DURABILITY	3	4	12	6	18	6	18	
<b>TOTAL</b>			98.5		69.3		60.8	

TABLE 7.23 Performance of Dutch external wall designs with future considerations

	AUTOCLAVED AERATED CONCRETE EXTERNAL WALL		PERFORATED CLAY EXTERNAL WALL (UNFILLED)		PERFORATED CLAY EXTERNAL WALL (FILLED)		GRADIENT CONCRETE EXTERNAL WALL	
	AAC (C2/300)		PL-I (unfilled)		Poroton-T8-MW		Gradient Concrete	
	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* weight
	6	27	2	9	4	18	4	18
	3	14.3	2	9.5	2	9.5	0	0
	3	7.5	1	2.5	3	7.5	4	10
	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-
	5	7.5	2	3	3	4.5	0	0
	4	6	3	4.5	3	4.5	0	0
	5	10	5	10	0	0	5	10
	6	18	6	18	6	18	6	18
		90.3		56.5		62		56

	AUTOCLAVED AERATED CONCRETE EXTERNAL WALL		PERFORATED CLAY EXTERNAL WALL (UNFILLED)		PERFORATED CLAY EXTERNAL WALL (FILLED)		GRADIENT CONCRETE EXTERNAL WALL	
	AAC (C2/300)		PL-I (unfilled)		Poroton-T8-MW		Gradient Concrete	
	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight
	6	21	2	7	4	14	4	14
	3	12	2	8	2	8	0	0
	3	9	1	3	3	9	4	12
	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-
	5	25	2	10	3	15	0	0
	4	20	3	15	3	15	0	0
	5	16.3	5	16.3	0	0	5	16.3
	6	18	6	18	6	18	6	18
		121.3		77.3		79		60.3

EGYPT (CURRENT CONSIDERATIONS)										
		TRADITIONAL EXTERNAL WALL		EXPANDED CLAY CONCRETE EXTERNAL WALL		EXPANDED GLASS CONCRETE EXTERNAL WALL		AEROGEL CONCRETE EXTERNAL WALL		
				Infra LightWeight Concrete		70% Expanded Glass - 6% Cement - 24% Void		UHPC+Aerogel		
CRITERIA	Relative weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	
TIME	3.3	1	3.3	3	10	5	16.7	5	16.7	
COST	5	3	15	2	10	0	0	0	0	
THICKNESS	3.7	4	14.7	4	14.7	4	14.7	4	14.7	
OP. ENERGY (HEATING)	1.3	3	4	5	6.7	5	6.7	5	6.7	
OP. ENERGY (COOLING)	3	1	3	2	6	3	9	3	9	
E.E	1	3	3	0	0	0	0	0	0	
CO <sub>2</sub> EM.	1	3	3	2	2	3	3	1	1	
RECYCL. P.	0.7	5	3.3	5	3.3	5	3.3	5	3.3	
LIFESPAN & DURABILITY	2	6	12	6	12	6	12	6	12	
<b>TOTAL</b>			61.3		64.7		65.3		63.3	

TABLE 7.24 Performance of Egyptian external wall designs with current considerations

EGYPT (FUTURE CONSIDERATIONS)										
		TRADITIONAL EXTERNAL WALL		EXPANDED CLAY CONCRETE EXTERNAL WALL		EXPANDED GLASS CONCRETE EXTERNAL WALL		AEROGEL CONCRETE EXTERNAL WALL		
				Infra LightWeight Concrete		70% Expanded Glass - 6% Cement - 24% Void		UHPC+Aerogel		
CRITERIA	Relative Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	
TIME	4	1	4	3	12	5	20	5	20	
COST	4.3	3	13	3	13	0	0	0	0	
THICKNESS	4	4	16	4	16	4	16	4	16	
OP. ENERGY (HEATING)	2.7	3	8	5	13.3	5	13.3	5	13.3	
OP. E (COOLING)	5	1	5	2	10	3	15	3	15	
E.E	3.7	3	11	0	0	0	0	0	0	
CO <sub>2</sub> EM.	3.7	3	11	2	7.3	3	11	1	3.7	
RECYCL. P.	3	5	15	5	15	5	15	5	15	
LIFESPAN & DURABILITY	3	6	18	6	18	6	18	6	18	
<b>TOTAL</b>			101		104.7		108.3		101	

TABLE 7.25 Performance of Egyptian external wall designs with future considerations

	AUTOCLAVED AERATED CONCRETE EXTERNAL WALL		PERFORATED CLAY BRICK EXTERNAL WALL (UNFILLED)		PERFORATED CLAY BRICK EXTERNAL WALL (FILLED)		GRADIENT CONCRETE EXTERNAL WALL		LAYERED EXTERNAL WALL	
	AAC (C2/400)		Porotherm 30		Poroton-T8-MW		Gradient 2		Layered Insulating	
	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight
	5	16.7	3	10	4	13.3	3	10	0	0
	2	10	2	10	1	5	0	0	2	10
	4	14.7	4	14.7	4	14.7	4	14.7	4	14.7
	5	6.7	5	6.7	5	6.7	5	6.7	5	6.7
	3	9	2	6	3	9	3	9	3	9
	5	5	4	4	4	4	0	0	3	3
	4	4	4	4	4	4	0	0	3	3
	5	3.3	5	3.3	2	1.3	5	3.3	1	0.7
	6	12	6	12	6	12	6	12	4	8
		81.3		70.7		70		55.7		55

	AUTOCLAVED AERATED CONCRETE EXTERNAL WALL		PERFORATED CLAY BRICK EXTERNAL WALL (UNFILLED)		PERFORATED CLAY BRICK EXTERNAL WALL (FILLED)		GRADIENT CONCRETE EXTERNAL WALL		LAYERED EXTERNAL WALL	
	AAC (C2/400)		Porotherm 30		Poroton-T8-MW		Gradient 2		Layered Insulating	
	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight	Score	Score* Weight
	5	20	3	12	4	16	3	12	0	0
	2	8.7	2	8.7	1	4.3	0	0	2	8.7
	4	16	4	16	4	16	4	16	4	16
	5	13.3	5	13.3	5	13.3	5	13.3	5	13.3
	3	15	2	10	3	15	3	15	3	15
	5	18.3	4	14.7	4	14.7	0	0	3	11
	4	14.7	4	14.7	4	14.7	0	0	3	11
	5	15	5	15	2	6	5	15	1	3
	6	18	6	18	6	18	6	18	4	12
		139		122.3		118		89.3		90

## Discussions and Recommendations

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The results shown in Tables 7.22 to 7.25 give an answer to the question: *Will massive technologies with additional function provide a more successful construction for Egypt and the Netherlands (with a closer view on insulating function)?*

**For the Netherlands: Yes, additional insulating massive technologies, particularly the Autoclaved Aerated Concrete (AAC), provide, currently and in the future, more successful construction compared to the layered traditional construction.**

### Explanation

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- 1 Autoclaved Aerated Concrete is the only technology that provides significantly a better performance over the traditional layered external wall.
- 2 When compared to the traditional layered external wall, the Autoclaved Aerated Concrete provides less construction time, more recyclability potentials and longer lifespan. However, the traditional external wall provides less cost and less thickness. In terms of the embodied energy and carbon dioxide emission, they both have very close performance. In the future, with more relative weight given to the recyclability potentials, the Autoclaved Aerated Concrete is expected to score even higher than traditional layered external wall.
- 3 The new Lightweight Aggregate Concrete mixtures (Aerogel Concrete, Expanded Glass Concrete, and Gradient Concrete) score much less than the other technologies currently and in the future. This is mainly due to both their high embodied energy, carbon dioxide and price.
  - a Aerogel Concrete: The aerogel is a very expensive aggregate and contains high embodied energy and carbon dioxide emission.
  - b The Expanded Glass Concrete mixture (70% Expanded Glass - 6% Cement - 24% Void): The air entraining agent, which is used with large quantities, is expensive. As for the expanded glass aggregate, its high embodied energy and carbon dioxide emission are what contributes to the mixture high embodied energy.

On the other hand, the construction time and the external wall thickness are the factors differentiating between the performances of the new lightweight mixtures. The Aerogel Concrete scores the best among the three technologies because it requires the least construction time and the least construction thickness among the three new technologies. Then comes the Gradient Concrete with the relatively better thickness compared to the Expanded Glass Concrete. Finally, comes the Expanded Glass Concrete

having the thickest profile and the highest required construction time among the three technologies.

- 4 Unfilled Perforated Clay Brick scores the lowest performance after the Expanded Glass Concrete. This is because it requires a relatively large thickness to fulfil the required U-value. This thickness then contributes to its high embodied energy, high carbon dioxide emission and slow construction time, which result in its low performance. These factors are enhanced in the Perforated Clay Bricks with filled insulation as it provides less thickness. However the recyclability potential for the Perforated Clay Bricks with filled insulation is the lowest among all other technologies.

**For Egypt: Yes, additional insulating massive technologies, particularly the Autoclaved Aerated Concrete (AAC) similar to the Dutch case, provide, currently and in the future, a more successful construction compared to the monolithic traditional construction.**

#### **Explanation**

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- 1 Unlike the Dutch case where the traditional external wall is competitive; in the Egyptian case, all additional insulating technologies except for the Gradient Concrete provide a better performance compared to the traditional monolithic external wall. This is because when compared to the traditional monolithic external wall; additional insulating technologies provide less construction time, less operational energy in both heating and cooling, and higher recyclability potentials.
- 2 The Autoclaved Aerated Concrete when compared to all other external wall constructions provides the least construction time, the least embodied energy, the least carbon dioxide emission and the highest recyclability potentials. In the future, with more relative weight given to the embodied energy, carbon dioxide emission and recyclability potentials, the Autoclaved Aerated Concrete is expected to score higher than all the other technologies (Autoclaved Aerated Concrete is still considered a new material in the Egyptian building industry. It is not known to many architects and construction investors).
- 3 The unfilled Perforated Clay Brick technology comes in the second position after the Autoclaved Aerated Concrete technology. It scores good compared to most additional insulating technologies, mainly because of its relatively low embodied energy and low carbon dioxide emission. When compared to the unfilled Perforated Clay Bricks, the filled Perforated Clay Bricks scores less due to its lower recyclability potential and higher cost.

- 4 Similar to the Dutch case, the new Lightweight Aggregate Concrete mixtures (Aerogel Concrete and Expanded Glass Concrete) score low compared to the Autoclaved Aerated Concrete. This is due to the expected high price of their ingredients and their high embodied energy. As for the Gradient Concrete, it even scores lower than the traditional non-insulated monolithic external wall. This is because it requires higher construction cost, in addition to its high embodied energy and carbon dioxide emission.
- 5 The Expanded Clay Concrete (Infra Lightweight concrete) scores very close to the new lightweight aggregate technologies. From one side, the availability of expanded clay aggregates in the Egyptian market contributes to its relatively acceptable construction cost compared to the new lightweight aggregates. On the other side, it has a higher thermal conductivity requiring a more operational cooling energy.
- 6 The layered insulating external wall has lower overall performance compared to the traditional un-insulated monolithic external wall. Although the layered external wall provides a relatively good operational energy performance (similar to the additional insulating technologies), it has poor performances regarding construction time, embodied energy, carbon dioxide emission, recyclability potentials and lifespan and durability. This contributes to its overall poor performance.

**Moreover these results generally highlight important considerations for the different newly developed materials, if they are considered in monolithic external wall constructions:**

- 1 Aerogel Concrete: Aerogel needs cost considerations. In addition, its manufacturing process needs consideration to lower its embodied energy and carbon dioxide emission.
- 2 The Expanded Glass Concrete mixture (70% Expanded Glass - 6% Cement - 24% Void): Different air entraining agent types with lower prices may be considered. Moreover, reconsidering the aggregate manufacturing steps is important to lower its embodied energy and carbon dioxide emission.

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## § 7.5 Summary and Conclusions

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This chapter assesses different massive external wall constructions to investigate whether additional insulating massive technologies provide more successful construction compared to the traditional external wall construction in the Netherlands and Egypt. In the first part of the chapter, the different additional insulating Dutch

external walls designed in Chapter 6 are analysed and compared to the traditional Dutch layered external wall. The performance factors considered in the analysis and the main results of the analysis are outlined below:

- Construction time: Autoclaved Aerated Concrete external wall requires the least construction time, whereas traditional layered external wall requires the longest construction time.
- Construction Cost: Traditional layered external wall is associated with the least construction cost, whereas Aerogel Concrete external wall is associated with the highest construction cost.
- Embodied Energy: Traditional layered external wall provides the least embodied energy, whereas expanded lightweight aggregate construction generally provides the highest embodied energy.
- Carbon dioxide emission: The Autoclaved Aerated Concrete provide the lowest carbon dioxide emission, whereas the Aerogel Concrete provides the highest carbon dioxide emission.
- Recyclability potentials: Autoclaved Aerated Concrete external wall has the best potential for recyclability, whereas Perforated Clay Bricks with filled insulation external wall has the least potential for recyclability.
- Thickness: Gradient Aerogel Concrete external wall has the least thickness, whereas perforated clay brick has the largest thickness.
- Lifespan: Perforated Clay Brick external wall has the longest lifespan, whereas traditional layered external wall has the shortest lifespan.

In the second part of this chapter, the different additional insulating Egyptian external walls designed in Chapter 6 are analysed and compared to the traditional Egyptian monolithic external wall. The main results of considering the performance factors in the analysis are outlined below:

- Construction time: Autoclaved Aerated Concrete external wall requires the least construction time, whereas layered insulating external wall requires the longest construction time.
- Construction Cost: Traditional monolithic external wall is associated with the least construction cost, whereas Aerogel Concrete external wall and Gradient Concrete are associated with the highest construction cost.
- Embodied Energy: Autoclaved Aerated Concrete external wall provides the least embodied energy, whereas expanded lightweight aggregate construction generally provides the highest embodied energy.
- Carbon dioxide emission: Autoclaved Aerated Concrete provides the lowest carbon dioxide emission, whereas the gradient Aerogel Concrete provides the highest carbon dioxide emission.

- Recyclability potentials: Autoclaved Aerated Concrete external wall has the best potential for recyclability, whereas Perforated Clay Bricks with filled insulation external wall has the least potential for recyclability.
- Operational energy: Gradient Concrete external wall is associated with the least operational energy, whereas traditional monolithic external wall is associated with the highest operational energy.
- Lifespan: Traditional monolithic brick external wall and Perforated Clay Brick external wall have the longest lifespan, whereas layered insulating external wall has the shortest lifespan.

In the third part, a scoring system is established. First, a grading system from 0 to 6 is set for each performance. Second, a relative weight for each performance is estimated. In both the Netherlands and Egypt; the construction time, construction cost and external wall thickness are noticed to be the most important criteria for assessing external walls. However in the future; the embodied energy, recyclability potentials and operational energy will gain more importance. In addition, the results of the analysis indicate that, in both the Netherlands and Egypt, the Autoclaved Aerated Concrete is the most successful external wall technology when compared to the traditional external wall and other insulating technologies.

# 8 Conclusions and Recommendations

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## § 8.1 Introduction

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The main purpose of this research is to map the changes required to the traditional design and construction process when massive technologies with additional function are applied in external walls. Moreover, the research aims at assessing the performance of massive solutions with additional function when compared to traditional solutions. To reach these objectives, a study of massive technologies applicable to external walls has been carried out. In addition, the performance of insulating technologies applicable to external walls in the Netherlands and Egypt has been assessed.

In the following section, answers to the research questions and drawn conclusions are presented. This is followed by discussing the changes required in the construction industry to support the application of the research results. Finally, possible future related research is suggested.

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## § 8.2 Answers to Research Questions and Conclusions

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The main research questions investigated in this research and their answers are:

*What changes are required to the present traditional design and construction process if massive technologies with additional function are implemented in external walls? Will these technologies provide a more successful construction in the Netherlands and Egypt (with a closer view on insulating function)?*

Changes required to the present traditional design and construction process if massive technologies with additional function are implemented in external walls depend on two factors: the product level of additional function massive technology and its customization level. The required process changes are presented in the graph of Figure 8.1.

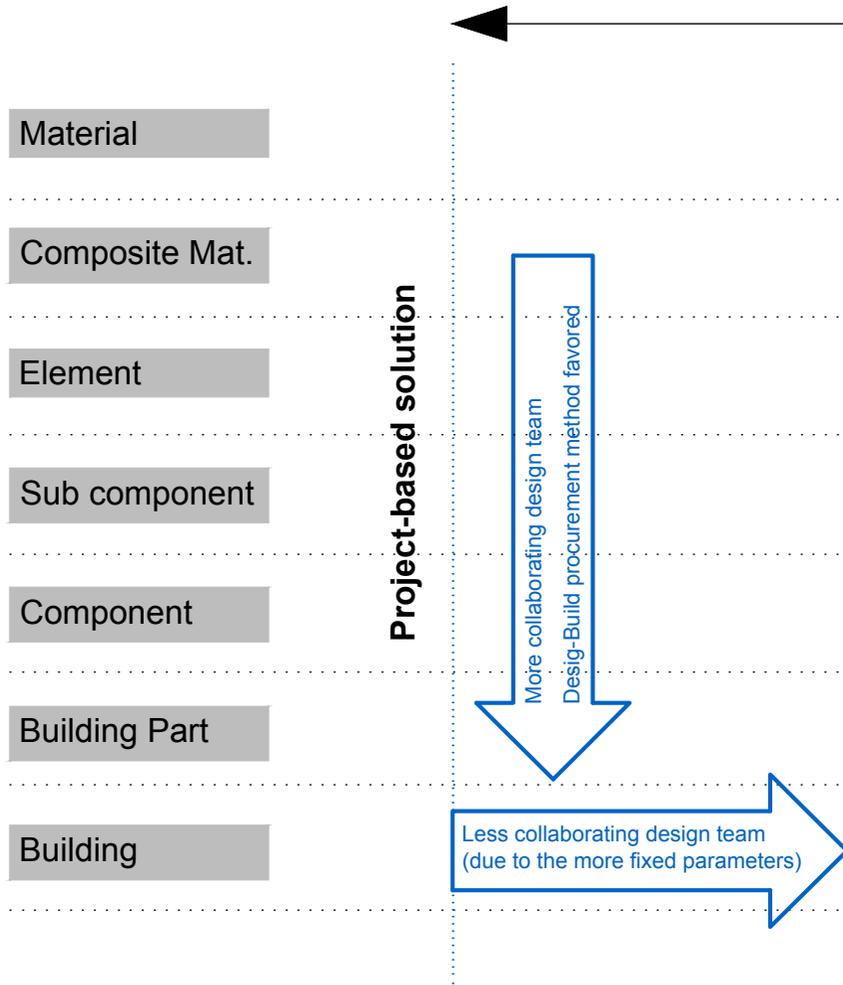
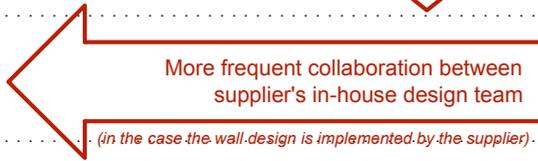


FIGURE 8.1 Recommended changes to design and construction process as related to the Product level and Customization level of addition functional massive technology

Customization level



Product-based solution



Recommended changes for the supplier (supplier solution)



Recommended changes for the design team (design team solution)



With a closer look on insulation technologies, additional insulating massive technologies will provide a more successful construction when compared to the traditional construction in both the Netherlands and Egypt. This general conclusion applies particularly to the Autoclaved Aerated Concrete technology.

In the following paragraphs, the steps of carrying out the research and conclusions drawn from each step are presented. The purpose of each step, presented in a separate chapter, is first stated in the form of a question followed by a summary of carried-out study and drawn conclusions.

## Chapter 2:

### *How traditional walls progressed in the Netherlands and Egypt?*

---

The massive external walls developed differently in the Netherlands and Egypt.

In the Netherlands, the traditional external wall had been known in ancient times to be monolithic and of a single layer of masonry construction. However by time, more functions needed to be fulfilled by the external wall, and the techniques for erecting the traditional external walls changed. It was developed through several stages into several sub-systems, each having a separate purpose and identity. The massive layer, which originally fulfilled all the external wall functions, became fulfilling mainly the load bearing function of the wall. Many typologies of massive external walls can be found nowadays in the Netherlands. However, the cavity wall partially filled with thermal insulation is the most commonly used massive wall typology.

In Egypt, the wall development was different. The former traditional external wall was part of a passively controlled system that worked integrally together to provide a controlled climate and an environmental-friendly construction. The passive system included Courtyards, Malkaf (wind catchers), and thick Walls. However, by time and passing through multiple changes, the massive external wall became a separate system that is merely responsible for the enclosure function (fire and sound). Few massive wall typologies are seen in Egypt. However, the single leaf masonry wall with renderings on both sides is the commonly used external wall typology.

### Chapter 3:

*How can a method be developed to analyse and understand external walls with additional function and their design and construction process?*

---

Two schemes can be developed to help understanding the different massive external walls: the component-function scheme, and the process scheme.

The component-function scheme, which is based on the theory of product architecture from the manufacturing industry, maps external wall components and their indented function in a structured way. The scheme involves two main aspects. The first aspect is the different product levels of the external wall components. The product level ranges from building materials to a complete building. The second aspect is the different functions the external wall performs. The scheme aims at showing the physical changes occurring to the external wall when functions are added or removed in the external wall construction.

The process scheme shows the effect of the functional changes on the design and construction. The scheme involves two main aspects. The first aspect is the different involved parties in the process. The second aspect is the different design and construction phases. This scheme is developed based on relevant literature, together with the author's experience as an architect. The scheme aims at showing the different involved parties in the different process stages and how design decisions are made.

According to the schemes, the analysis of the traditional Dutch and Egyptian external walls shows the following outcome. The Dutch traditional massive external wall shows a modular behaviour in its component-function behaviour. This leads to a layered external wall profile and a separate design decision process for its components. The Egyptian external wall shows a different behaviour. Due to its simple functions, the wall construction consists of a simple single-leaf monolithic construction. Accordingly, a simple design process with fewer decisions and fewer involved parties results, compared to the traditional Dutch external wall.

### Chapter 4:

*What are the existing and new massive technologies with additional function?*

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Eight different existing and new additional technologies can be identified. These technologies can provide different external wall functions and can be listed as follows:

- Lightweight Aggregate Concrete, which may vary in the type of aggregate used, Aerated Concrete, and Perforated Clay Bricks provide an additional insulating function.
- Air Permeable Concrete provides an additional ventilating, heat exchanging and filtration function.

- PCM Concrete provides an additional thermal storage function.
- Thermally Activated Massive Walls provide an additional heating/cooling function.
- Translucent Concrete provides an additional light transmitting function.
- Gradient Concrete provides different additional functions based on the type of concrete used.

The study of the different technologies shows that the beginning of the twenty-first century has witnessed the development of many new massive technologies with additional function. Most of these technologies are developed in the field of concrete and cementitious materials.

All the listed technologies provide a potential for being used in external walls. However, they may not be all fully developed for being applied in external walls. Some of these technologies, such as the Aerogel Concrete, Air Permeable Concrete and Gradient Concrete still require more research and development in order to be fully developed for their intended external wall functions.

## Chapter 5:

*What changes are required to the traditional design and construction process if massive technologies with additional function are implemented in external walls?*

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Similar to product architecture theory from the manufacturing industry, the product architecture of the external wall and the way functions are related to components affect the external wall's design and construction behaviour. However, changes required to the traditional design and construction process can vary according to two factors. First is the product level in which the additional function occurs. This can range from material integral solutions to element integral solutions or to component integral solutions. Second is the degree of customization of the solution in the project. This can range in two extreme forms: from project-based solution completely tailored to the project requirements, to product-based solution completely designed independent from the project requirements. According to these two factors, a guidance scheme showing the expected process changes can be developed. The scheme can be helpful for different stakeholders.

For the case of design team based solutions, the positioning within the scheme determines the degree of collaboration level between the design team and the type of procurement method. For the case of suppliers based solutions, the positioning within the scheme determines the level of change in the company's market and sales vision, the level of knowledge of the supporting team, and the level of changes in the supply chain organization.

For the case of design team based solutions, moving from material level to component level solution requires two changes within the process. First is the need for a more collaborating design team in the project design phases. Second is the need for the contractor's involvement in the design stage. This can make the Design-Build procurement method a more favoured method over the traditional Design-Bid-Build method. On the other hand, moving from open design parameters (with high degree of customization) towards more fixed design parameters (with low degree of customization) requires less collaborating design team.

For the case of supplier based solutions, moving from material solutions to component level solution requires three changes from the supplier's side. First, more changes within the company's market and sales vision need to take place. Second, the company needs to acquire more design knowledgeable supporting team. Finally, more organizational changes within the company in the supply chain need to take place. On the other hand, moving from fixed design parameters (with low degree of customization) to more open design parameters (with high degree of customization) requires more frequent collaboration between the supplier's in-house design team.

#### Chapter 6:

*How can additional insulating massive external wall technologies be compared with the traditional massive external walls in the Netherlands and Egypt?*

---

In order to compare additional insulating massive external wall technologies with the traditional external walls in Netherlands and Egypt, two factors need to be considered. First is to design comparable external walls. Second is to define the aspects and criteria for comparison between the different external walls.

To design comparable external walls, the typical building of each context needs first to be defined. In Egypt, the typical building is defined to be an apartment building of four floors with non-load bearing external walls and of concrete construction. In the Netherlands, the typical building is defined to be row houses of three floors with load-bearing external wall of 100 kN/m and of concrete construction. Second, the rules and regulations that affect the external wall design for each context needs to be determined.

Due to the differences between the two contexts in both the typical building selected and the rules and regulations in each context, the wall designs using different additional insulating massive external wall technologies in Egypt and the Netherlands are different. The external wall designs for the Dutch cases result in different external wall thicknesses due to the necessity of fulfilling the minimum required U-value by the building code. The external wall designs for the Egyptian cases result in different

external walls with different materials but having a constant thickness of 25 cm similar to the traditional monolithic external wall.

As for the measuring criteria; construction time, construction cost, wall thickness, operational energy, embodied energy, carbon dioxide emission, recyclability and reuse potential, and lifespan are noted to be the most appropriate criteria to be used in assessing the different wall designs in the Netherlands and in Egypt.

## Chapter 7:

### *How do the additional insulating massive external walls perform in comparison with the traditional massive external walls?*

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For both the Netherlands and Egypt, the Autoclaved Aerated Concrete is more successful than the traditional external wall construction. Even with the expected future considerations, the Autoclaved Aerated Concrete shows better performances. However, on a more detailed level, the results revealed the following performances:

#### **For the Dutch external walls:**

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- Construction time: Autoclaved Aerated Concrete external wall requires the least construction time, whereas traditional layered external wall requires the longest construction time.
- Construction Cost: Traditional layered external wall is associated with the least construction cost, whereas Aerogel Concrete external wall is associated with the highest construction cost.
- Embodied Energy: Traditional layered external wall provides the least embodied energy, whereas expanded lightweight aggregate construction generally provides the highest embodied energy.
- Carbon dioxide emission: Autoclaved Aerated Concrete provide the lowest carbon dioxide emission, whereas Aerogel Concrete provides the highest carbon dioxide emission.
- Recyclability potentials: Autoclaved Aerated Concrete external wall has the best potential for recyclability, whereas traditional layered external wall has the least potential for recyclability.
- Thickness: Gradient Aerogel Concrete external wall has the least thickness, whereas perforated clay brick has the biggest thickness.
- Lifespan: Perforated clay brick has the longest lifespan, whereas traditional layered external wall has the shortest lifespan.

### For the Egyptian external walls:

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- Construction time: Autoclaved Aerated Concrete external wall requires the least construction time, whereas layered insulating external wall requires the longest construction time.
- Construction Cost: Traditional monolithic external wall is associated with the least construction cost, whereas Aerogel Concrete external wall and Gradient Concrete are associated with the highest construction cost.
- Embodied Energy: Aerated Autoclaved Concrete external wall provides the least embodied energy, whereas expanded lightweight aggregate construction generally provides the highest embodied energy.
- Carbon dioxide emission: Autoclaved Aerated Concrete provides the lowest carbon dioxide emission, whereas gradient Aerogel Concrete provides the highest carbon dioxide emission.
- Recyclability potentials: Autoclaved Aerated Concrete external wall has the best potential for recyclability, whereas layered insulating external wall has the least potential for recyclability.
- Operational energy: Gradient Concrete external wall is associated with the least operational energy, whereas traditional monolithic external wall is associated with the highest operational energy.
- Lifespan: Traditional monolithic brick construction and perforated clay brick have the longest lifespan, whereas layered insulating external wall has the shortest lifespan.

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## § 8.3 Required Changes in the Construction Industry

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Some steps are required in order to implement the research results, particularly the second part of the research question which states that Autoclaved Aerated Concrete is the best technology for both the Netherlands and Egypt.

In the Netherlands, Autoclaved Aerated Concrete is already available but not considered as the common construction technology. Therefore, the following steps are required:

- 1 Raising the awareness of architects and decision makers about the holistic benefits/ performances of Autoclaved Aerated Concrete is an important step. At this stage, this awareness should be led by research institutes and governments. Governments should encourage the use of the technology through for example providing a faster track approval to developers and decision makers adopting this technology. The marketing role of the suppliers in this awareness becomes also important.

- 2 On the other hand, highlighting the drawbacks of other additional function technologies indicates the areas where technology suppliers and developers need to focus in order to compete in the field of external walls:
  - For Expanded Glass Concrete, the embodied energy and carbon dioxide emission incorporated with the production of the expanded glass aggregates needs to be enhanced. Moreover, the cost incorporated with the air entraining agent used needs to be considered.
  - For Aerogel Concrete, the price of Aerogel needs to be reduced.
  - For Perforated Clay Bricks, the embodied energy incorporated with the production of the bricks needs to be reduced.
  - For Perforated Clay Bricks with filled insulation, the issue of recyclability needs to be considered.

In Egypt, since Autoclaved Aerated Concrete is not known in the market, the required moves become different than in the case of the Netherlands:

- 1 Applying the technology requires not only the awareness of architects and decision makers, but also encouraging the investors to invest in producing such technology locally.
- 2 The government should provide new building codes that support this type of technology.
- 3 Similar to the Dutch governmental encouragement, the Egyptian government should support and facilitate the use of Autoclaved Aerated Concrete through, for example, faster track approval and/or taxes reduction. The governmental support in the Egyptian case is important as incorporating integral insulating technologies will contribute to solving the energy problem in Egypt.
- 4 Unlike the Netherlands where only AAC is better than the other technologies, in Egypt, all the additional function technologies, except for Gradient Concrete, are better than the traditional external wall system. This makes Egypt a good market for all those additional function technologies. Applying any of these technologies requires considering the previously mentioned points. However, in order for these technologies to overcome the performance of Autoclaved Aerated Concrete, they also need to enhance/consider specific performances (as mentioned in Point 2 in the Netherlands required steps)

## § 8.4 Possible Future Related research

The following recommendations for future research are based on the findings of the present study:

### Assessing the technologies highlighted in Chapter 4 (Integral non-insulating walls)

Only insulating massive technologies were analysed in terms of their holistic performance in Chapter 7 due to the high degree of uncertainties of other technologies, being new, in addition to the limited timeframe of this research. Other additional function technologies highlighted in Chapter 4 needs to be further analysed with respect to their construction time, cost, embodied energy, carbon dioxide emission, operational energy, recyclability potentials and total thickness.

In spite of the absence of the assessment of the exact performance of such technologies, it is expected that the complexity of such systems will reflect negatively on:

- The construction time as it will require more time to be assembled on-site.
- The initial construction cost.
- The architecture of the building as they may influence its appearance by increasing wall thicknesses, or putting limitation on finishing surfaces.

### Additional function technologies for other building components

This research dealt merely with massive additional function technologies focusing on external walls. A similar study on additional function technologies, but applied to other massive building components, such as the building structure, can generate interesting results.

### Appropriateness of each technology (cases in which each technology fits best?)

This study mainly focused on the process changes when massive technologies with additional function are implemented in external walls. It did not discuss in which cases each technology becomes suitable for being implemented. A study on cases in which each technology fits is important to encourage the application of additional functional massive technologies and assist the decision makers.

### Incorporating the client's concerns and users' concern to the scheme

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The guidance scheme mainly focused on the design and construction process aspects as related to the product level and customization level. Incorporating other aspects like the client's interests in terms of budget and time to the graph is possible in future studies. Moreover, incorporating the users concerns such as the psychological effect on the users can be considered in future studies.

### Testing and Experiments for new potential technology materials

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Many new material technologies and mixtures such as Aerogel Concrete and Air Permeable Concrete provide preliminary potential for being used in external walls. Accordingly, they were selected in this research in different wall designs. Reference materials had to be used as many properties of these materials are not available in the literature due to their newness. However, in order to realistically apply these technologies in external walls, more testing and experiments in different fields are still required. These tests and experiments include sound tests, fire tests, and drying shrinkage tests.

### Onsite casting for additional function technology materials

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Different materials have been studied based on masonry application, which is the typical wall format in the Netherlands and Egypt. A study of their onsite casting possibilities, as well as performances of these technologies, may provide interesting results for external wall construction as well as for other building components.

### Reinforcement potentials for new potential technologies

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In some cases, reinforcement of walls may be required. This may be essential for walls subjected to strong lateral forces or in the case of onsite casting. The study of the behaviour of the new materials with different reinforcements is important to widen their fields of application for walls and other building components.

### Mortar behaviour

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The study of mortar behaviour, especially for new lightweight material blocks (like Aerogel), is essential. In this study and for the sake of simplicity, it was assumed that normal mortar or glue can work. However, the mortar behaviour in case of the lightweight blocks needs to be researched through special tests and experiments.

### Mass production of new technology materials

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Many new technology materials; such as Air Permeable Concrete, Aerogel Concrete, and Expanded Glass mixture; depend in their production on small scale sampling setup. A study on their production on a much larger scale (mass production) will likely provide more accurate results related to their performances; especially their possible production difficulties, embodied energy, carbon dioxide emission and cost.



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# Summary

It is believed that the basic construction materials used in creating human shelters over several millennia were acquired from earth and plants in all parts of the world. They were used according to the climatic conditions and their availability. As society developed, the building requirements exceeded the capabilities of these primitive shelters giving the rise to massive walls constructed from heavy materials. This gave more security and protection against outdoor conditions.

Brick and stone were the materials used in walls. They were used in a monolithic form. However, with the rise in quality of life, the massive walls alone became incapable of fulfilling all the developed needs. Adjacent systems and layers had then to be attached to the massive layer and the massive layer became responsible for fewer functions.

Nowadays, each external wall function is usually represented by a separate layers or systems. Such layers or systems are designed be separate entities in a more fragmented design and construction process. However, new massive technologies with additional function have recently become available. Such technologies can provide the external wall with more functions. These technologies will affect the traditional fragmented design and construction process. The thesis has three objectives. First is *Identifying and exploring new massive technologies with additional function for external walls*. Second is *mapping process changes when massive technologies with additional function are considered for external walls*. Third is *assessing the performance of massive solutions with additional function compared to that of traditional solutions*.

**Chapter 2** describes the development of the traditional massive external wall in two different contexts, the Netherlands and Egypt. In the Netherlands, the traditional external wall that has been known to be monolithic transformed with time into several sub-systems, each having a separate purpose and identity. Nowadays the cavity wall partially filled with thermal insulation is the most commonly used massive wall typology in the Netherlands. In Egypt, the former traditional external wall that has been part of an integral building system became a separate building element. Nowadays the single leaf masonry wall with renderings on both sides is the commonly used external wall typology.

**Chapter 3** provides a method for analyzing the design and construction process of different massive external walls. Two schemes are developed for the analysis. First is the component-function scheme which maps external wall components and their intended functions in a structured way. The scheme is based on the theory of product architecture from the manufacturing industry. Second is the design and construction process scheme which shows the different involved parties in the different external

wall construction stages and how design decisions are made. The scheme is based on relevant literature together with the author's experience as an architect.

**Chapter 4** provides the state of the art for massive technologies with additional function. Eight technologies providing different additional functions were highlighted and explained. This included, Lightweight Aggregate Concrete, Aerated Concrete, and Perforated Clay Bricks providing additional insulating functions; Air Permeable Concrete providing additional ventilating, heat exchanging, and filtration functions; PCM Concrete providing additional thermal storage functions; Thermally Activated Massive Walls providing additional heating/cooling functions; Translucent Concrete providing additional light transmitting functions; Gradient Concrete providing different additional functions based on the concrete type used.

In **Chapter 5** the overviewed technologies are analysed in external wall construction as per the developed schemes of Chapter 3. The analysis shows the design and construction process changes required in the traditional design and process when massive technologies with additional function are implemented in external wall. That was presented in a guidance scheme for different stakeholders which shows the expected process changes as related to the product level and customization level.

The first part of **Chapter 6** focuses on designing comparable additional function massive external walls for the two contexts, the Netherlands and Egypt. Only additional Insulating massive technologies are taken into consideration. In order to reach those comparable designs, first, the typical building in each context was defined. That was followed by defining the regulations, which could affect the external wall design, in each context. Accordingly, five different additional insulating massive walls were designed for the Netherlands. As for Egypt, six different insulating massive walls were designed.

In the second part of Chapter 6, the criteria for wall assessment were defined. Construction time, cost, wall thickness, operational energy, embodied energy, and recyclability and reuse potential are noted to be the most appropriate criteria to be used in assessing the different wall designs.

The analysis of the different insulating wall technologies is presented in **Chapter 7**. The results show that for both, the Netherlands and Egypt, the Autoclaved Aerated Concrete is the most successful external wall technology when compared to the traditional external wall and other insulating technologies.

The final **Chapter 8** 'Conclusions and Recommendations' summarize the research results, discusses the changes required in the construction industry to support the application of the research results, and highlights potentials for possible future related work.

# Samenvatting

De meeste constructiematerialen, die de afgelopen millennia voor huisvesting gebruikt zijn, waren afkomstig van wat beschikbaar was op aarde, zoals stenen en hout. Welke materialen precies gebruikt werden was afhankelijk van de klimatologische omstandigheden en de beschikbaarheid. Toen de maatschappij zich ontwikkelde, waren deze zogenaamde primitievere materialen niet afdoende voor de eisen die aan de gebouwde omgeving werden gesteld. Dit had tot gevolg dat wanden uit zwaardere materialen werden geconstrueerd, welke ook meer bescherming boden tegen invloeden van buiten.

Voor wanden werden baksteen en natuursteen in een monolithische bouwwijze gebruikt.

Alhoewel de levenskwaliteit door de massieve wanden verbeterde, konden de wanden alleen niet aan alle toenemende eisen voldoen. Het gevolg was dat extra functionele lagen bevestigd moesten worden aan de massieve wanden. De massieve wand verloor hierdoor een deel van zijn functies.

Tegenwoordig is bij veel bouwwerken elke afzonderlijke functie in een gevelpakket door een individuele laag vertegenwoordigd. Deze lagen of complete systemen, zijn vaak op zichzelf staande delen die los van elkaar ontwikkeld zijn. Daarentegen zijn sinds kort massievere constructies met extra functionaliteit beschikbaar. Deze nieuwe productgroep bestaat uit producten die de massieve wand van extra functies voorzien, welk op hun beurt het traditionele ontwerp- en bouwproces beïnvloeden.

Deze dissertatie heeft drie doelen. De eerste is: het identificeren en onderzoeken van nieuwe massieve buitenwandtechnologieën die toegevoegde functies hebben. De tweede is: Het in kaart brengen van procesveranderingen die optreden als voor buitenwanden massieve technieken worden toegepast. En ten derde: De prestaties van deze massieve technologieën in buitenwanden in vergelijking tot traditionele constructiewijzen.

**Hoofdstuk 2** beschrijft de ontwikkeling van de traditionele massieve buitenwand in twee verschillende contexten, Nederland en Egypte. In Nederland heeft de traditionele monolithische massieve buitenwand zich getransformeerd in één bestaande uit subsystemen. Elk subsysteem heeft hierin zijn eigen identiteit en functie. De meest gebruikte massieve wand in Nederland is de zogenaamde geïsoleerde spouwmuur. In Egypte was de traditionele wand deel van een integraal bouwsysteem dat zich zo ontwikkelde dat het meerdere separate bouwdelen werden. Tegenwoordig is een halfsteens wand met aan beide zijden pleisterwerk de gangbare bouwwijze.

**Hoofdstuk 3** beschrijft een methode om de productie- en constructiemethoden voor de verschillende massieve buitenwanden te analyseren. Twee schema's worden voor deze analyse gebruikt. De eerste is een component - functie schema, dat de relatie beschrijft tussen de componenten van de wand en de functies die deze zouden moeten vervullen. Het is gebaseerd op het idee van architectonische standaardproducten in de bouwindustrie. Het tweede schema, het ontwerp en bouwschema, toont de verschillende betrokken partijen in de planningsfase van de massieve wand en hoe ontwerpbeslissingen genomen worden.

**Hoofdstuk 4** toont de state-of-the-art massieve wanden en hun functies. Acht verschillende toegevoegde functies worden beschreven en uitgelegd. Hieronder: lichtgewicht aggregaatbeton, cellenbeton en geperforeerde kleiachtige stenen, die in extra isolatie kunnen voorzien; luchtdoorlatend beton dat in extra ventilatie, in warmte-uitwisseling en in een filterende functie kan voorzien; pcm beton dat extra thermische energie kan opslaan; thermisch geactiveerde massieve wanden die voorzien in verwarm- en koelbehoeften; doorzichtig beton dat voorziet in extra lichttoetreding; gradiënt beton dat naar gelang van het soort beton dat gebruikt is, in verschillende extra functies kan voorzien.

In **hoofdstuk 5** worden de technieken voor de buitenwanden geanalyseerd volgens de schema's van hoofdstuk 3. De analyse zet de wijzigingen in ontwerp en verwerkingsmethoden, die nodig zijn om extra functies in de massieve buitenwand te implementeren, uiteen. Dit wordt getoond in een schema met advies voor de verschillende belanghebbenden. Het schema toont ook de verwachte veranderingen in het productieproces gerelateerd aan de mate van individualisering.

Het eerste deel van **hoofdstuk 6** focust op het ontwerp van twee bijna gelijke massieve buitenwanden die in Nederland en Egypte toegepast kunnen worden. Alleen extra isolatie als toegevoegde functie voor de massieve technieken is uitgewerkt in het ontwerp. Om vergelijkbare ontwerpen te kunnen maken, is eerst elk gebouw in zijn context gedefinieerd. Hierna zijn de betreffende bouwbesluiten die van toepassing zijn en die het ontwerp beïnvloeden gedefinieerd. Als resultaat hiervan zijn voor Nederland vijf en voor Egypte zes verschillende massieve wanden ontworpen.

In het tweede deel van hoofdstuk 6 worden de criteria voor de beoordeling gedefinieerd. Bouwtijd, kosten, constructiedikte, energiebehoefte tijdens gebruiksfase, embodied energy, recyclebaarheid en hergebruik zijn de criteria om de verscheidene ontwerpen te beoordelen.

De analyse van de verschillende geïsoleerde wanden wordt in **hoofdstuk 7** beschreven. De resultaten wijzen erop dat voor beide locaties, Nederland en Egypte, de cellenbetonwand de beste prestatie had vergeleken met traditionele, geïsoleerde wandsystemen.

In het laatste hoofdstuk, **hoofdstuk 8**, 'Conclusies en aanbevelingen' wordt het onderzoek samengevat, worden de aanpassingen die nodig zijn om de resultaten van het onderzoek te gebruiken in de bouwindustrie besproken en worden eveneens mogelijkheden voor toekomstig onderzoek uiteengezet.



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## Chapter 1

Figure 1.1: Rockwool dk

## Chapter 2

Figure 2.1: Alethe

Figure 2.3: Käthe und Bernd Limburg

Figure 2.6: Erebus and Tony Hisgett

Figure 2.8: Victoria and Albert Museum

Figure 2.12: Chatmouettes

Figure 2.13: Charlesdrakew

Figure 2.17: Nour el Refai

Figure 2.18: Hassan Fathy

Figure 2.19: Hassan Fathy

Figure 2.20: Marwa Dabaieh

Figure 2.21: Hasnain

Figure 2.22: Marwa Dabaieh

Figure 2.29: Xella

Figure 2.30: Xella

## Chapter 4

Figure 4.1: Vmenkov

Figure 4.2: Romary

Figure 4.3: AsMeskens

Figure 4.5: Fruggo

Figure 4.6: Elgewen

Figure 4.7: BjoernEisbaer

Figure 4.8: Ralf Lotys

Figure: 4.11: Thomas Dix

Figure 4.13: Lutz Artmann, Berlin

Figure 4.15: [www.saviozfabrizzi.ch](http://www.saviozfabrizzi.ch)

Figure 4.21: Marco Bernardini

Figure 4.22: Ansgar Walk  
Figure 4.23: Xella  
Figure 4.24: www.bre.co.uk  
Figure 4.26: Kozuch  
Figure 4.29: Wienerberger  
Figure 4.32: Hermann A.M. Mucke  
Figure 4.33: Hpschaefer  
Figure 4.34: Xella  
Figure 4.35: KS-QUADRO Bausysteme GmbH  
Figure 4.36: Wienerberger  
Figure 4.39: Basf  
Figure 4.40: Michal Pomianowski  
Figure 4.45 (a): Ole Daniels and Jesper Nørgaard  
Figure 4.45 (b): Danish Technological Institute  
Figure 4.49: BigRiz  
Figure 4.52: Luxgineer

## Chapter 5

Figure 5.31: Lionel Allorge  
Figure 5.34: KS-QUADRO Bausysteme GmbH

## Appendix 1 Air Permeable Concrete

### Properties of Air Permeable Concrete (0.53–0.55 natural packing density) with different formulations

[Based on laboratory tests by Imbabi (Wong, Glasser, & Imbabi, 2007)]

Water/cement weight ratio	Degree of filling	Strength (MPa)	Averaged permeability (m <sup>2</sup> /Pa h)	Averaged concrete porosity
0.25	0.5	10.8	0.6	0.32
0.25	0.6	18.2	0.32	0.28
0.25	0.7	25.0	0.18	0.22
0.3	0.5	10.7	0.6	0.32
0.3	0.6	15.3	0.32	0.28
0.3	0.7	21.0	0.18	0.22
0.35	0.5	8.5	0.6	0.32
0.35	0.6	12.7	0.32	0.28
0.35	0.7	15.1	0.18	0.22

TABLE 8.1 Properties of Air Permeable Concrete with different formulations

### Coefficient of Performance of Air Permeable Concrete

[from the work done by Ole Daniels and Jesper Nørgaard (Daniels & Nørgaard, 2011)]

Coefficient of performance (COP) indicates how efficient the solution is regarding the energy performance. COP for heat pumps operating in office buildings is up to 4-5, which very efficient. In order for Air Permeable Concrete to be efficient, it has be higher than the 4-5 value of the heat pump.

The dynamic heat capacity of Air Permeable Concrete is noted to be 281 kJ/m<sup>2</sup> K with an air flow of 15 l/s m<sup>2</sup> and a heat exchanger efficiency of 0.80. (Depending on the heat exchange efficiency, the air will gain/ lose temperature when passing through the concrete, have the same temperature as the concrete is corresponding heat exchange efficiency = 1.00.)

Imbabi achieved permeability of 0.18-0.60m<sup>2</sup>/Pa h.

These values are used to calculate the electrical power needed to achieve the desired air flow rate. Based on Darcy's law, the pressure difference is calculated as follows:

$$\Delta p = \frac{A}{Q} \cdot \frac{L}{k}$$

- $\Delta p$**  Pressure difference across object [Pa]
- A** Inlet surface area [m<sup>2</sup>]
- q** Air flow rate [m<sup>3</sup>/s]
- L** Thickness of treated object [m]
- k** Permeability [m<sup>2</sup>/Pa h]

The pressure difference is the only variable in this scenario. The electrical energy required to drive the air is calculated from the following equation with fan efficiency = 0.80.

$$E_p = \frac{\Delta p \cdot q}{\eta} \cdot t$$

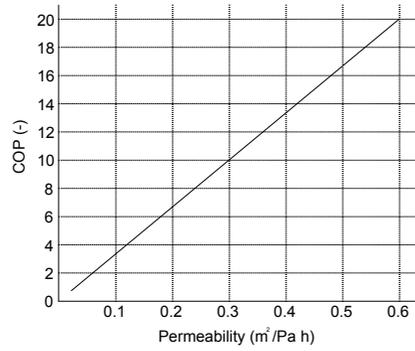
- $E_p$**  Electrical power [J]
- $\eta$**  Fan efficiency [-]
- t** Time [s]

The coefficient of performance is then calculated from the energy transferred to the concrete in relation to the energy used to drive the air as shown in following equation.

$$COP = \frac{E_{con}}{E_p}$$

- $E_{con}$**  Energy transferred to concrete element [J]

With permeability values of 0.18, 0.32 and 0.60m<sup>2</sup>/Pa h in permeability and duration of 12 h period, COP-values are 5.8, 10.3 and 19.3 respectively. These values are all greater than the COP of a normal heat pump (which has a value of 4-5), indicating the efficiency of this solution when all parameters are constant. When all parameters are constant the relation between permeability and COP is linear as shown in the following diagram.



The graph shows that relatively small permeability (higher than  $0.15 \text{ m}^2/\text{Pa h}$ ) can provides COP higher than the 5 of the heat pump.



## Appendix 2 Interviews

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### Correspondence form – For implemented projects

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The interview is conducted as part of the PhD project “Integrating Building Functions into Massive External Walls” at the Façade Research Group/ TU Delft.

#### General Information

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*Interviewed expert:*

*Position:*

*Project/ technology involved:*

*Date of interview/ correspondence:*

#### General questions

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- 1 What was the motivation behind using this type of technology in the project?
- 2 Why do you think this technology is not commonly used when compared to the traditional wall construction?

#### Process questions

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- 1 In terms of design, which disciplines were involved in the design of the external wall?
- 2 What kind of design input did you need from other disciplines in order to proceed with your design tasks?
- 3 What other design decisions were made (maybe by other disciplines) in order to reach this design?
- 4 Did the technology require special simulation programs?
- 5 Did the technology require special engineering skills?
- 6 Did the contractors face difficulties in applying this technology? If yes, what are they?

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## Correspondence form – For new technologies

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The interview is conducted as part of the PhD project “Integrating Building Functions into Massive External Walls” at the Façade Research Group/ TU Delft.

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### General Information

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*Interviewed expert:*

*Position:*

*Technology involved:*

*Date of interview/ correspondence:*

---

### General questions

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- 1 Are you familiar with this technology? Have you ever been involved in using it?
- 2 Do you feel it can be promising for external walls?

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### Process questions

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If this technology is to be implemented in external walls:

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- 1 In terms of design, which disciplines will be involved in the design of the external wall?
- 2 What kind of design input will you need from other disciplines in order to proceed with your design tasks?
- 3 What other design decision will need to be made (maybe by other disciplines) in order to reach this design?
- 4 Will the technology require special simulation programs?
- 5 Will the technology require special engineering skills?
- 6 Will the contractors face difficulties in applying this technology? If yes, what are they?

## Appendix 3 Design Process in an Integrated External Wall: Zollverein Design School Project

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### Abstract

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Through the last decades, the external wall industry has witnessed significant development. New materials were introduced, energy performances were enhanced, and new functions were added. But on the other hand, the industry is still depending on scattered decisions taken by scattered disciplines. Every specialist is concerned with certain aspects related to his discipline, which results mostly in a final product composed of many layers, each representing a function. More functions means more layers.

This strategy doesn't give possibilities for integrated solutions (more functions with fewer parts). Implementing integrated solutions requires, then, a design process that differs from the traditional scattered decision-making process.

The Zollverein School discussed in this paper is a project with an integrated external wall solution. Through observing the decisions taken in its design, we can understand how this integrated solution had an uncommon design process. Problems, solutions and decisions, in every stage had to be shared among all specialists, unlike the traditional scattered method.

The project is analyzed as one of the case studies in the research project "Integrating building services into solid external walls". The research aims to enhance the external walls through proposing new integrated design solutions for massive external walls.

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## Introduction

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The building envelope has witnessed significant development in the last decades in terms of materials and energy performance. In addition, new functions and services are continuously added to the external wall as the users' demands increase. But with all of these developments, the industry is still depending on scattered decisions made by scattered disciplines. The architect is usually concerned with the finishing material, the structural engineer is concerned with the wall structure and thickness, the climate engineer is concerned with the material and thickness of insulating material, and the mechanical, electrical and plumbing engineers are concerned with building services added or embedded in the wall. For the most part, no one interferes in the decision made by others. This has resulted in the common layered system we are used to nowadays.

Uncommonly, the Zollverein Design School is a project that came with an external wall solution different than the normal layered external wall. The project's minimal design approach led to a slim integrated external wall. The design process was also unique. The following paragraphs will discuss the Zollverein School based on an interview with Holger Techen who was involved as a structural engineer in the project.

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## Zollverein School: General project description

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The Zollverein School of Management and Design in Essen Germany is a teaching and research institution that works with local and regional project partners on business, management and design research. The design of the school is based on a design competition that was won by SANAA Architects from Tokyo. The design is based on an extremely minimal design approach represented in the use of simple geometries that was influenced by the simplicity of the surrounding industrial buildings.

The design provided by the architect in the competition was an oversized cube, which measures 35 meters, by 35 meters, by 35 meters. The external wall was a 25 cm single skin fair-faced concrete external wall with glass windows that look like they were randomly thrown on to the external wall. However, they were very carefully placed in order to achieve optimum lighting (Fig. 2). For flexibility, the floor plans were open and undivided, only enclosed by the external walls, which gave the external wall a structural importance in the project (Fig. 1).

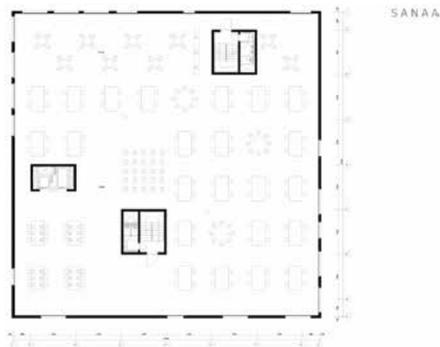


FIGURE 1 Zollverein School: first floor plan



FIGURE 2 Zollverein School: exterior view

## Reasons for adopting an integrated external wall solution in Zollverein Design School

As mentioned earlier, the initial model represented by the architect in the competition was based on an external slender wall of thickness 25 cm with rough concrete finishing on both sides, the inner and the outer (Fig. 3). In the design development stage, it was confirmed that the 25 cm external wall was sufficient from the structural aspect, however, it was not sufficient from the climate aspect: at least 18 – 20 cm thick insulation layer was essential.

The first traditional solution, then, was a typical double-skin fair faced concrete wall with external concrete layer 12 cm thick, core insulation 18 – 20 cm thick, and an inner concrete surface of about 25 cm thick. This solution resulted in a 50 – 55 cm wall (Fig. 4). Although the wall thickness significantly increased, a more serious problem was raised, which is the expansion joints. In such case, the expansion joints were mandatory in the outer concrete layer, and that was totally refused by the architect. The monolithic concrete surface was a basic requirement in the project.

In order to get rid of the expansion joints, there was a necessity to thicken the outer concrete layer from 12 cm to 25 cm. That was essential in order to overcome stresses on concrete due to temperature, however, the inner wall may have been reduced to 12 cm (Fig. 5). In such solution, special fixation with stainless steel joints was required between the two concrete walls, which raised the cost significantly, and was consequently refused.



FIGURE 3 Architect's proposed external wall

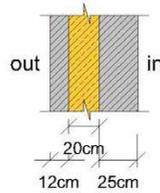


FIGURE 4 First solution (design development stage)

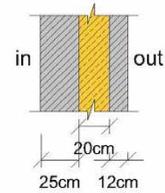


FIGURE 5 Second solution (design development stage)

There was a need for an unconventional, more compact solution. And after plenty of discussions and trials, a conceptual solution that was inspired from the heat radiators in slabs was proposed. The idea was to circulate heated water in tubing set in the concrete external wall. However, this active thermal insulation system of the exterior walls does not serve as a heating system, but is considered as an equivalent passive measure of thermal insulation which will allow minimum wall thickness. In a preliminary sketch, it was assumed that the external wall could be 30 cm thick.

## Technical challenges in the Zollverein's integrated external wall

For designing a non-standardized system, a special design process had to be developed and a number of design decisions had to be made. The following points will discuss in details those design decisions

### 1 Temperature & piping system

After the preliminary concept was reached, it was important as a first step to have some preliminary calculations from the climate engineer regarding the heating system (water temperature and pipe spacing, location, and diameter). That is because this heating system was expected to have the greatest influence on other aspects and disciplines.

The climate engineer was able to determine from the pipes' properties together with the data given from the structural engineer regarding the concrete properties and exact wall thickness, that the water temperature in the pipes should be 27° C. As for the pipes, they should be 2 cm (0.8 in.) in diameter, the spacing between them should be 20 – 40 cm and they should be placed 10 cm away from the inner surface.

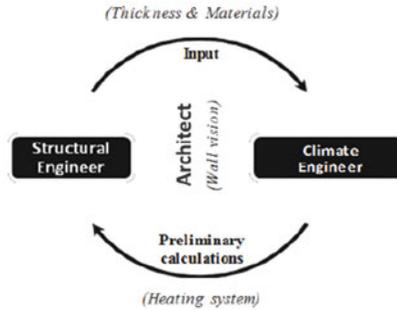


FIGURE 6 Data exchange in the early design process steps

## 2 Temperature & Concrete Stresses

From the previous first estimations, the climate engineer was able to calculate the extreme temperatures on the concrete surface. The temperatures were 0° C to 5° C on the outer surface (when the external temperature is -20° C), and more than 16° C on the inner surface (as required by German code and regulations). While in the case of a system failure it was expected that the temperature on the concrete surface temperature would be -20° C on the outer surface, and 8° C on the inner surface. And here appeared the first question: can the 30 cm thick concrete hold this temperature difference between the outer surface and the inner surface without cracking (without providing expansion joints)?

This had to be checked again with the structural engineer and a comprehensive research was done to determine the various types of stress caused by temperature changes in the concrete walls in a realistic manner. The proposed design was then approved from the structural aspect.

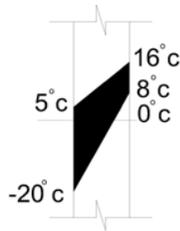


FIGURE 7 Extreme temperatures on the concrete surfaces

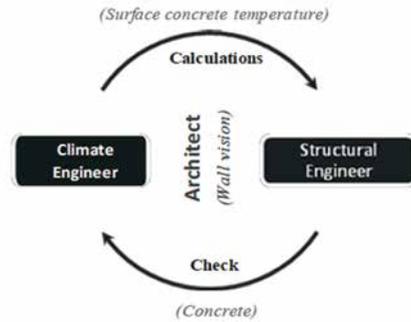


FIGURE 8 Data check between climate engineer and structural engineer

### 3 Energy consumption

From the climate estimations, the building services engineer also started his calculations to determine the energy consumption needed for heating the water to the required temperature, then pumping it to the walls. The energy consumption for such a system was enormous and was refused by the building services engineer. But fortunately, the project is located near a coal-mine. The mine had stopped working; however, large volumes of mine water with a naturally average temperature of 30°C were being continuously pumped from a depth of about 1000 m on the colliery grounds. The water was being pumped into the river in order to prevent the earth from rising.

It was an ideal solution to use this water in the building's external wall. So part of the mine water now flows through a heat exchanger at the top of the mining shaft designed specifically for this purpose, then water is pumped out to the Zollverein School at a rate of 600 m<sup>3</sup>/h in the pipes embedded in the exterior walls.

But the pipes' spacing estimated previously by the climate engineer was designed to accommodate

27°C water temperature. So, the climate engineer had to redesign the system according to the available 30°C water temperature. As a result, the piping spacing was increased.

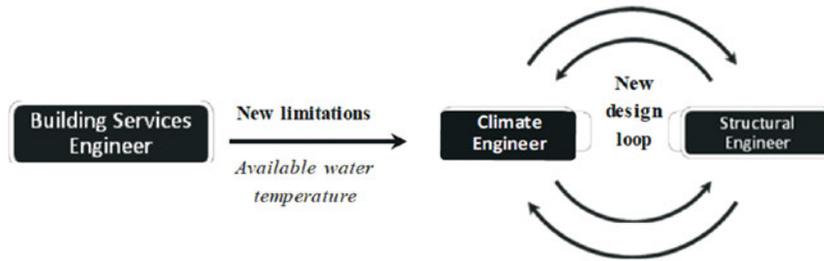


FIGURE 9 New data may require new design

#### 4 Special piping system

Because the pipes are totally embedded in concrete, the pipes had to be with no joints or connections in order to avoid any leakage problems that might occur. That resulted in very long pipes that made the handling and placing of pipes during the construction process a very difficult and complicated task.

Due to these difficulties, the building services engineer refused to take the responsibility of the new system and another building services engineer willing to take on the challenge was engaged at a late stage. In addition, an extra reinforcement grid had to be added to the wall by the structural engineer, not for structural reasons, but only to hold the long pipes in their locations.

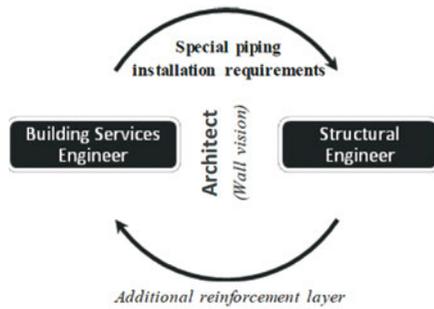


FIGURE 10 Special requirements led to a special system

## 5 Windows arrangement

The structural load transfer in walls, being only 30 cm thick and 10.5 m high, had an influence on the unique arrangement of the 134 different sized windows. The minimum distance between windows had to be at least 80 cm. And due to the complexity and high interdependency of disciplines in such a system, window opening locations had to be fixed by the architect at an early stage.

## 6 Coordination

The system complexity in such wall system required a continuative iterative coordination process in the design phase. On the other hand, for onsite coordination, concrete workers had to be taught how to handle and deal with the pipes together with the reinforcement.

## Non-technical challenges in the Zollverein's integrated external wall

The project also faced some non-technical difficulties, among them are the following points.

## 1 1- Time

---

Time is always a challenge in any project. And in the Zollverein School project, the integrated wall required more time compared to conventional standard solutions. In addition to the extra time needed to overcome the previous technical challenges, it took the design team nearly 6 months before that to reach a decision about applying an integral solution. And it took them about two more months to convince the client about using this unconventional solution: financing a building without insulation, and taking on the duty of pumping hot water to the building.

## 2 2- Tendering

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The uniqueness of the external wall solution also reflected on the project's tendering task process. Due to the complexity of the design, the tendering documents needed to be very precise in order to avoid technical implementation difficulties and additional costs. Moreover, due to the high degree of interdisciplinary design coordination in the walls, many contract subsections for building services had to be tendered in advance together with the structural work.

## 3 3- Risks

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Although the project was finally implemented without significant problems during construction or after its occupancy, still the project raises many fears as it depends on outsourced energy that might not be reliable. What if the coal-mine stops working? Or what if the temperature of water increases due to natural and environmental reasons? Such problems will not be solved easily, and may even require effort similar to the effort that was put into designing this integral system.

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## Conclusion

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It is clear in this project that the design process in the integrated solution was different than in a traditional layering solution.

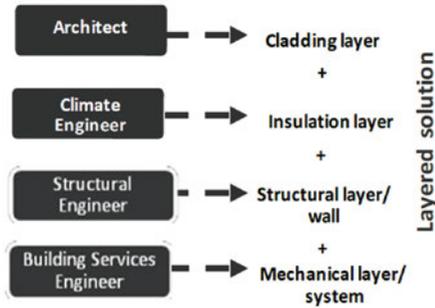


FIGURE 11 Typical process in a layered external wall

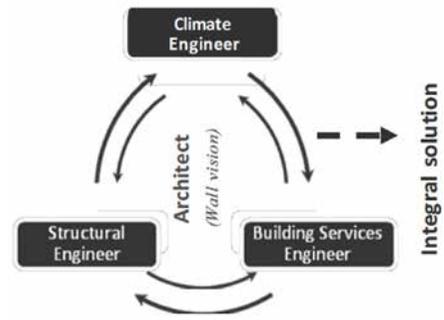


FIGURE 12 Integrated process in zollverein School's external wall

The following points can be concluded from this integrated design case:

- In this integrated design, problems and solutions affected all involved disciplines, either directly or indirectly. All disciplines had to be involved in the decisions made.
- The building typology, location, and architectural requirements were all aspects that influenced the design team.
- It took some time to realize the need for an integrated solution in the project. It was not a decision made instantly, but was based on testing alternative traditional solutions that didn't achieve the expectations.
- Unexpectedly, the construction cost of the project was only 10% higher than if a traditional solution was implemented. The integrated solution contributed to the construction cost reduction in some aspects. For example, eliminating the need for formwork for a double-skin wall, contributed to reducing the manufacturing cost and construction time.
- In this integrated solution, the team didn't face challenges only in the design process, but tendering and construction processes were also challenging.

The Zollverein Design School is a good example for a project that departed from a standard layered approach to a new integrated approach. Being the first case study in the research project, it explains how the desire of having a new solution will generate a new design process. It also shows how an integrated solution can be unique and customized. A solution for the same building, with the same design team, and with the same architectural requirements if implemented in another location, can be different.

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## Appendix 4 Structural calculations

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### Dutch wall Design calculations for vertical loads

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#### 1. Simplified method for calculating vertical resistance

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Check  $F/A < \text{material compressive strength}$

A = Load bearing horizontal cross-sectional area of the wall in  $\text{m}^2$

F= Loads on wall

Loads (as assumed in design) is 100 kN/m

#### 2. Checking Slenderness ratio

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Check  $H/A \leq 30$

H= Height of the wall

(for simplicity, the eccentricity will be not be included in the calculations)

### Wall Calculations

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*Load of 100 KN is considered in this calculation*

					Vertical loads resistance check		Slenderness ratio check
		Wall Thickness (m)	Area (per meter) (m <sup>2</sup> )	Wall Height (m)	Actual stress on wall (N/mm <sup>2</sup> )	Material compressive strength (N/mm <sup>2</sup> )	Slenderness ratio = Wall Height / Area
EXPANDED GLASS EXTERNAL WALL		0.41	0.41	3	0.24	2.50	7.33
AEROGEL CONCRETE EXTERNAL WALL		0.36	0.36	3	0.28	3.00	8.33
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL		0.32	0.32	3	0.32	1.60	9.52
PERFORATED CLAY BRICKS EXTERNAL WALL (UNFILLED)		0.54	0.54	3	0.19	1.80	5.56
PERFORATED CLAY BRICKS EXTERNAL WALL (FILLED)		0.36	0.36	3	0.28	6	11.11
GRADIENT CONCRETE EXTERNAL WALL	Regular Concrete	0.04	0.04	3		20.00	
	60% Aerogels - 40% Concrete	0.04	0.04	3		6.40	
	70% Aerogels - 6% Cement - 24% Void	0.16	0.16	3		0.40	
	Totald	0.24	0.24	3	0.42		12.50

TABLE 8.2 Vertical load resistance and slenderness check for the Dutch external wall designs

## Dutch wall calculations for lateral loads as per Eurocode 6

The following steps and calculation methods are used to check for the lateral loads as per the *EN 1996-1-1 (2005) (English): Eurocode 6: Design of masonry structures - Part 1-1*:

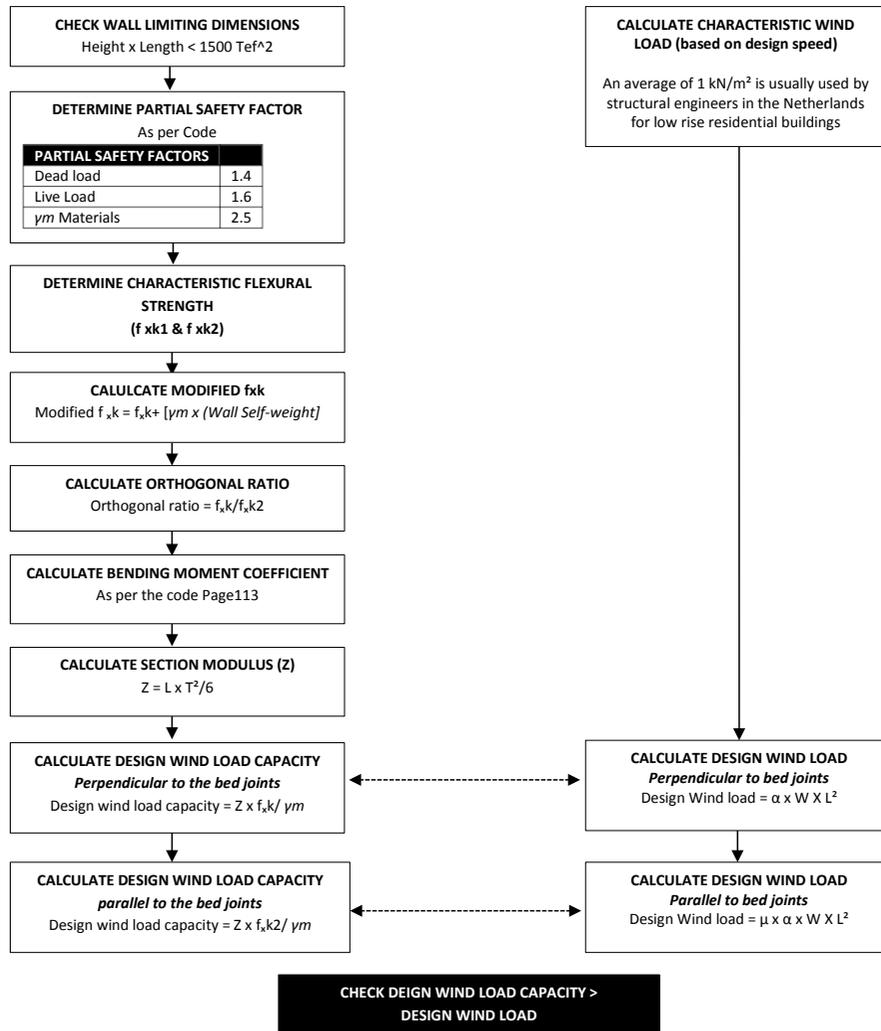


FIGURE 8.2 Steps for checking the lateral loads as per EN 1996-1-1 (2005) (English): Eurocode 6: Design of masonry structures - Part1-1

Wall calculations check as per previous steps:

	Wall thickness (m)	Wall Height (m)	Wall Length (m)	Check limiting dimensions Height x Length < 1500 Tef <sup>2</sup>		Determine characteristic flexural strength		
				1500 T <sup>2</sup>	Max. Wall length	f <sub>t,k1</sub> plane of failure parallel to bed joints Using thin mortar (n/mm <sup>2</sup> ) (Eurocode6 P.41)	f <sub>t,k2</sub> plane of failure perpendicular to bed joints Using thin mortar (n/mm <sup>2</sup> ) (Eurocode6 P.41)	
EXPANDED GLASS CONCRETE EXTERNAL WALL	0.41	3.00	4.20	251.54	83.85	0.20	0.30	
AEROGEL CONCRETE EXTERNAL WALL	0.36	3.00	4.20	194.40	64.80	0.20	0.30	
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	0.32	3.00	4.20	148.84	49.61	0.15	0.30	
PERFORATED CLAY EXTERNAL WALL (UN-FILLED)	0.54	3.00	4.20	437.40	145.80	0.15	0.15	
PERFORATED CLAY EXTERNAL WALL (FILLED)	0.36	3.00	4.20	194.40	64.80	0.15	0.15	
GRADIENT CONCRETE EXTERNAL WALL	0.23	3.00	4.20	79.35	26.45	0.20	0.30	
GRADIENT CONCRETE EXTERNAL WALL	0.24	3.00	4.20	86.40	28.80	0.20	0.30	

	Modified f <sub>xk</sub>		Calculate Orthogonal ratio	Calculate bending moment coefficient		Calculate Section modulus	Calculate Design Wind load Capacity		Calculate Design Wind	
	Wall Self weight (kn/m <sup>2</sup> )	Modified f <sub>k</sub> (n/mm <sup>2</sup> )	Orthogonal ratio $\mu = f_{k1}/f_{k2}$	H/L	$\alpha$ (Eurocode 6 P.113)	Section Modulus Z = L x T <sup>2</sup> /6 (m <sup>3</sup> /m)	Design Wind load Capacity Perpendicular to bed joints (kn)	Design Wind load Capacity Parallel to bed joints (kn)	Design Wind load Perpendicular to bed joints (kn) = $\alpha \times W \times L^2$	Design Wind Load Parallel to bed joints (kn) = $\mu \times \alpha \times W \times L^2$
	1.69	0.22	0.72	0.71	0.07	0.03	3.35	2.41	1.16	0.84
	1.43	0.21	0.72	0.71	0.07	0.02	2.59	1.86	1.16	0.83
	0.83	0.16	0.53	0.71	0.07	0.02	1.98	1.06	1.29	0.69
	2.98	0.17	1.14	0.71	0.06	0.05	2.92	3.32	1.01	1.14
	2.07	0.17	1.14	0.71	0.06	0.02	1.30	1.48	1.01	1.15
	1.74	0.23	0.76	0.71	0.06	0.01	1.06	0.81	1.13	0.86
	1.74	0.23	0.76	0.71	0.06	0.01	1.15	0.87	1.13	0.86

## Egyptian wall calculations for lateral loads

A As per Egyptian Code for Design and Construction of Concrete Structures (201):2008

- The average wind speed in Cairo is 33 m/sec, resulting in an average wind force of 0.68 kN/m<sup>2</sup>.
- Lateral forces on non-load bearing walls resulting from earthquake is 0.1 x Wall self-weight.

	Wall Thickness	Density (Kg/m <sup>3</sup> )	Wall self-weight (kN/m <sup>2</sup> )	Earthquake load = 0.1 x Wall self-weight (kN/m <sup>2</sup> )	Total Lateral loads= Earthquake + Wind load (kN/m <sup>2</sup> )
EXPANDED CLAY CONCRETE EXTERNAL WALL	0.25	760	1.862	0.1862	0.8662
EXPANDED GLASS CONCRETE EXTERNAL WALL	0.25	468	1.1466	0.11466	0.79466
AEROGEL CONCRETE EXTERNAL WALL	0.25	450	1.1025	0.11025	0.79025
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	0.25	400	0.98	0.098	0.778
PERFORATED CLAY BRICK EXTERNAL WALL (UNFILLED)	0.25	800	1.96	0.196	0.876
PERFORATED CLAY BRICK EXTERNAL WALL (FILLED)	0.25	652	1.59	0.159	0.839
GRADIENT CONCRETE EXTERNAL WALL	0.25	793	1.86396	0.186396	0.866396

B As per Egyptian Code for Masonry Construction (ECP 204 – 2005), the following table presents the minimum wall thickness required with respect to the wall length and lateral force applied (*ECP 204 – 2005. Page 114*)

Loads perpendicular to the wall (kN/m <sup>2</sup> )	Ratio of Length to Thickness (L/ t) for walls supported from 3 sides (free from the top) to the ratio of length to height (L/H)									
	(L/H) =0.5	1.00	1.50	2.0	3.0	4.0	5.0	6.0	7.0	8.0
0.4	21.2	23.1	27.0	31.8	23.9	36.2	40.7	44.9	49.0	55.5
0.5	19.0	20.7	24.1	28.4	30.3	32.4	36.4	40.2	43.8	49.6
0.6	17.3	18.9	22.0	25.9	27.7	29.5	33.2	36.7	40.0	45.3
0.7	16.0	17.5	20.4	24.0	25.6	27.3	30.7	34.0	37.1	41.9
0.8	15.0	16.3	19.1	22.5	24.0	25.6	28.8	31.8	34.7	39.2
0.9	14.0	15.4	18.0	21.2	22.6	24.1	27.1	30.0	32.7	37.0
1.0	13.4	14.6	17.0	20.1	21.4	22.9	25.7	28.4	31.0	35.1
1.1	12.3	13.9	16.2	19.2	20.4	21.3	24.5	27.1	29.5	33.5
1.2	12.2	13.3	15.6	18.3	18.3	20.9	23.5	25.9	28.2	32.0

- c Accordingly, the following table presents the minimum wall thicknesses required for the designed walls

	Total Lateral loads= Earthquake + Wind load (kN/m <sup>2</sup> )	L =4	H = 3	L/H =4/3	T=L/Tw (minimum thickness for such load as per previous table)	Wall Thickness
EXPANDED CLAY CONCRETE EXTERNAL WALL	0.8662	4	3	1.33	0.216	0.22
EXPANDED GLASS CONCRETE EXTERNAL WALL	0.79466	4	3	1.33	0.203	0.21
AEROGEL CONCRETE EXTERNAL WALL	0.79025	4	3	1.33	0.203	0.21
AUTOCLAVED AERATED CONCRETE EXTERNAL WALL	0.778	4	3	1.33	0.203	0.21
PERFORATED CLAY BRICK EXTERNAL WALL (UNFILLED)	0.876	4	3	1.33	0.216	0.22
PERFORATED CLAY BRICK EXTERNAL WALL (FILLED)	0.839	4	3	1.33	0.222	0.22

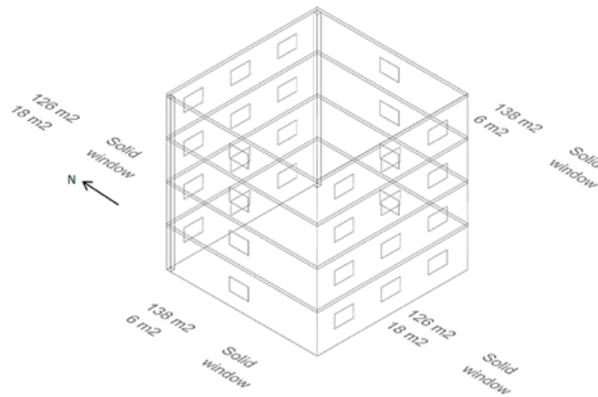
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GRADIENT CONCRETE EX- TERNAL WALL	0.866396	4	3	1.33	0.216	0.22
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Since walls are designed to be 25 cm, they all fulfil the minimum requirements of the code.

## Appendix 5 Heating & cooling loads for the Egyptian designed walls

To measure the effect of the different external wall technologies on the operational energy performance, the energy performance for cooling and heating loads were simulated. The program TRNSYS was used for the simulation. A typical medium size apartment building was simulated as per the conditions presented in the following diagram. A typical 2-cm plaster finish internal and external finish was added to the wall construction.



The following results were generated:

	Total Heating Demand	Peak Total Heating demand	Total Cooling Demand	Peak Total Cooling demand	Total Heating Demand	Peak Total Heating demand	Total Cooling Demand	Peak Total Cooling demand
	(kWh/m <sup>2</sup> /year)	W/m <sup>2</sup>						
TRADITIONAL MONOLITHIC	27.53	39.99	18.93	32.91				
	39.93	47.50	49.22	50.27				
	42.38	49.18	57.79	52.63				
	66.57	70.43	123.21	100.00				
TOTAL					44.11	70.43	62.29	100.00
EXPANDED CLAY CONCRETE EXTERNAL WALL	16.10	31.10	9.97	20.76				
	20.65	35.32	34.44	34.20				
	23.54	37.81	45.14	39.13				
	48.79	59.59	112.40	95.45				
TOTAL				27.27	59.59	50.49	95.45	
EXPANDED GLASS CONCRETE EXTERNAL WALL	13.97	29.21	8.72	19.33				
	20.82	35.14	31.93	31.85				
	20.39	35.64	42.98	39.13				
	45.72	57.91	110.51	93.57				
TOTAL				25.23	57.91	48.54	93.57	
AEROGEL CONCRETE EXTERNAL WALL	13.71	28.97	8.57	19.19				
	20.41	34.83	31.59	31.57				
	19.97	35.35	42.69	39.16				
	45.32	57.70	110.26	93.35				
TOTAL				24.85	57.70	48.28	94.30	
AUTO-CLAVED AERATED CONCRETE EXTERNAL WALL	14.30	29.53	9.01	19.74				
	21.24	35.46	32.27	32.51				
	20.78	36.04	43.26	39.50				
	46.24	58.25	110.75	94.30				
TOTAL				25.64	58.25	48.82	94.30	
PERFORATED CLAY BRICK EXTERNAL WALL (UN-FILLED)	16.42	31.72	10.16	21.17				
	21.06	36.02	35.12	34.88				
	24.01	38.56	46.04	40.30				
	49.76	60.78	114.64	97.35				
TOTAL				27.81	60.78	51.49	97.35	

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	Total Heating Demand	Peak Total Heating demand	Total Cooling Demand	Peak Total Cooling demand	Total Heating Demand	Peak Total Heating demand	Total Cooling Demand	Peak Total Cooling demand
	(kWh/m <sup>2</sup> /year)	W/m <sup>2</sup>						
PERFORATED CLAY BRICK EXTERNAL WALL (FILLED)	13.56	28.84	8.59	19.35				
	20.16	34.59	31.37	31.73				
	23.08	37.10	42.49	39.49				
	45.23	57.65	110.09	93.71				
T O T A L				25.51	57.65	48.13	93.71	
GRADIENT CONCRETE EXTERNAL WALL	12.57	27.93	8.00	18.73				
	18.65	33.48	30.16	30.81				
	21.53	36.06	41.44	39.44				
	43.69	56.86	109.17	92.71				
T O T A L				24.11	56.86	47.19	92.71	
LAYERED EXTERNAL WALL	14.68	29.84	9.12	19.71				
	21.90	35.94	32.77	32.61				
	21.46	36.38	43.71	39.10				
	46.76	58.46	111.17	94.16				
T O T A L				26.20	58.46	49.19	94.16	



## Appendix 6 Questionnaire

### Scoring the importance of different external wall performances in the Dutch market for a typical residential project (For Dutch Architects)

- 1 1: completely unimportant
- 2 2: unimportant
- 3 3: neutral
- 4 4: important
- 5 5: very important

	FROM THE DUTCH INDUSTRY POINT OF VIEW (1 - 5)	FROM YOUR POINT OF VIEW AS AN ARCHITECT (IF DIFFERENT) (1 - 5)	EXPECTED CHANGES IN THE FUTURE (IF DIFFERENT) (1 - 5)	COMMENTS (IF ANY)
Construction Time Reduction				
Construction Cost Reduction				
Embodied Energy Reduction				
Carbon Dioxide Emission Reduction				
Recyclability Potentials				
Cooling Loads Energy Reduction				
Heating Loads Energy Reduction				
Wall Thickness Reduction				

## Scoring the importance of different external wall performances in the Egyptian market for a typical residential project (For Egyptian Architects)

- 1 1: completely unimportant
- 2 2: unimportant
- 3 3: neutral
- 4 4: important
- 5 5: very important

	FROM THE DUTCH INDUSTRY POINT OF VIEW (1 - 5)	FROM YOUR POINT OF VIEW AS AN ARCHITECT (IF DIFFERENT) (1 - 5)	EXPECTED CHANGES IN THE FUTURE (IF DIFFERENT) (1 - 5)	COMMENTS (IF ANY)
Construction Time Reduction				
Construction Cost Reduction				
Embodied Energy Reduction				
Carbon Dioxide Emission Reduction				
Recyclability Potentials				
Cooling Loads Energy Reduction				
Heating Loads Energy Reduction				
Wall Thickness Reduction				

# Curriculum vitae



- 1983 Born in Giza, Egypt
- 2000 - 2005 Bachelor of Architectural Engineering from Cairo University, Egypt
- 2005 – 2008 Architect at Dar Al-Hanadasah Consultants and MADA Architects
- 2008 - 2009 Master of Architecture from McGill University, Canada
- 2009 – 2011 Architect at Egyptian Group for Engineering Consultation (EGEC)
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