HOPCA

Hospital Layout Design Optimization using Computational Architecture

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Hospital Layout Design Optimization using Computational Architecture

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, Prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Wednesday, 18 January 2023 at 15:00 o’clock

by

Cemre ÇUBUKÇUOĞLU
Master of Science, Yaşar University, Turkey
born in İzmir, Turkey

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This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	Chairperson
Prof.dr.ir. I.S. Sariyildiz	Delft University of Technology, promotor
Prof.dr. M.F. Tasgetiren	Auburn University, promotor
Dr. P. Nourian	Delft University of Technology, copromotor

Independent members:

Prof.dr.ir. P.J.M. van Oosterom	Delft University of Technology
Prof.ir. P.G. Luscuere	Delft University of Technology
Prof.dr. L.C.M. Itard	Delft University of Technology
Prof. dr. C. Wagenaar	University of Groningen
Prof.dr.ir. A.A.J.F. van den Dobbelsteen	Delft University of Technology, reserve member

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12 December 2022
İzmir & Delft

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Summary

Hospital facilities are known to be functionally complex buildings in various ways, namely due to their non-trivial spatial connectivity requirements. There are several typical problems in hospitals that can be attributed to the configuration of the building, namely the inefficient circulation of medical staff, difficult wayfinding for visitors, lengthy and complex procedures, long walking times, and so on. This Ph.D. research aims to investigate the relation between the performance of hospital buildings focusing on their configurational layout at various levels of abstraction, and to develop a computational design methodology for configurational layout optimization of hospital buildings. To this end, spatial layout methods were devised and tested by using Computational Design techniques derived from the fields of Graph Theory, Operations Research, and Computational Intelligence. The presented research was carried out based on the actions performed in three main parts: **Literature Review, Preliminary Research, and Method Development with Case Studies**. Firstly, a worldwide literature review was conducted on “configurational layout in general” and “hospital layout” studies to highlight the correspondence between configurational layout methods and hospital layout problems in the current literature. Secondly, preliminary research was conducted on configurational design requirements to identify a typical program of requirements (PoR) and spatial connectivity, adjacency, and closeness requirements of hospitals (REL-Chart), for which expertise knowledge, on-site observations, hospital design codes, and standards were utilized. In addition, international hospital design guidelines were reviewed and a discrete event simulation method that can model the patient flows was developed and programmed as a design toolkit to define the space requirements in CAD software by considering the patient waiting times. The last part is Method Development & Case Studies, in which two parallel tracks of work were reported on “Reconfiguration of existing hospitals” and “Designing hospitals from scratch”. The core concept of the reconfiguration track is assigning hospital units to the existing locations such that the assignment cost (flows of people distances) is minimized. The core concept of designing from scratch is based on a holistic approach consisting of stacking, zoning, and routing. In stacking, a spectral clustering method was proposed for defining the levels of hospital units. In the stage of zoning, hospital units were assigned to the faces of a mesh-surface representation of the floorspace such that the closeness of the interrelated spaces is minimized subject to various constraints. In routing, the corridors were designed by assigning circulation routes to the edges of a mesh-surface representation of the available floor space

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considering wayfinding and work-related interruptions. Due to the nature of the problems, in the first track for redesigning existing hospitals, Quadratic Assignment Problem (QAP) formulation with geodesic distances and a heuristic optimization algorithm were proposed. In the second track for designing new hospitals, Mixed Integer Programming (MIP) formulations were suggested. The two models have been programmed as a computational design toolkit that is available in popular CAD software in architecture using C# and Python programming languages. The models are not case-based; but for the test and validation of the layout results, each of the models was applied to a real-world case study hospital in Izmir, Turkey. The models were created considering Turkey's hospital design codes and standards and specific to mid-size general hospitals, however, the models can be modified later according to the different regulations of other countries. Effectively, this project presents an interdisciplinary methodological framework that can tackle hospital layout design problems by integrating Computational Design workflows, Graph Theory techniques, Operations Research, and Computational Intelligence into the field of Architectural Space Planning.

TREFWOORDEN Computational Intelligence in Design, Architectural Space Planning, Configurational Layout Optimization, Hospital Design, Tool Development

Samenvatting

Het is bekend dat ziekenhuisvoorzieningen in verschillende opzichten functioneel complexe gebouwen zijn, met name door hun niet-triviale eisen inzake ruimtelijke connectiviteit. Er zijn verschillende typische problemen in ziekenhuizen die kunnen worden toegeschreven aan de configuratie van het gebouw, namelijk de inefficiënte circulatie van medisch personeel, moeilijke oriëntatie voor bezoekers, langdurige en complexe procedures, lange looptijden, enzovoort. Dit doctoraatsonderzoek heeft tot doel de relatie te onderzoeken tussen de prestaties van ziekenhuisgebouwen met de nadruk op hun configuratorische lay-out op verschillende abstractieniveaus; en een computationele ontwerpmethodologie te ontwikkelen voor de optimalisatie van de configuratorische lay-out van ziekenhuisgebouwen. Daartoe werden ruimtelijke lay-out methoden ontworpen en getest met behulp van computationele ontwerptechnieken die zijn afgeleid van de gebieden grafentheorie, operations research en computationele intelligentie. Het gepresenteerde onderzoek werd uitgevoerd op basis van de acties die in drie hoofdonderdelen werden uitgevoerd: **Literatuuronderzoek, Vooronderzoek, Methodeontwikkeling & Case Studies**. Ten eerste werd een wereldwijd literatuuronderzoek uitgevoerd naar "configurational layout in het algemeen" en "ziekenhuis layout" studies om de overeenkomst tussen configurational layout methoden en ziekenhuis layout problemen in de huidige literatuur te benadrukken. Ten tweede werd een vooronderzoek uitgevoerd naar de vereisten voor configuratief ontwerp om een typisch programma van Eisen (PvE) en eisen voor ruimtelijke connectiviteit, nabijheid en nabijheid van ziekenhuizen (REL-Chart) te identificeren, waarvoor gebruik werd gemaakt van expertise, waarnemingen ter plaatse, ontwerpcodes en -normen voor ziekenhuizen. Bovendien werden internationale richtlijnen voor ziekenhuisontwerp bestudeerd en werd een discrete simulatiemethode ontwikkeld die de patiëntenstromen kan modelleren en geprogrammeerd als een ontwerphulpmiddel om de ruimtevereisten in CAD-software te definiëren door rekening te houden met de wachttijden van de patiënten. Het laatste deel is Method Development & Case Studies, waarin twee parallelle werksporen werden gerapporteerd over "Herconfiguratie van bestaande ziekenhuizen" en "Ontwerpen van ziekenhuizen vanaf nul". Het kernconcept van het herconfiguratiespoor is het toewijzen van ziekenhuiseenheden aan de bestaande locaties op zodanige wijze dat de toewijzingskosten (stromen van mensen × afstanden) geminimaliseerd worden. Het kernconcept van het "from scratch" ontwerpen is gebaseerd op een holistische benadering die bestaat uit stapelen, zoneren en routeren. Bij het stapelen is een spectrale clustermethode voorgesteld voor het definiëren van de niveaus van ziekenhuiseenheden. Bij de indeling in zones werden de ziekenhuisafdelingen toegewezen aan de vlakken van een maasvlak dat de vloerruimte zo weergeeft dat de onderlinge ruimten zo dicht mogelijk bij elkaar komen te liggen, rekening houdend met verschillende beperkingen. Bij de routing werden de gangen ontworpen door circulatieroutes toe te wijzen aan de randen van een mesh-oppervlak van de beschikbare vloerruimte, rekening houdend met *wayfinding* en werkgerelateerde onderbrekingen. Gezien de aard van de problemen werd in het eerste spoor voor het herontwerpen van bestaande ziekenhuizen een *Quadratic Assignment Problem* (QAP) formulering met geodetische afstanden en een heuristisch optimalisatiealgoritme voorgesteld. In het tweede spoor voor het ontwerpen van nieuwe ziekenhuizen, werden Mixed Integer Programming (MIP) formuleringen voorgesteld. De twee modellen zijn geprogrammeerd als een computationele ontwerp-toolkit die beschikbaar is in populaire CAD-software in de architectuur met behulp van de programmeertalen C# en Python. De modellen zijn voor het testen en valideren van de lay-out resultaten, elk van de modellen werd toegepast op een *real-world case studie* ziekenhuis, namelijk twee ziekenhuizen in Izmir, Turkije. De modellen werden gemaakt rekening houdend met Turkije's ziekenhuis ontwerpcodes en standaarden en specifiek voor middelgrote algemene ziekenhuizen, zodat de modellen kunnen later worden aangepast aan de verschillende regelgevingen van andere landen. Effectief presenteert dit project een interdisciplinair methodologisch kader dat de ziekenhuis lay-out ontwerpproblemen kan aanpakken door het integreren van *Computational Design workflows*, Graaftheorie technieken, Operations Research, en *Computationele Intelligentie Operations Research* in het gebied van Architecturale Ruimteplanning.

TREFWOORDEN Computationele Intelligentie in Ontwerp, Architecturale Ruimteplanning, Configurationele Lay-out Optimalisatie, Ziekenhuisontwerp, Tool Ontwikkeling

Özet

Hastane tesislerinin, önemli mekansal bağlantı gereksinimleri nedeniyle işlevsel olarak karmaşık binalar olduğu bilinmektedir. Hastanelerde, sağlık personelinin bir yerden bir yere gitmesinde yaşadığı zorluklar, ziyaretçiler ve hastalar için yön bulma güçlükleri, uzun süreli ve karmaşık yapıdaki prosedürler, uzun yürüme mesafeleri ve benzeri problemler binanın plan konfigürasyonuna atfedilebilecek birçok tipik problem arasında yer almaktadır. Bu doktora araştırmasının amacı, hastane binalarının konfigürasyonel düzen optimizasyonu için bir hesaplamalı tasarım metodolojisi geliştirmek ve hastane binalarının performansları ve konfigürasyonel düzenleri arasındaki ilişkiyi araştırmaktır. Bu amaçla, Graf Teorisi, Yöneylem Araştırması ve Hesaplamalı Zeka alanlarından türetilen Hesaplamalı Tasarım teknikleri kullanılarak mekansal yerleşim yöntemleri geliştirilmiş ve test edilmiştir. Sunulan araştırma üç ana bölümde gerçekleştirilen eylemlere dayalı olarak yürütülmüştür: **Literatür Taraması, Ön Araştırma, Yöntem Geliştirme & Vaka Çalışmaları**. İlk olarak, mevcut literatürde genel konfigürasyonel yerleşim yöntemleri ile hastane yerleşim problemleri arasındaki uyumu vurgulamak için “genel olarak konfigürasyonel yerleşim” ve “hastane özelinde konfigürasyonel yerleşim” çalışmaları üzerine dünya çapında bir literatür taraması yapılmıştır. İkinci olarak, tipik bir ihtiyaç programı (PoR) ve hastanelerin mekânsal bağlantı, bitişiklik ve yakınlık gereksinimlerini (REL-Chart) belirlemek için bir ön araştırma yapılmış ve bunun için uzman bilgisi, saha çalışmaları ve yerinde gözlemler, hastane tasarım standartlarından yararlanılmıştır. Ayrıca, uluslararası hastane tasarım kılavuzları incelenmiş, hasta akışlarını modelleyebilen bir ayrık olay simülasyon yöntemi geliştirilmiş ve hasta bekleme süreleri dikkate alınarak alan gereksinimlerini tanımlamak için CAD yazılımında karar verme destek aracı geliştirilmiştir. Son bölüm, “Mevcut hastanelerin yeniden yapılandırılması” ve “Hastanelerin sıfırdan tasarlanması” üzerine iki paralel çalışmanın rapor edildiği Yöntem Geliştirme ve Vaka Çalışmaları bölümüdür. Yeniden yapılandırma kısmının temel konsepti, hastane birimlerinin mevcut konumlara atama maliyetini (insan akışları × mesafeler) en aza indirecek şekilde atanmasıdır. Sıfırdan tasarımın temel konsepti, istifleme (katların belirlenmesi), bölgeleme (birimlerin yerleştirilmesi) ve yönlendirmeden (koridor tasarımı) oluşan bütünsel bir yaklaşıma dayanmaktadır. İstifleme aşamasında, hastane birimlerinin katlarını tanımlamak için spektral bir kümeleme yöntemi önerilmiştir. Bölgelendirme aşamasında, hastane birimleri, çeşitli kısıtlamalara tabi olarak birbiriyle ilişkili alanların yakınlığı en aza indirilecek şekilde yerleştirme işlemi yapılmıştır. Tanımlanan zemin alanı gridlere bölünüp mekanlar herbir grid yüzeye atanmıştır. Yönlendirmede, yön bulma ve iş verimliliği ilkeleri göz önünde bulundurularak dolaşım rotaları ve koridorlar tasarlanmıştır. Tanımlanan zemin alanı gridlere bölünmüş olup her bir koridor grid kenarlarına atanmıştır. Problemlerin doğası gereği, mevcut hastanelerin yeniden tasarlanmasına yönelik ilk yolda, jeodezik mesafelerle Karesel Atama Problemi (QAP) formülasyonu ve sezgisel bir optimizasyon algoritması önerilmiştir. Yeni hastanelerin tasarlanmasına yönelik olan ikinci yolda ise Karma Tamsayılı Programlama (MIP) formülasyonları önerilmiştir. Bu iki model, C# ve Python programlama dilleri kullanılarak mimaride popüler CAD yazılımlarında kullanılabilen bir hesaplamalı tasarım araç seti olarak programlanmıştır. Modeller yerleşim sonuçlarının test edilmesine ve doğrulanmasına hazır bir şekilde jenerik olarak oluşturulmuştur. Her bir model test edilmek için gerçek hayat problemlerine yani İzmir, Türkiye'deki iki hastaneye vaka çalışması olarak uygulanmıştır. Modeller, Türkiye'nin hastane tasarım standartları göz önünde bulundurularak ve orta ölçekli genel-amaçlı hastanelere özgü olarak oluşturulmuştur; ancak modeller daha sonra diğer ülkelerin standartlarına ve kurallarına göre değiştirilebilir. Bu çalışma, Hesaplamalı Tasarım iş akışlarını, Graf Teorisi tekniklerini, Yöneylem Araştırmasını ve Hesaplamalı Zeka alanlarını Mimari Mekan Planlaması alanına entegre ederek hastane yerleşim tasarımı problemlerini çözebilecek disiplinler arası bir metodolojik çerçeve sunmaktadır.

ANAHTAR KELIMELER Tasarımda Hesaplamalı Zekâ, Mimari Mekân Planlaması, Konfigürasyonel Yerleşim Optimizasyonu, Hastane Tasarımı, Araç Geliştirme

1 Introduction

1.1 Context and Motivation

Hospitals are one of the most complex types of buildings in Architecture. The main factor separating hospitals from other building types is that no other building shows such a wide range of user groups with changing physical needs and different attitudes. Hospitals serve 24/7 and involve a diverse spectrum of functions with corresponding occupants and materials. In addition to their well-known clinical and nursing activities in recent years, they began to provide additional activities and functions such as administration, service (food, laundry, etc.), in some cases, research, teaching, and shopping. All these units require certain physical relationships, which determine the layout of the hospitals as a challenging task. The excess functions of hospitals can also be understood from the excess of design codes/standards, some are common to each country and some of them differ [1]. These regulations and standards direct the construction of the hospitals however, hospital planning requires a systematic way of decision-making in their design; rather than an unconscious application of those regulations and standards so they should not be the only thing that is considered during the hospital design.

According to the World Health Organization (WHO) statistics [2], the population living in urban areas is around 70% in Turkey [3], which leads to challenges in achieving growth and flexibility in hospitals. Hence, responding to the needs of the future expansion of the hospitals causes more configurational problems. WHO statistics also showed that limited number of medical staff and hospital beds per population in Turkey [4]. This could cause difficulties associated with patients and medical staff such as medical error, stress levels, or work concentration [5]. According to governmental statistical reports, the annual population growth rate from 2007 to 2020 is an average of 13% per year [6]. The elderly population has increased by 22.5% in the last five years [6]. As the population ages, the demand for health care services in Turkey is growing. Therefore, in the last decades, the healthcare sector in Turkey arises the need for growth due to rapid population

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growth and urbanization. The concept of city hospitals began to develop and the quality of the health services in terms of both quantity and quality has noticeably increased and improved. The quality of health services can be measured by the productivity, waiting times, efficiency, patient satisfaction and stressed medical staff [7], [8]. Therefore, in hospital design, these kind of efficiency factors have started gain more importance in the time being.

On the other hand, a spatial configuration has an impact on the efficient (social, economic, environmental) functioning of such complex buildings by enabling certain patterns of movement. It also affects accessibility, human behaviour, and human movement patterns [9]. For instance, in hospitals, a spatial configuration has an impact on the occurrence of workflow interruptions, which is an unplanned or unscheduled interference by another person, causing discontinuation of the current task, a noticeable pause, or a required change from one task to another [10]. Mostly, unwanted interruptions are caused by others e.g. visitors of patients rather than fellow physicians and nurses. As an example (See Figure 1.1), due to the spatial proximity between the medicine room and the public corridor in a hospital, unwanted interruptions of nurses are occurred by relatives of patients. These kinds of unwanted interruptions distract the medical staff from performing the task at hand and raise the probability of the occurrence of errors in the healthcare processes [10]. Therefore, another challenge in hospital design is to understand how configurations influence human performance (decisions and movement) and working efficiency [11].

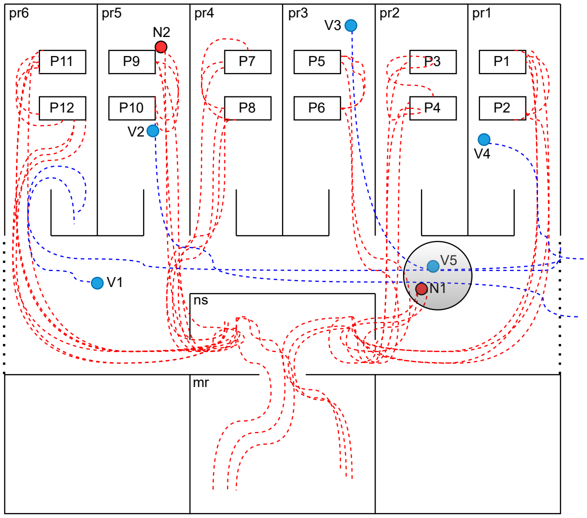

FIG. 1.1 interaction between a nurse (N1) and a visitor (V5) that occurs in the corridor, triggered by the spatial proximity between nurse and visitor, during the medicine distribution process [12]

In the literature, it is seen that the unsuitable layout of the working spaces causes over-expenditure and/or waste of personnel's working time. From the perspective of hospital personnel, around 67% of employees have challenges in adequately performing tasks because of the unsuitable layout of the work spaces as presented in [13]. For example, medical staff, especially nurses, sometimes waste their time walking more than the medical activities [14] because of the spatial connectivity problems between related units. In one research, it is seen that nurses spend 28.9% of their time a day walking [15]. Other research also presented that the layout form of the inpatient unit has an impact on the walking time of nurses (See Figure 1.2), e.g. authors in [16] established that nurses walked 4.7 steps per minute in an inpatient area with radial-form; 7.9 steps per minute in an inpatient area with rectangular-form.

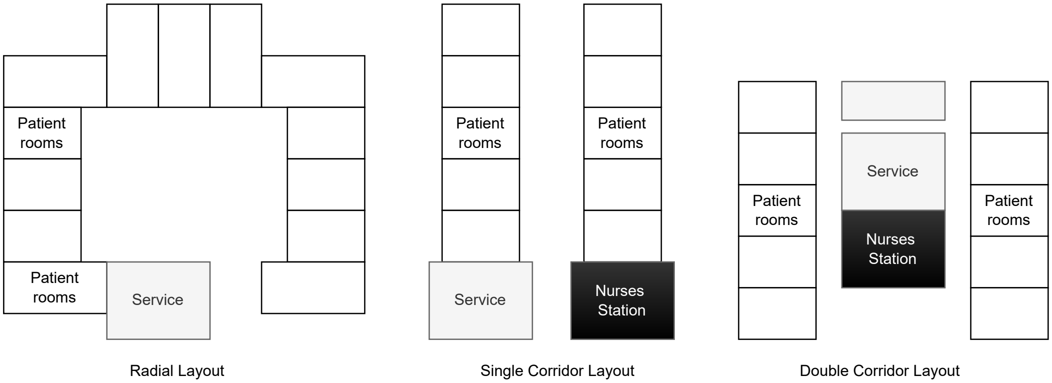

FIG. 1.2 Different nursing unit layouts [20]

Another study [17] showed how the adjacencies of functionally different areas within operating rooms can influence the circulating nurse's workflow patterns and disruptions. As can be seen from the pattern of the circulating nurses' movement in Operating Room-A of the studied hospital (Figure 1.3), the circulating nurse spent the least amount of time on patient-related activities i.e. about 4 hours in a day or 13% of total time spent on activities.

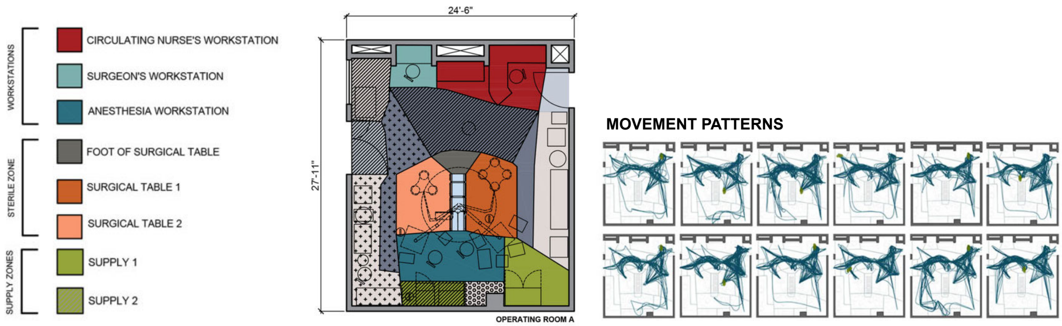

FIG. 1.3 Patterns of circulating nurses in an operation room [17]

Here we refer to the evidence-based design (EBD) movement in [healthcare] architecture, which is related to how design elements affect healthcare outcomes [18]. The outcomes targeted by EBD commonly involve patient-related outcomes, but can also cover staff-related factors such as productivity, satisfaction, and worker safety [19]. These quality factors (patient safety, outcomes, worker satisfaction, etc.) in the interest of EBD should be considered crucial properties of the whole system [5]. Therefore, hospital planning requires holistic approaches, which depend not only on the individual contributions of the components but also on their complex interactions [18] (e.g. considering not only physical factors but also human factors in design).

Another key feature of hospitals that makes the design process complicated is to have the changing environment. The hospital configuration is influenced by rapid technological changes, growing user needs, and social requirements, which can lead to changes in functional relationships. For instance, one development in medicine can strengthen the link between a clinic and a diagnosis unit thus causing to have more flow of people and material between these units. Due to these kinds of uncertain changes, hospitals should be planned, in a way that they can adapt themselves to those changes. As well in [21], it was emphasized that the need arose to design hospitals in such a way that they could be adapted to the constantly changing demands without too much difficulty or expense. Hospital buildings that can be still usable soon can become functionally outdated; therefore, flexibility could extend their lives. Inner courtyards and entrance halls can offer the architects more area for manoeuvring to more flexible rules that apply to the medical units.

Due to all the above issues, hospitals can face serious organizational and functional problems in their configuration, which sometimes end up in serious illnesses or deaths. The hospitals inherently call for systematic design methodologies for the identification of healing environments, which is the main motivation of this research.

Before the development of systematic frameworks that will be specialized for hospital layout designs, we must comprehend hospital performance concerning its configurational layout, considering the following matters.

Circulation spaces provide access between hospital departments and allow for efficient movement of people, beds, wheelchairs, and trolleys [22]. They comprised corridors, internal lobbies, streets, lifts, ramps, elevators, staircases, etc. for providing transportation between rooms/buildings (See Figure 1.4). Providing an efficient logistics system is important in hospitals. Transportation systems of people, waste, and materials are influenced by building configuration e.g. the routing to be followed by the waste vehicles or by the waste-carrying personnel should be determined as far as possible from the clean areas and intense patient traffic. In some departments, logistical problems cannot be accepted e.g. handling medicines between the emergency & medicine preparation rooms.

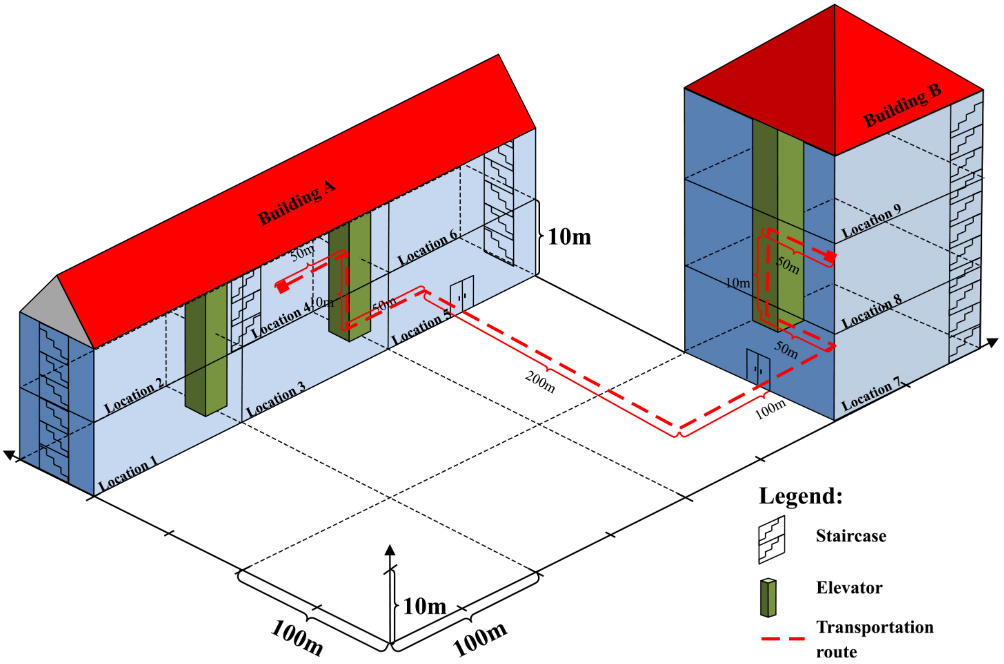

FIG. 1.4 Transportation routes within the hospital [23]

Corridors are the main effect that causes daily traffic. As an example, corridors should allow easy movement and be wide enough for passing wheelchairs. On the other hand, regarding the contributing hygiene, separating the corridors according to the cleanliness levels is very important to prohibit and/or control easily transmittable diseases and hospital infections (See Figure 1.5). It is important to create an effective wayfinding system in corridor planning for facilitating efficient movement within the hospitals. Especially in outpatient spaces, the form of spaces affects the wayfinding behaviour of patients e.g. difficulty in wayfinding influences the stress level of the patient.

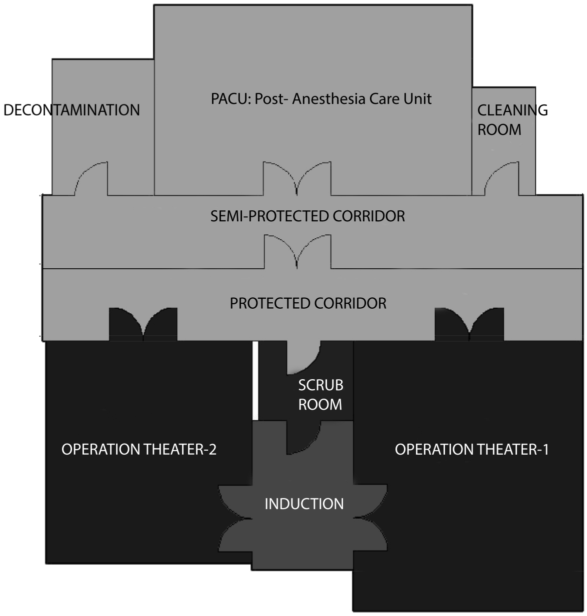

FIG. 1.5 A small-scale example of an operating theatre (OT) layout solution with different types of corridors. As shown, access to the protected area is assured by a clean corridor. [24]

Providing optimal functional adjacency and connectivity in hospitals is important by allowing some connections to ensure accessibility or prohibiting some connections to ensure privacy and/or safety. Related departments must be adjacent and at the same time, they should have efficient connections among the interrelated spaces. As an example, an MRI (Magnetic Resonance Imaging) department design, should be close to the Emergency Department and Ambulatory care unit. On the other hand, MRI should be adjacent to one of the building sides to allow machine installation. Relationship charts (REL-Charts) [25] are one of the most beneficial tools for visualizing adjacency, closeness, and connectivity requirements (See Figure 1.6).

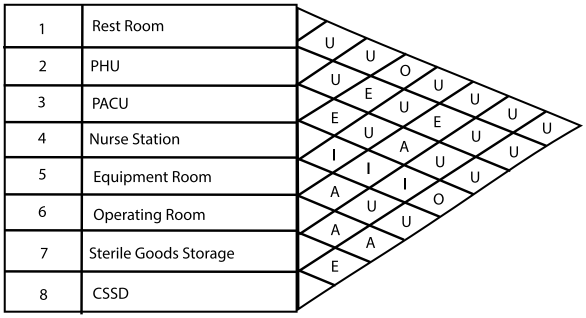

FIG. 1.6 Relationship chart for an operating theatre in a hospital [26]

Operational planning (sequence of events, number of beds, number of doctors, nurse assignments, appointment scheduling) has an impact on layout design decisions e.g. space locations and square meters. Towards delay in patient care, patient waiting times, the average length of the queue, bed utilization, doctor utilization (working efficiency), and patient and employee flows must be carefully understood and the layout must fit its procedures (and purposes). Some of the simulation tools and process models (e.g. in Figure 1.7) can be useful for achieving the goal of matching the layout with the operational logic of hospitals.

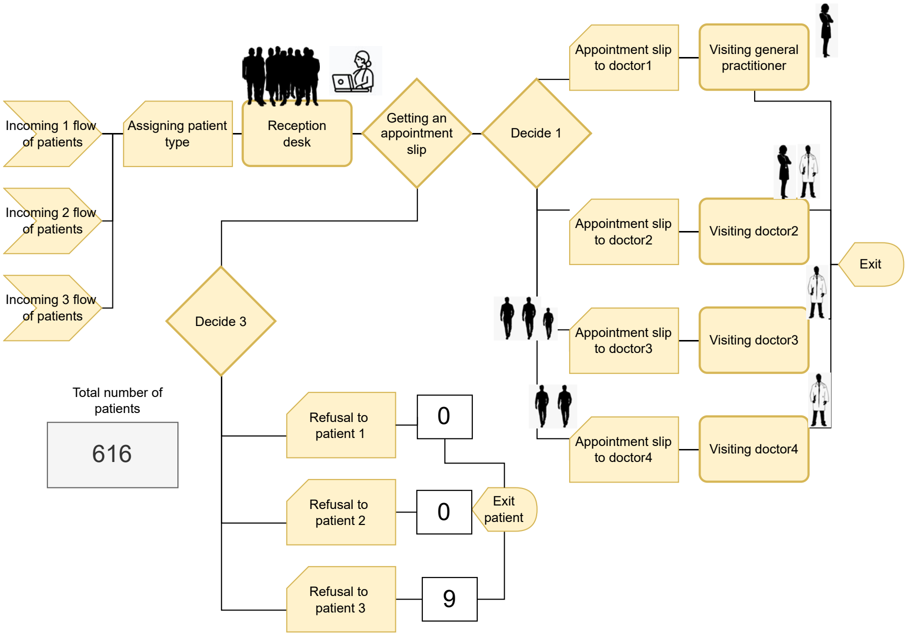

FIG. 1.7 Process Flow Chart of a patient admission and treatment area [29]

Space requirements are other factors that should be focused on during the layout design. They pertain to hospital standards, such as minimum floor area standards or aspect ratios. The design of physician rooms must handle the sizes, and shapes that are convenient with the physical work-producing abilities of medical staff during the treatment. Space requirements must also handle people's expectations e.g. waiting areas must be spacious enough for visitors. On the other hand, daylighting factors are important to produce healing environments in hospitals [27]. For instance, rooms' orientation, and floor plan shapes help to control solar radiation in hospital buildings [28]. There are also some standards related to the need for daylighting in specific units in hospitals e.g. minimum illuminance levels, the existence of windows, and the neighbourhood of façade.

1.2 Problem Statement

Hospitals are seen as functionally complex structures throughout history, with the ever-increasing complexity of the *functional requirements*[1]. Therefore, in hospitals, problems in spatial configuration may cause challenges associated with many aspects: functional logistics, time issues such as traveling distances, waste of time, movement of the personnel, hygiene problems due to the unsuitable movement of the materials, privacy-safety issues due to the placement of spaces in a high-traffic area, satisfying natural lighting requirements, wayfinding of the patients, operational planning, the complication of medical procedures, undesirable work-related interactions (e.g. nurses being interrupted by visitors in the corridors). We established that in the current literature there are limited studies that explicitly address such configurational design problems in the context of hospital layout planning/design. Therefore, the key problems addressed in hospital layout design are given with corresponding problem statements, as follows.

- There is a need for an explicit configurational layout methodology for optimizing a hospital configuration concerning **physical matters & human factors** in terms of accessibility and visibility-related matters, which are directly attributable to the layout/configuration of the hospital.

---

[1] The requirements, which a building must satisfy in order to support and enhance human activities.

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  - The ergonomic efficiency pertains to travel time which is a physical quantity, and comfort which is a human factor related to human movement; the combination of these factors can be regarded as a matter of accessibility in an integral way. For example, natural lighting requirements in space planning of hospitals are also typically important to ensure that the spatial configuration of the hospital is naturally well-lit, not only to reduce energy consumption but also to ensure that the hospital environment is comfortable and effective as a human healing environment.

- In this configurational layout optimization methodology, we need to consider performance indicators that can assess the abstract configuration of a building for optimizing its functionality concerning **patients** (e.g. ease of way-finding), **staff** (e.g. average walking-time), and **operations** (e.g. fitness for workflows).

1.3 Research Questions

Considering the discussion in the previous section, this research addresses the following research questions:

The main question is:

- **How to logically deduce a configurational layout of hospitals from functional requirements?**

To answer this overarching question, the research investigates further four sub-questions, which are addressed in different chapters of this thesis:

1. How to define spatial adjacency, connectivity, and closeness requirements in hospitals? (Chapter 3.2)
2. How to define a program of requirements in relation to design codes and standards concerning human comfort in following medical procedures? (Chapter 3.3)
3. How to improve the layout configuration of an existing hospital? (Chapter 4.2)
4. How to obtain a configurational layout for a new hospital? (Chapter 4.3)

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1.4 Objectives

In association with the aforementioned research questions, the research is formulated to achieve the following objectives:

The main objective is:

- **Developing a computational design methodology for logically deducing a configurational layout of hospitals from functional requirements.**

Followed by 4 sub-objectives:

1. Defining spatial adjacency, connectivity, and closeness requirements in hospitals (Chapter 3.2)
2. Defining program of requirements considering design codes and standards concerning human comfort in following medical procedures (Chapter 3.3)
3. Developing a method for improving the layout configuration of an existing hospital (Chapter 4.2)
4. Developing a method for obtaining a configurational layout for a new hospital (Chapter 4.3)

1.5 Scope

In this research, we mainly focus on human factors and physical matters related to configurational layout optimization and ergonomic aspects on medical staff, patients and operations as highlighted in section 1.2. The following subjects are thematically related to the research topic, and yet they fall out of the scope of the research:

- Contamination Spread
- Epidemiology
- Medical Procedures
- Fire

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1.6 Research Methodology

As the main goal of this dissertation is to develop a computational design methodology for the configurational layout of the hospitals, the research follows a mixed-methods approach including both quantitative and qualitative works. As a general philosophy, while developing the methods, the process starts with an abstract configurative arrangement of spatial units using hospital design guidelines; follows by the topological placement of rooms and corridors; continues by systematic exploration of feasible geometric interpretations of plan layout patterns; and, ends with the dimensional specification of them according to the design brief (See Figure 1.8).

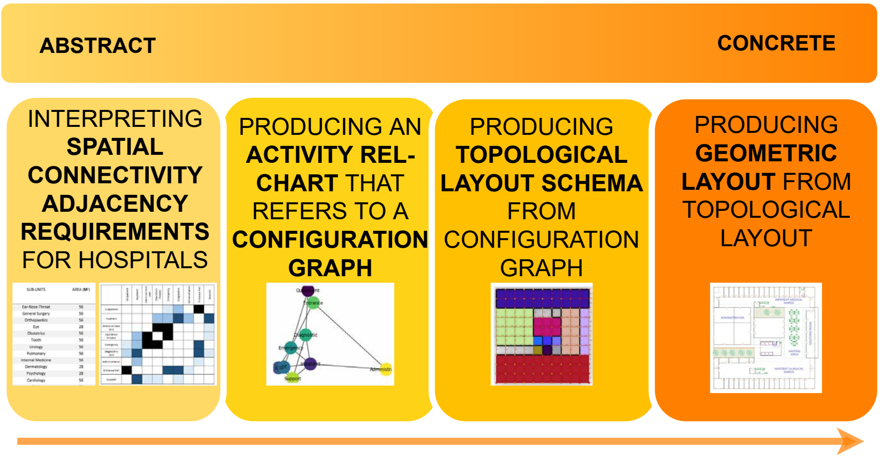

FIG. 1.8 “From abstract to concrete” process considered in this research

Each step of the process (in Figure 1.8) contains different tasks that correspond to each research question. This research starts with a worldwide literature review to understand hospital problems pertaining to its configuration and to look at the state-of-art for establishing configurational layout optimization methods on the specification of hospital space planning in the current literature. The second part of this dissertation contains preliminary research that deals with defining spatial adjacency, closeness and connectivity requirements in the form of an activity-relationship chart (often abbreviated as an ARC model or a REL-Chart) and a comprehensive program of requirements (PoR) for hospitals considering design codes and standards. This part also simultaneously supplies background information that can be served as input for the following section: Method Development & Case Studies. This stage focuses on developing methods for two different tasks that are commonly related to configurational layout optimization for hospital design: [A] Reconfiguration of the existing hospitals; [B] Designing a new hospital from scratch. Methods presented in this dissertation have been programmed and put in the form of design toolkits, namely QAP_Solver and MIP_Solver. Followingly, the developed methods are validated through application to real-world hospital case studies by using developed tools. An overview of the applied research methodology is available in Figure 1.9 and elaborated here on.

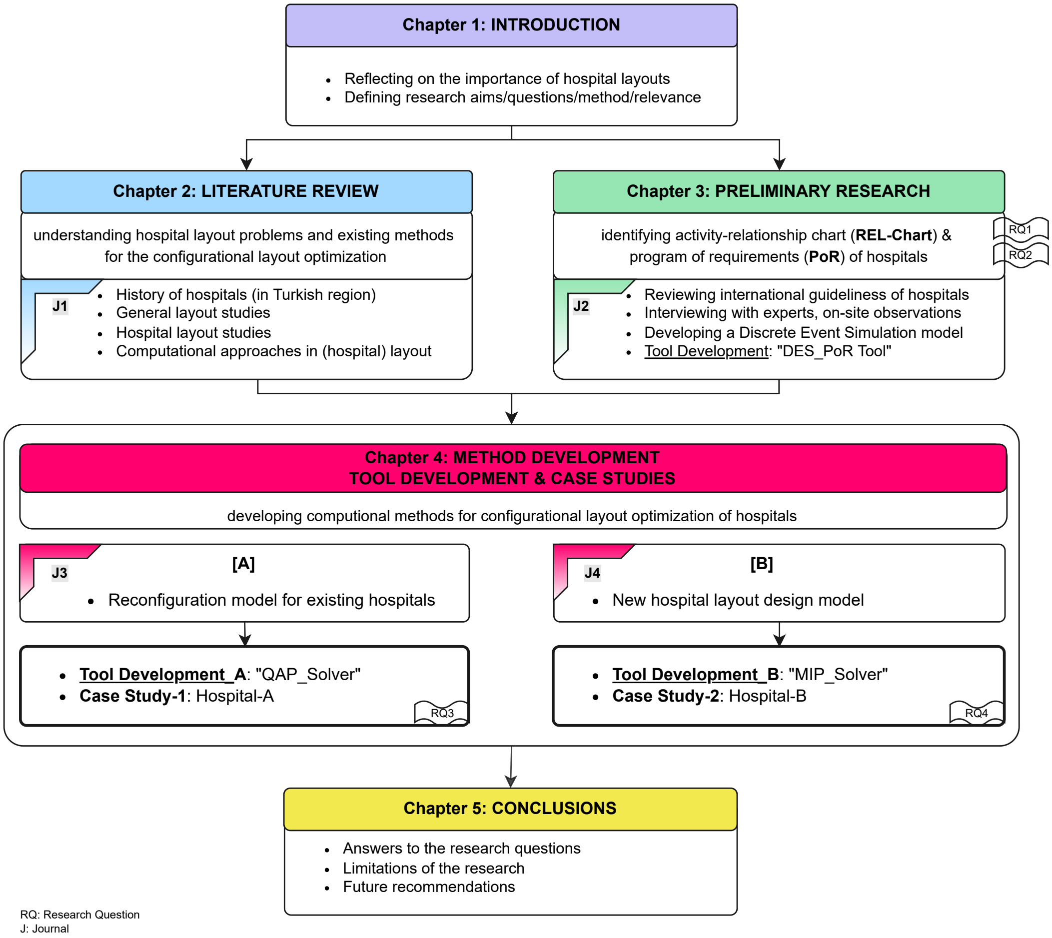

FIG. 1.9 book structure according to the methodology

Part 1 – Literature Review

This chapter begins with a historical review focusing on the development of hospitals in the Turkish Region throughout history for understanding the chronological background of the topic. This chapter continues with a systematic generation of a reference database considering published papers from 1950 onwards that deal with a taxonomy including keywords related to Architectural Layout, Facility Layout, and Hospital Layout. Then, a world-wide literature review is presented to identify the required developments in this field as well as to be able to understand general problems in hospital design and develop relevant methods and tools that can handle our research questions.

Part 2 – Preliminary Research

This chapter presents a typical REL chart and a PoR of hospitals to provide an example of the most abstract input information for hospital design processes. This chapter starts with reviewing the international hospital design guidelines to understand the functional units of a hospital and their spatial relations. This is followed by collecting expert knowledge from various medical practitioners and healthcare architects and by realizing on-site observations to understand the hospital layout problems or to perceive the ideal planning in hospitals. As a next step, a computational tool, called DES_PoR tool, is proposed that is calculated space requirements based on hospital design codes and standards and performed a discrete event simulation (DES) for patient-flow modeling. In this tool, outputs of the DES model (waiting times, number of patients treated by doctors in a day, etc.) facilitate the validation of the match between space planning elements such as PoR and REL charts and the operational logic of the building.

Part 3 – Method Development & Case Studies

This chapter introduces a computational design methodology for reaching a configurational layout for hospitals including two proposed models, namely reconfiguration of the existing hospitals (track A), and designing a new hospital layout (track B). The proposed methods in this chapter were produced by utilizing from multidisciplinary approach including **Computational Design workflows, Graph Theory techniques, Operations Research, and Computational Intelligence.** In the first track, the model presents a Quadratic Assignment Problem (QAP) formulation with a heuristic optimization algorithm to minimize travel time between interrelated functional units by using actual spatial distances with a geodesic distance calculation method. The voxelization process is applied to the existing hospital building for the assignment of the hospital facilities to the existing voxels that refer to existing locations. The second track presents a holistic method that considers stacking (defining levels), zoning (placement of the functional units), and routing (defining corridors between functional units) stages of the hospital design. In each stage, Mixed-Integer Programming (MIP) formulations are proposed, in particular, the zoning stage considers minimizing the closeness of the interrelated areas subject to various constraints related to space area requirements, cohesion, adjacent rooms, fixed locations for some spaces, non-overlapping spaces, adjacency to North, East, West, South (Hereinafter abbreviated as NEWS) borders because of lighting requirements, discrete entrance requirements, flexibility requirements for the spaces that can need future expansion, privacy/community requirements; on the other hand, routing includes maximizing way-finding subject to route separation for minimizing chances of interruptions of the medical staff and several validity constraints. Ultimately, each method is programmed in parametric CAD software and formed as a computational design toolkit (QAP-Solver & MIP-Solver) and applied to real-world case study hospitals for validation of the methods.

1.7 Relevance

1.7.1 Societal Relevance: Problems Caused by Poor Layout

Hospitals are essential public buildings that serve 24/7 with a diverse spectrum of functional units, different types of users, and healthcare system complexities. Spatial layout configuration has an impact on the efficient functioning of those buildings. The poor layout design can cause many problems that mainly affect humans in terms of the safety and security of the patients, recovery time, and the comfort and ergonomics of the medical staff. Problems related to distance and way-finding (accessibility) as well as those related to views, daylight, and direct sunlight (visibility) in hospitals can be directly attributed to the layout. A secondary set of problems related to noise, the efficiency of piping and wiring schemes, as well as cleanliness and reduction of the chances of cross-contamination can be attributed to adjacencies and transportation efficiency, which again can be traced to layout issues. Some of these problems in particular have been reported in Section 2.5. Arguably, if these problems are formulated in terms of minimizing such costs and risks (and/or maximizing benefits) in explicit relation to the layout of the building the result will be probably better. So, the societal relevance of this thesis is to solve these invisible human-factors problems by handling the layout problem as both arrangements of units and circulation routes in hospitals play an important role in human life.

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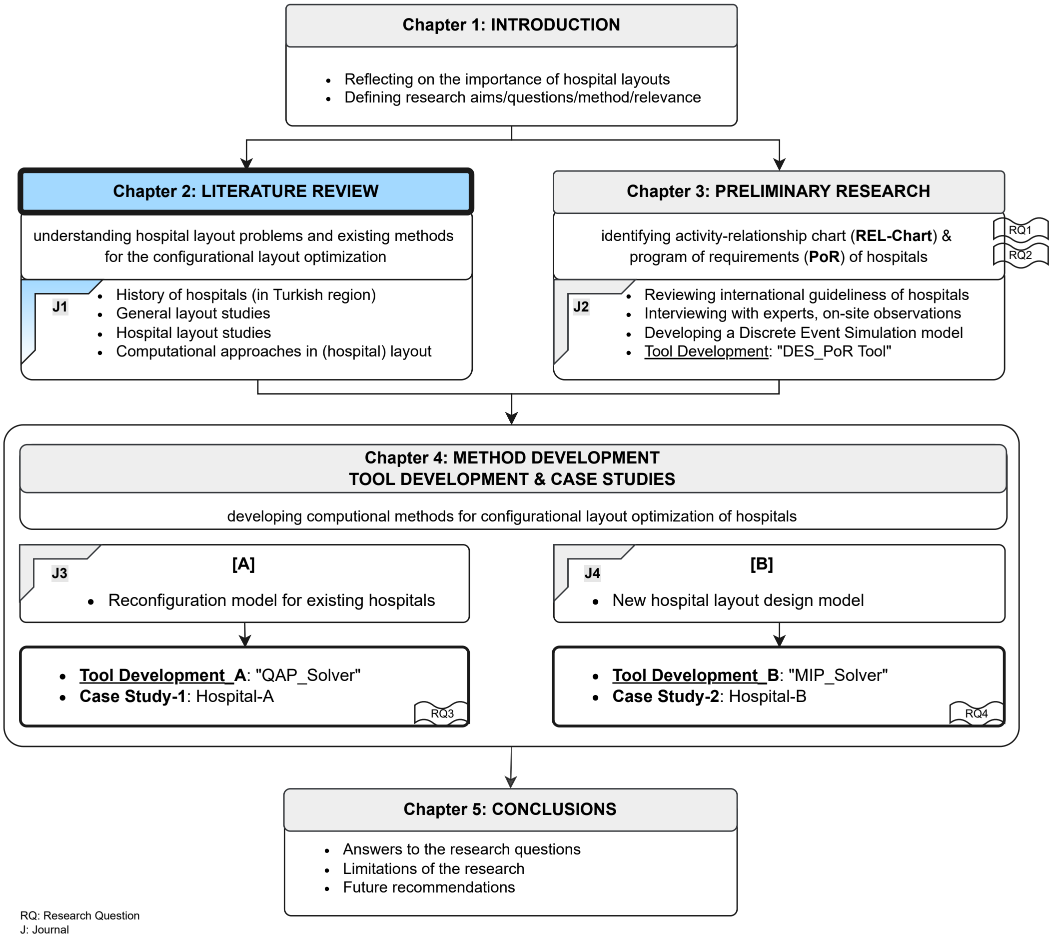
1.7.2 Scientific Relevance: Operations Research Formulation of HLP

The scientific relevance of this thesis is to develop new computational techniques, methods, and design tools for Hospital Layout Design Optimization using Computational Architecture techniques. This research is an interdisciplinary work between Architecture and Industrial Engineering. More specifically, it combines multiple scientific areas in one framework. These areas can be listed as Healthcare Architecture, Computational Intelligence, Architectural Space Planning, Graph Theory, and Operations Research.

– The contributions are attained to both disciplines. From the Architecture point of view, new layout design tools and methods are developed for optimizing buildings, in particular for facilitating the performance-aware design of hospitals. From the point of Engineering, a new application field is opened for Industrial Engineering disciplines in addition to existing ones (such as logistics, finance, and production).


Chapter 1: INTRODUCTION
Reflecting on the importance of hospital layouts
Defining research aims/questions/method/relevance
Chapter 2: LITERATURE REVIEW
understanding hospital layout problems and existing methods for the configurational layout optimization
J1
History of hospitals (in Turkish region)
General layout studies
Hospital layout studies
Computational approaches in (hospital) layout
Chapter 3: PRELIMINARY RESEARCH
identifying activity-relationship chart (REL-Chart) & program of requirements (PoR) of hospitals
RQ1
RQ2
J2
Reviewing international guideliness of hospitals
Interviewing with experts, on-site observations
Developing a Discrete Event Simulation model
Tool Development: "DES_PoR Tool"
Chapter 4: METHOD DEVELOPMENT
TOOL DEVELOPMENT & CASE STUDIES
developing computional methods for configurational layout optimization of hospitals
J3
[A]
Reconfiguration model for existing hospitals
J4
[B]
New hospital layout design model
Tool Development_A: "QAP_Solver"
Case Study-1: Hospital-A
RQ3
Tool Development_B: "MIP_Solver"
Case Study-2: Hospital-B
RQ4
Chapter 5: CONCLUSIONS
Answers to the research questions
Limitations of the research
Future recommendations
RQ: Research Question
J: Journal

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2 Literature Review

In this chapter, firstly, the history of hospitals specific to the Turkish region has been reviewed for understanding the chronological background of the topic. Then, a systematic worldwide literature review has been realized on the “general layout studies” and specifically “hospital layout studies” by generating a reference database with relevant keywords regarding the topic on hand in this dissertation. In the general layout studies part, both facility layout and architectural layout methods in the current literature have been reviewed. In the review of hospital layout studies, the problems considered for hospital layout planning have been listed and the methods of how they are handled in the current literature have been reviewed. This allows us to understand the key problems of hospitals regarding their configurational layout and the relevant optimization and simulation methods to solve them. In addition, a review of computational tools that were developed for architectural layout planning has been done and this helped us to see the limitations in the current computational design industry for layout planning that can be used for hospital design.

2.1 Historical Review of Hospitals in the Turkish Region

This sub-chapter has been submitted by: Cubukcuoglu, C., Durmuslar, F. and Sariyildiz, S., 2022. Architectural Evolution of Hospital Buildings. Journal of Architectural Histories.

This chapter presents the historical review of hospitals, the developments in Medicine, and their effects on the layout of hospitals throughout history. From the ancient to the early modern period, it was examined the alterations of treatment and diagnosis methods as changing lifestyles and living conditions of each historical stage, thus allowing us to observe their influences on hospital buildings and spatial compositions. In particular, it was focused on prehistoric, ancient Egypt, ancient Greek, Roman, Byzantine, Seljuk, and Ottoman periods, in which the biggest changes in hospital evolution were observed in the past. Since this dissertation focuses on Turkey’s hospitals, the review has mostly reflected the Turkish region hospitals chronologically by following the periods in Figure 2.1.

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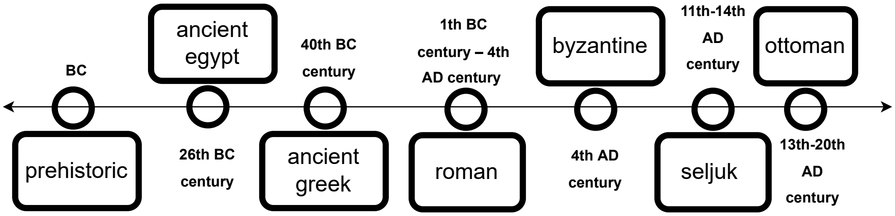

FIG. 2.1 Historical development of hospitals

2.1.1 Prehistoric Period of Hospitals

In past excavations, there are some papyruses and clay tablets found related to medical issues. Along with these remains, magical treatment methods against illnesses were based on magic. The first hospitals, which date back prehistoric period, were part of religious institutions.

2.1.2 Ancient Egypt Period Hospitals (26th BC century)

In ancient times, temples were used as healing centers in Egypt, India, and Iran. According to [30], [31], the origin of medicine reaches Thebes and the first institution that acted as kind of a hospital in Ancient Egypt was the House of Life. The other functions of these institutions were storing and producing books, and educating the doctors, scribes, and priests. In addition, they were defined as sanctuaries in which health services were done [32]. One example of a House of Life still surviving in archaeology is in the city of Akhenaten at Amarna [33] (See Figure 2.2).

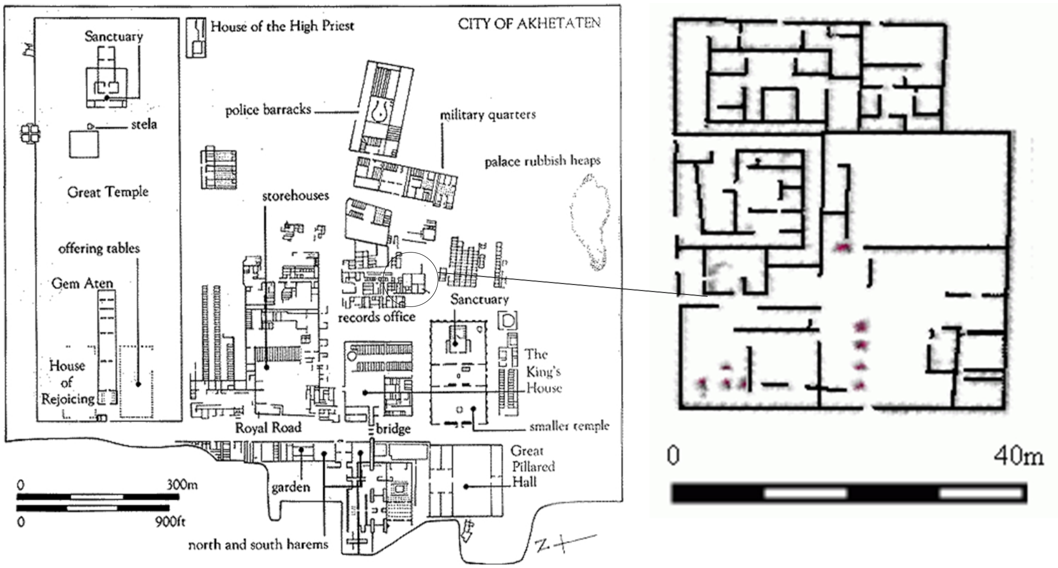

FIG. 2.2 Site plan of settlement of Akhenaten (Left); Plan of House of Life in Akhenaten (Right) [33]

2.1.3 Ancient Greek Period Hospitals (40th BC century)

In the ancient Greek period, there were not such buildings that acted as hospital facilities. Physicians and other specialists treated sick people in their homes based on sacred treatment methods [34]. The earliest form of hospitals was established as healing temples, called Asclepions located in Epidaurus, Kos, Pergamum, and Knidos [35]. There were a fountain, spring, temple, and altar inside them. After they had started to act as medical schools and resting places for patients under treatment, they also included a library, amphitheater, and monumental health facilities over time. The site plans of Asclepios are given in Figure 2.3.

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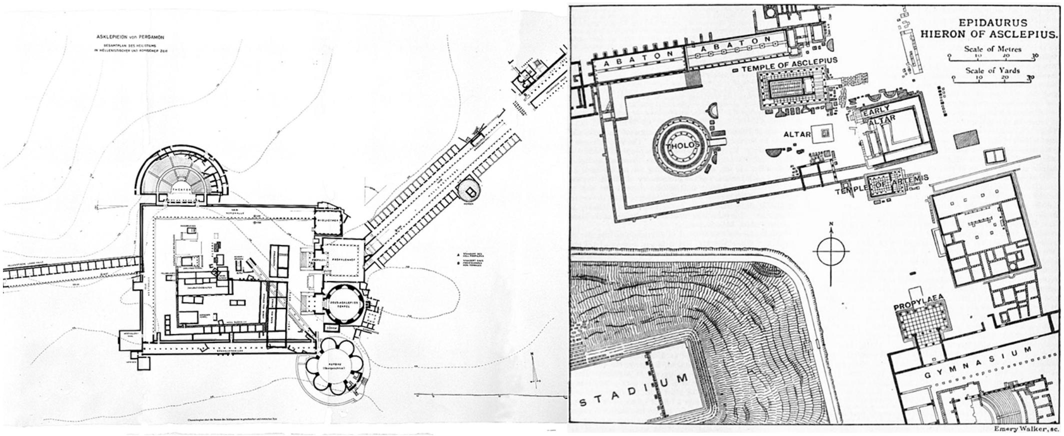

FIG. 2.3 The plan of Asclepion in Pergamum (Left) [36]; The site plan of Asclepion in Epidaurus (Right) [37]

2.1.4 Roman and Byzantine Period Hospitals (1th BC Century – 4th AD Century)

Following the Greeks, Asclepion healing centers improved during ancient Rome. They also acted like a sacred health spa. As a continuation of this, the concept of Roman baths also appeared in course of time in Anatolian [38]. Around 100 BC, the Roman people established military hospitals, called valetudinarian, for the treatment of sick and injured soldiers [39], [40] (See Figure 2.4).

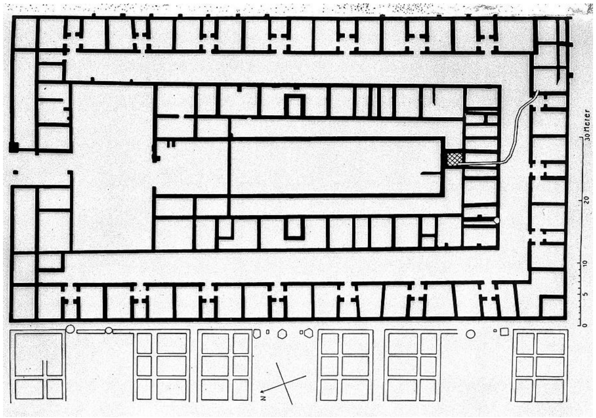

FIG. 2.4 Plan scheme of military hospitals, Valetudinarium (Roman Period) [20]

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In the Byzantine period, a new approach to healing was developed with Christianity [39]. Healing and hospitals became an issue of the church [39]. However, Byzantines opened the first public hospitals, which included room, board, and therapeutic care, based on scientific medicine, to anyone who needed such services. These hospitals are named xenodocheia or xenons (hospices or hostels also known as the house of strangers) [41]. Healing centers were organized as modern hospital structures in Byzantine Period. There were doctors, and nurses in hospitals. Wards of hospitals were classified according to illness and treatment [42] like specializations in today's hospitals. Baths as treatment elements were incorporated into the architectural planning of hospitals in this period [43]. (See Figure 2.5).

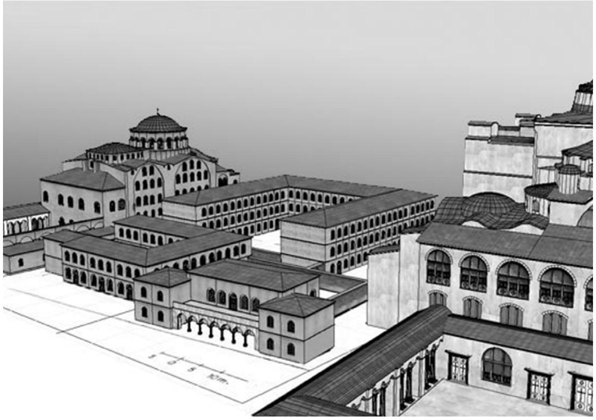
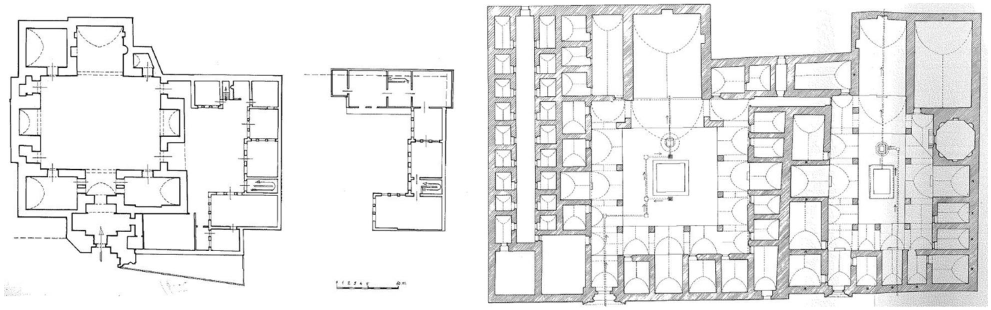


FIG. 2.5 Hospital of Sampson, Byzantine Period [44], [45]

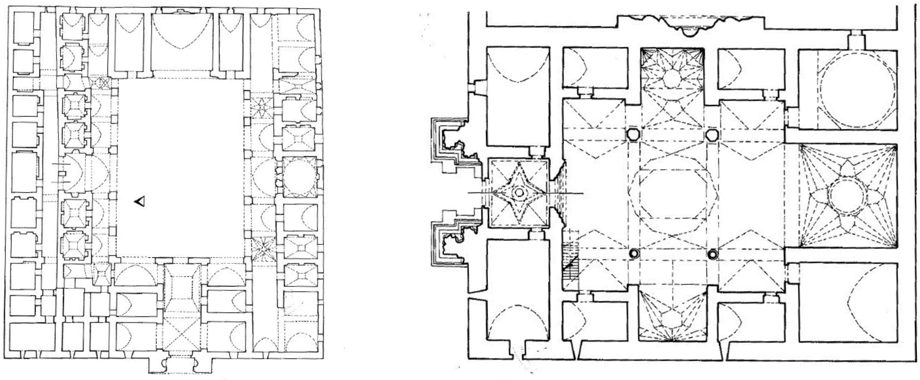
2.1.5 Seljuk Period Hospitals (11th – 14th AD Century)

During the Anatolian Seljuk period, Muslims have been searching for treatment and medicine instead of those efforts based on magic [46], [47]. In this period, *darüşşifa* healing centers were part of madrassas that acted as educational institutions, schools, or universities. Konya, Kayseri, and Sivas were the most important cities in Anatolian Seljuk's period in terms of social and cultural features [48]. From the perspective of the architecture of Seljuk's hospitals, they brought the moon and sun motifs together with the animal figures inspired by the twelve animal calendars together with the dome constructions that played an important role in the development of gothic architecture in Europe. These Seljuk hospitals, in addition to being the oldest Islamic hospitals that have arrived today, also had great impacts on the history and the development of the world hospitals. (See examples in Figure 2.6 and Figure 2.7).



Nureddin Hospital in Damascus (1154)

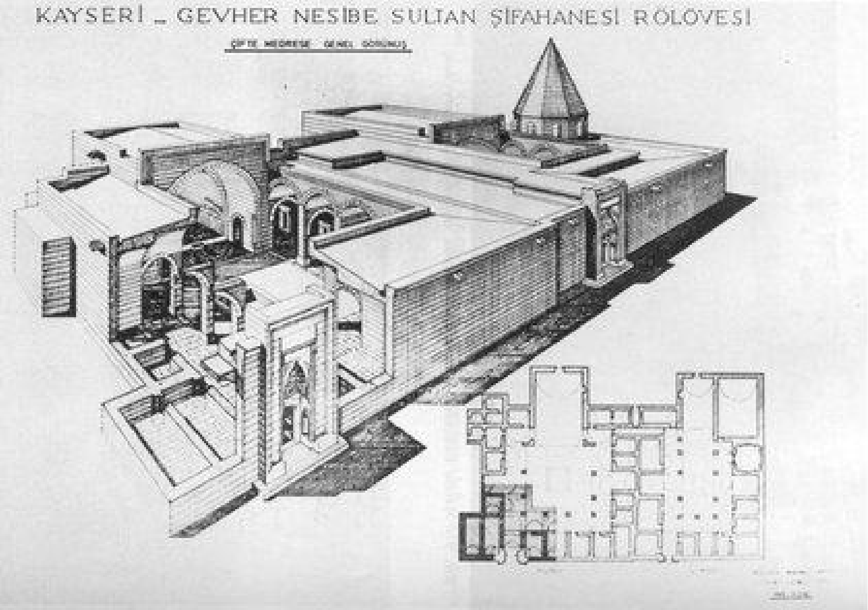
Gevher Nesibe Darüşşifa in Kayseri (1206)



Izzeddin Keykuvad Darüşşifa in Sivas (1217)

Divriği Darüşşifa (1228)

FIG. 2.6 Hospital plans in Seljuk Period [46], [47]



Res. 11 — Kayseri Gevher Nesibe Darüşşifası ve Tıp Medresesinin rölövesi (M. Akok ve C. Erol).

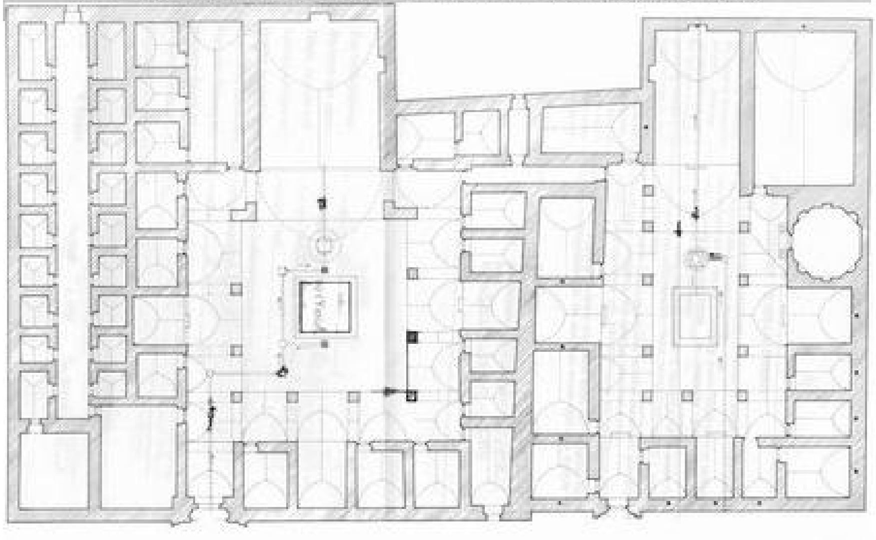


FIG. 2.7 Gevher Nesibe Sultan Hospital in Kayseri [49]

The Place of İbn-i Sina in the History of Medicine:
During the 11th century, İbn-i Sina (980- 1037) became one of the most significant physicians with many contributions to the development of medicine and medicine education. He began to receive treatment at a very young age [50]. He had a privileged place in both Islamic and European medicine by investigating new ideas and proposing theories. He is also known as Avicenna in Europe. He has written several books about medical works. The most famous one is “El Kanun Fi’t Tıb” (The Canon of Medicine), which has been taught in medical schools over the centuries in Asia and Europe. Besides medicine, he also contributed to the fields of mathematics, astronomy, physics, chemistry, geology, philosophy, theology, poetry, and music [50].

2.1.6 Ottoman Empire Period Hospitals (13th – 20th AD Century)

In the Ottoman Empire period, the importance of healthcare increased with the increasing of epidemical illnesses around the world. Hospitals designed as open madrassahs [30], [32], [51]. There were some improvements in plan schemes during Selim III (18th century) period as a such sanctuary and pharmacy units were added to the building plans. In the 19th century with the Abdulhamit period, the hospital buildings were separated according to illness levels to prevent epidemical illnesses. As another development in this period, the pavilion type of hospitals appeared while each pavilion worked as a kind of little hospital [30] (See Figure 2.8).

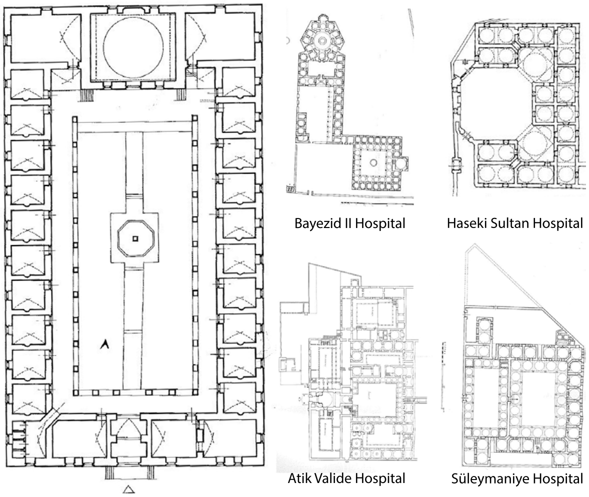

Bayezid II Hospital
Haseki Sultan Hospital
Atik Valide Hospital
Süleymaniye Hospital

FIG. 2.8 Yıldırım Bayezid Hospital in Bursa [46], [47], [52] (left) and Ottoman Hospitals [46], [47], [53] (right)

2.1.7 Analysis of Historical Developments of Hospitals

In prehistoric times, physicians treated sick people at their homes until the awareness of the need for such buildings as hospitals for medical diagnosis and treatments. These kinds of buildings had realized in the late ancient periods and came through many changes over time. There have been many developments in their design approaches due to the increasing needs of people. In addition, their functional missions are sometimes altered according to medical requirements and patient preferences. Despite years of evolution, their designs are still challenging in terms of functional, operational, and architectural. In this section, the purpose is to understand and assess the architectural developments of hospital buildings in each inherent historical stage, which collectively reflects the medical and architectural changes of the hospital buildings.

From the ancient to the early modern period, both functionality and architectural features of hospital buildings have changed over time. The definition of hospitals transformed due to the life-style of each historical period. In ancient times, hospitals were the places where sick people pray and spend their time before dying. Then, hospitals have gained the definition of healing places where sick people are treated in various ways. In time, it has gained more functions as educational places, religious places in some cases entertainment places. During the ancient period, very important physicians such as Hippocrates, Galen, and Asclepios whose ideas are still taught to medical students, started medicine education as well as in later times İbni Sina had many contributions to Medical Science. From the perspective of architecture, it can be observed in the history of hospitals that all developments are built upon the current ones. With the improvements in hospital buildings, their spatial compositions also changed and somehow got more functionally complex. It is also observed that some of the important facts affected the types of hospitals. For instance, military hospitals seem to be in an increasing period of wars whereas special hospital types (such as sanatoriums) are seen in the period of epidemic diseases (like the 19th-century plague).

2.2 Systematic Generation of a Reference Database for Review of Layout Problems

We defined a taxonomy of problems related to layout configurations as shown in Figure 2.9. Here we discuss the general problem of Configurational Layout, Hospital Design, and their relations. More specific references to literature concerning approaches used for problem-solving will appear in the next chapters wherever a specific problem-solving approach is discussed.

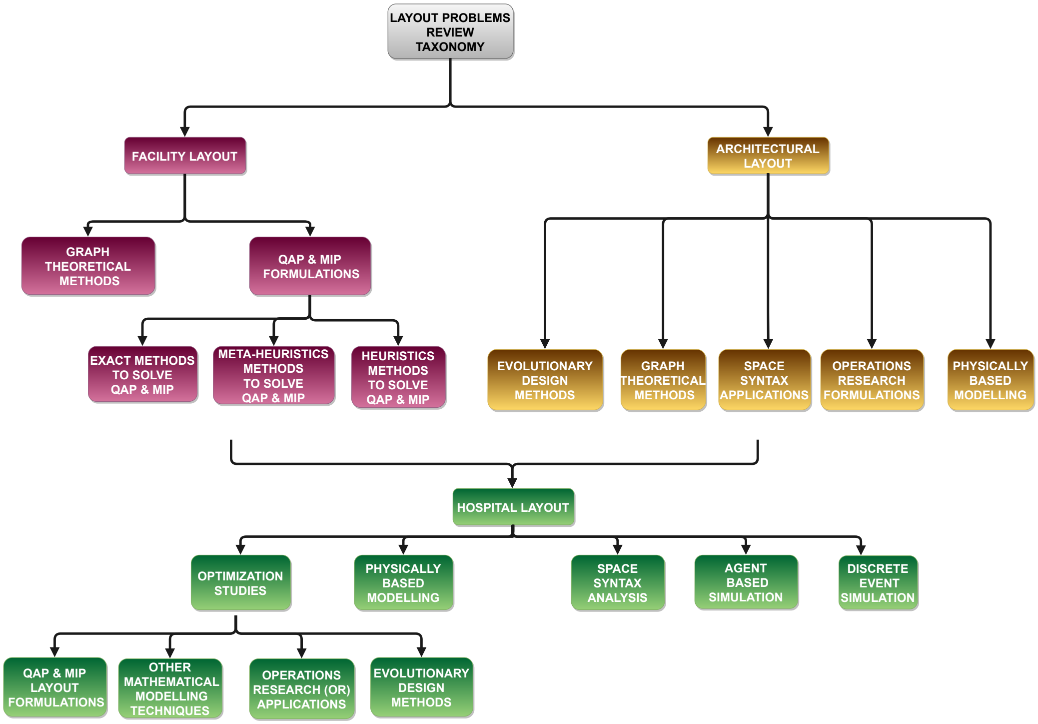


FIG. 2.9 Layout problems review taxonomy

Here, research experiences from journal papers were taken as the base material for the review on “configurational layout in general” and specifically on the topic of “hospital layout”. For gathering relevant studies within the scope of the general layout review, following the taxonomy, two topics were defined as inputs: “Facility

Layout" and "Architectural Layout" during the search process. This serves the purpose of limiting the results to the most corresponding papers and getting a manageable number of papers excluding outliers. The search process was realized by using two online databases Science Direct and Scopus starting from the 1950s to 2018 as shown in Table 2.1.

TABLE 2.1 Literature search process with identified keywords

	1st search_FLP		2nd search_FLP		3rd search_FLP	
Type of Search	Title / Abstract / Keywords		Title / Abstract / Keywords		Title / Abstract / Keywords	
Publication Date	All years		All years		All years	
Search Keywords	"facility layout" AND "quadratic assignment problem" AND "heuristics" OR "meta-heuristics" OR "exact" AND NOT "hospital"		"facility layout" AND "mixed integer programming" AND "heuristics" OR "meta-heuristics" OR "exact" AND NOT "hospital"		"facility layout" AND "graph theory" OR "graph theoretical" AND NOT "QAP" AND "MIP"	
Document Type	Journal Article		Journal Article		Journal Article	
Language	English		English		English	
Databases	Science Direct	Scopus	Science Direct	Scopus	Science Direct	Scopus
Last Seen	8.02.2018		8.02.2018		8.02.2018	
Matches Found	12	56	2	17	7	33
Combined*	31 papers in total		13 papers in total		21 papers in total	

	4th search_ALP		5th search_HLP	
Type of Search	Title / Abstract / Keywords		Title / Abstract / Keywords	
Publication Date	All years		1950 to Present	
Search Keywords	"architectural layout" AND "evolutionary algorithms" OR "graph theory" OR "space syntax" OR "operations research"		"hospital" AND "layout" OR "configurational layout" OR "space planning" OR "spatial layout" OR "spatial configuration" OR "architectural configuration" OR "plan layout" OR "floor plans" OR "spatial arrangement" OR "architectural layout" OR "layout planning"	
Document Type	Journal Article		Journal Article	
Language	English		English	
Databases	Science Direct	Scopus	Science Direct	Scopus
Last Seen	8.02.2018		10.01.2018	
Matches Found	12	56	105	784
In Scope			32	31
From references			5	
Combined*	53 papers in total		45 papers in total	

* in scopes

TOC

2.3 Facility Layout Problems

Facility layout problems (FLP) are a class of operations research problems[2] that attracted the attention of researchers since the 1960s [54]. It deals with selecting the most effective arrangement of physical facilities within a plant. Its design has a great influence on the performance of production systems [55]. According to the literature, between 20% and 50% of the total manufacturing costs correspond to material transportation. However, this total cost can be reduced by 30% [26], [56] through effective layout planning. Therefore, facility layout planning generally concentrates on material handling costs as an objective in a production facility [26]. There are several problem formulations and solving techniques in the literature to deal with FLPs. Those techniques can be useful in different building types beyond the manufacturing plants considering different types of objectives such as customer satisfaction, utilization of space, ergonomics, equipment, and people, and efficient flow of information and people. Problem formulation techniques for FLPs in the literature can be designed according to the nature of the facility layout arising from

- departmental area requirements (equal/unequal),
- number of rows (single/double/multi),
- number of floors (single/multi),
- number of objectives (single/multi),
- static layout (constant flow of materials over the entire time planning horizon),
- dynamic layout (changing flow of materials or product demands from period to period),
- and some special cases.

In the reviewed literature, the majority of the facility layout problems have been addressed as combinatorial optimization problems e.g. quadratic assignment problem (QAP) and its variants, mixed integer programming (MIP) techniques, and graph theoretical approaches. One of the most popular problem formulation techniques for FLPs is the quadratic assignment problem (QAP) a mathematical model developed by Koopmans and Beckmann (1957) [57]. In the QAP, the facility departments can only be assigned to predefined grid locations such that the total cost (flows between facilities x distances between locations) is minimized (See

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[2] The term, operations research is a discipline that aims at finding the most appropriate solution for a given purpose in a situation where certain constraints exist.

Figure 2.10). Due to the quadratic nature of its objective function, the majority of the works implemented heuristic algorithms rather than exact methods to cope with the QAP-type facility layouts. A broader review of the QAP literature on the topics of general layout and hospital layout can be found in Chapter 4.1 of this thesis. On the other hand, FLPs have been formulated as MIP for the continuous representation of areas and to avoid overlapped departments in the early 1990s. MIP consists of both integer and real variables in its formulation. The length and width of the departments are also decision variables in this problem, thus allowing unequal areas in the layout. In this way, it overcomes the drawback of QAP, which only accepts equal area departments [58], [59]. In this formulation, distances between departments are considered as the rectilinear distance from their centroids. In addition, the facility can be considered rectangular or non-rectangular depending on the problem on hand. Therefore, the basic MIP model focuses on distance-based function, which includes the flow of the material and rectilinear distances between department centers. A detailed review of the MIP techniques on both configuration layouts in general and on the specific hospital layout can be found in Chapter 4.2 of this thesis.

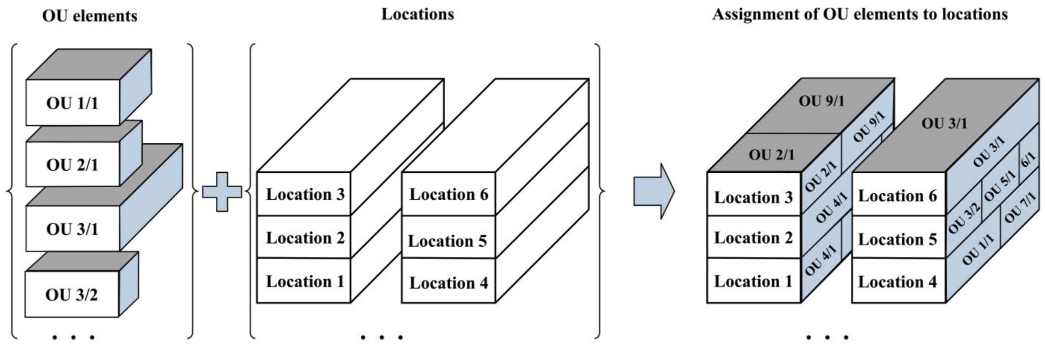

FIG. 2.10 QAP-type layout problem representation from Helber et al. (2014) [60]

In addition to the above-mentioned approaches, facility layout problems have been formulated as the weighted maximal planar graph (WMPG) problem in the literature. It is an NP-hard problem and hence hard to solve for realistic problem sizes in a limited amount of time [61]. According to this approach, facilities are corresponding to graph vertices and edges are relationships between them. This problem aims at finding a maximal planar subgraph, which has the highest sum of edge weights within the graph. A planar graph is embedded in the plane without any edges intersecting. For a maximal planar graph, no additional edge can be added to the subgraph without violating its planarity [62]. To tackle facility layout problems with graph theory, the main procedure started with constructing a weighted maximal planar graph using a relationship chart (adjacencies) and then creating the dual graph of this planar graph. Finally, it continues with converting the dual graph to a block plan layout considering the desired areas and shapes of the facilities (Figure 2.11). The most advantageous part of this formulation is the ease of capturing the adjacency information using graph theory. On the other hand, the last step, which is creating the floor plans, is the most challenging part of this problem in the literature [63].

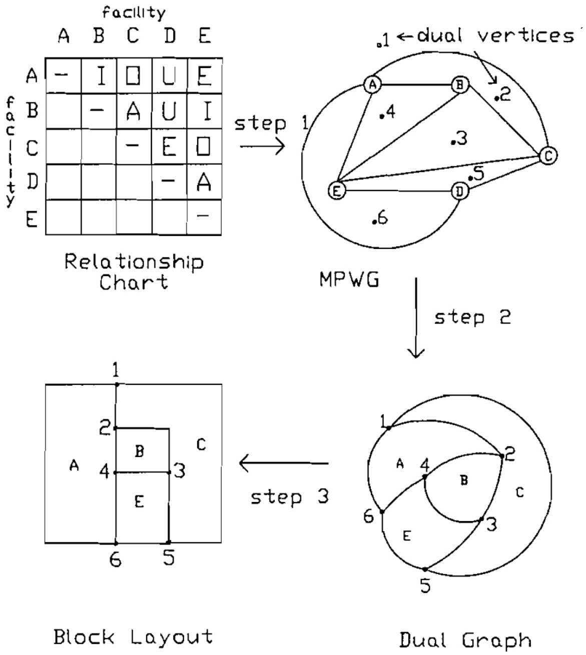

FIG. 2.11 Layout development by graph theory Hassan (1992) [64]

In the reviewed literature, Seppanen and Moore (1970) [65] is an early work that introduced a graph model for facilities layout planning. They further offered a solving approach based on string grammar in Seppanen and Moore (1975) [66]. Carrie et al. (1978) [67] developed an algorithm that made use of strings to represent the graphs. Foulds and Robinson (1978) [68] proposed a deltahedron heuristic algorithm to represent a WMPG and to keep it as planar throughout the construction stage to maximize the adjacency score. Giffin et al. (1986) [69] proposed a new heuristic method especially for generating block plan layouts to maximize REL Chart scores of adjacent pairs of facilities. Hassan and Hogg (1989) [64] developed a computerized method to convert a dual graph into a block layout

(See Figure 2.11). Al-Hakim (1991) [70] developed two graph-theoretic improvement heuristics, which are related to edge elimination and edge replacement, using a new operation for edge replacement, called -operation. Goetschalckx (1992) [61] used a spiral algorithm to create hexagonal adjacency graphs and then obtain the block layout respectively to maximize the adjacency score. Welgama et al. (1994) [71] proposed a new knowledge-based system, which comprised web grammar rules, for converting a dual graph into a block plan. Giffin et al. (1995) [72] used a deltahedron heuristic by interchanging edges to construct WMPG. A novel study by Kim and Kim (1995) [62] introduced new improvement heuristics for unequal area facility layout to minimize transportation distance. Irvine and Rinsma-Melchert (1997) [73] presented a new iterative method to generate a planar orthogonal layout or floorplan satisfying specific adjacency and areas of each facility [73]. John and Hammond (2000) [74] presented a heuristic approach for creating a WMPG through a non-optimal graph, which is a non- WMPG. Osman et al. (2002) [75] introduced an integer linear programming (ILP) model for the WMPG problem using a new iterative approach, namely the greedy randomized adaptive search procedure (GRASP). The same author also used GRASP to solve the WMPG problem in Osman et al. (2003) [76]. Lee et al. (2005) [77] proposed a new method for calculating distances using Dijkstra's algorithm [78] of the graph theory for multi-floor facility layout. As a novel study, Osman (2006) [79] proposed a tabu search algorithm to create WMPG. Jokar and Sangchooli (2011) [80] attempted to create block plan layout from a maximal planar graph introducing a new algorithm, called BLAD (Block Layout Algorithm for Deltahedron heuristic). Zheng (2014) [81] presented a method to generate connectivity graph to contribute the facility layout generation from abstract stage. Ahmadi-Javid et al. (2015) [82] recently presented a new formulation of WMPG problem using ILP model and solved it with a cutting plane algorithm.

2.4 Architectural Layout Problems

Architectural layout problems (ALP) differ from FLPs with various features. FLPs usually optimize transportation distance and in a few cases, adjacency score while controlling the variables that refer to the assignment of facilities to predefined places. However, ALP deals with more goals that are more related to the functional performance of the buildings such as ensuring sufficient and appropriate daylight. In conjunction with the development of computational tools in architectural design, various computational techniques have been utilized to solve so-called challenging architectural layout design problems for more than a decade.

2.4.1 Meta-heuristics algorithms for the design of ALP

In the reviewed literature, authors referred to nature-inspired metaheuristics to solve architectural space planning problems hence the evolutionary approaches are the most common ones. However, this approach is not capable of finding optimal solutions compared to exact solution methods. Specifically, they are capable of finding Pareto-optimal solutions in multi-objective optimization problems (e.g. Figure 2.12).

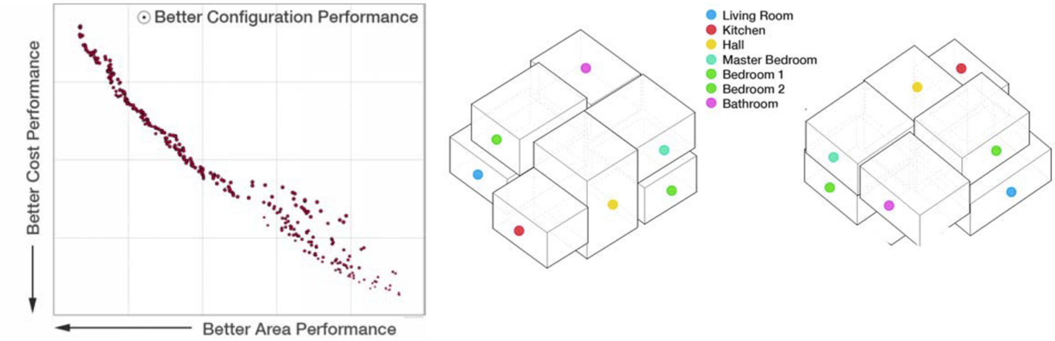

FIG. 2.12 A multi-objective layout development by NSGA-II algorithm (Chatzikonstantinou, 2014) [83]

In the reviewed literature related to this field, Jo and Gero (1998) [84] proposed a GA algorithm to optimize interactions and travel costs among interrelated spaces for an office layout. Michalek et al. (2002) [85] used both GA and SA to minimize heating costs, cooling costs, lighting costs, wasted space, hall size, and access way size for residential layouts. Bau⌧ys and Pankra⌧ovaité (2005) [86] proposed an improved version of GA to minimize heating costs, lighting costs, wasted space, doorways, and hallways for residential layout. Wong and Chan (2009) [87] introduced evolutionary algorithms (EA) for optimizing adjacency preferences and limitations and the range of relative ratios between spaces for residential layouts. Rodrigues et al. (2013a, 2013b) [88], [89] proposed a novel approach using a hybrid technique that combined evolutionary strategy and stochastic hill climbing to optimize connectivity, adjacency, spaces overlapped, openings overlapped, and orientation of openings, floor dimensions, compactness, and overflow for residential layout. Chatzikonstantinou (2014) [83] studied a multi-objective architectural space planning problem using NSGA-II (See Figure 2.12). Song et al. (2016) [90] used a new version of GA, namely implicit redundant representation genetic algorithm (IRRGA), to maximize symmetry, structural safety, stair connectivity, and façade exposure in a residential layout. As an example of 3-dimensional layout work, Dino (2016) [91] introduced Evolutionary Architectural Space layout Explorer, called EASE, to optimize unique fitness functions based on size, absolute dimension, compactness, jaggedness, the convexity of space, adjacency for a library layout. Bahrehmand et al. (2017) [92] proposed an EA to maximize overflow quality, topological quality, spatial quality, and user rating for a museum layout. As an example of a holistic approach, Dino and Üçoluk (2017) [93] first configured the space layout and foremost designed the façade of the building. In the first step, they used EA to optimize unique fitness functions based on space size, space absolute dimension, space compactness, space jaggedness, space convexity, facade, floor, neighbourhood, and separation. The next step of this study continues with a Pareto ranking approach using NSGA-II to maximize the energy and daylight performance of a building. Recently, a study by Guo and Li (2017) [94] proposed a multi-agent topology finding system and an evolutionary optimization process. A detailed review of the use of metaheuristic optimization algorithms on the ALP can be found in our collaborative study titled “Performative computational architecture using swarm and evolutionary optimization: A review” in [95]. As shown in [95], the consideration of heuristic algorithms in layout studies is very scarce.

2.4.2 Graph Theoretical Approaches for the design of ALP

The graph theory for the representation of architectural layouts has been demonstrated in a few works of the reviewed literature despite its potential on ALPs. In early works by [96], and [97], the advantages of graph theory applications to ALPs have been discussed.

In the reviewed literature, Levin (1964) [98] firstly proposed graph theory applications for spatial layouts. Grason (1970) [99] developed a planar graph grammar (PGG) to simplify the graph into sub-graphs by proposing a computerized space-planning model. Ruch and Julia (1978) [100] proposed three levels of hierarchical abstract representation comprised of a graph, bubble diagram, and schematic plan. During the bubble diagram generation, they generated a straight-line embedding of the graph using Tutte’s algorithm [101] and assigned lengths to the edges of the straight-line embedding of the graph to create touching circles. Roth et al. (1982) [102] presented a framework for the design of a floor plan with given adjacencies [102]. The first step in this framework is directing and colouring a planar adjacencies graph to create a coloured directed graph. The second step is determining the dimensions of sub-graphs. The last step is to determine envelope dimensions using the PERT technique [103] of the critical path method (minimum distance path for building envelope to minimize heat losses). Roth et al. (1988) [104] proposed another workflow for architectural floor planning. In this approach, program requirements are firstly defined with given adjacencies. Then, they decomposed a graph into subgraphs to create a simplified graph using min-cut and max-flow algorithms. They later solved the planarity problem to create planar graphs using edge-elimination or vertex-adding methods. The last step is the geometrical step for plan dimensioning to generate dimensioned floor plans using the PERT technique [103]. Schwarz et al. (1994, 1994) [105], [106] proposed a novel approach using the 2D compaction technique of VLSI layouts and at the same time presenting an automated building design for space planning. A novel approach by Medjoub and Yannou (2000, 2001) [107], [108] proposed topological solutions through graphs. They presented to refine them into geometrical solutions using dynamic space ordering heuristics based on both topological (adjacency or proximity) and dimensional constraints (length or width) for space planning. Roth and Hashimshony (1988) [109] dealt with an architectural space planning problem using graph theory (See Figure 2.13).

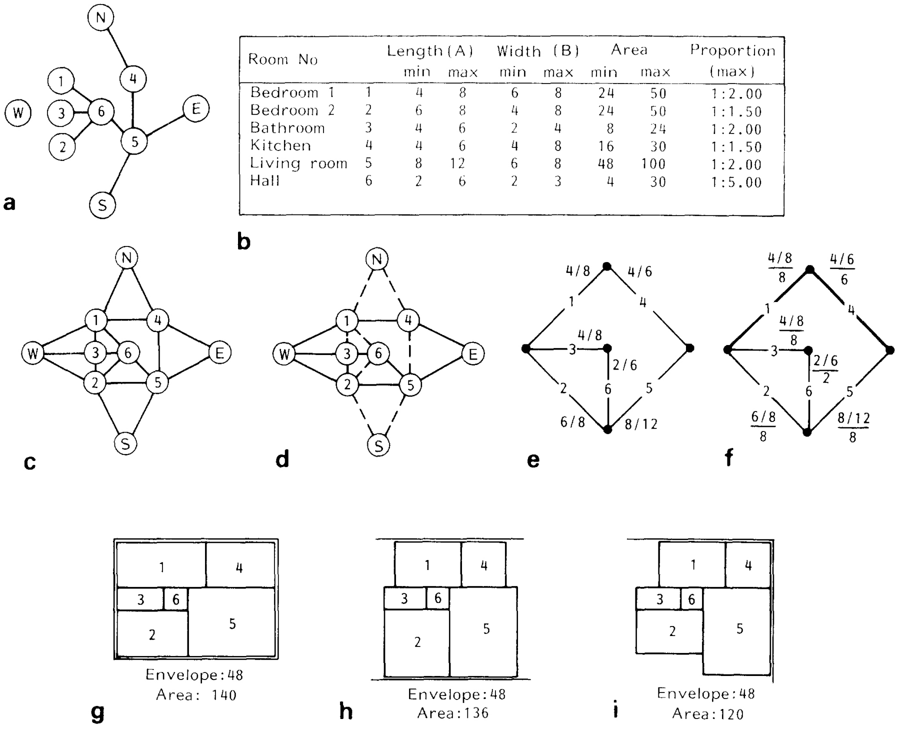
Room	No	Length (A) min	Length (A) max	Width (B) min	Width (B) max	Area min	Area max	Proportion (max)
Bedroom 1	1	4	8	6	8	24	50	1:2.00
Bedroom 2	2	6	8	4	8	24	50	1:1.50
Bathroom	3	4	6	2	4	8	24	1:2.00
Kitchen	4	4	6	4	8	16	30	1:1.50
Living room	5	8	12	6	8	48	100	1:2.00
Hall	6	2	6	2	3	4	30	1:5.00

FIG. 2.13 Architectural layout development by graph theory, Roth and Hashimshony (1988) [109]

2.4.3 Space Syntax Applications for the design of ALP

This approach is benefitted from not only space syntax analysis but also graph theoretical approaches. This is a novel approach proposed by Nourian et al. (2010) [110][111][9]. They presented a design methodology, called syntactic design methodology, for the configurative design of architectural plan layouts (See Figure 2.14). They offered real-time Space Syntax analyses to provide feedback on the spatial performance considering depth, integration, difference factor, control, and choice measurements. In this design methodology, convex graph drawings were obtained by using the customized Tutte algorithm, and kissing disk drawings were obtained from the force-directed graph drawing algorithm.

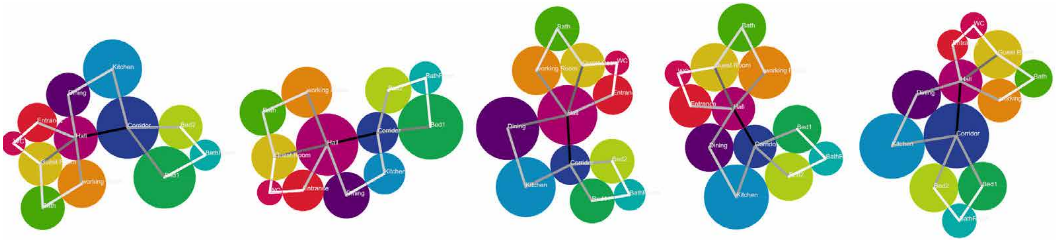

FIG. 2.14 Layout design development by space syntax analysis with a few samples of bubble diagrams produced by graph drawing algorithms, Nourian et al. (2010) [110]

2.4.4 Operations Research Applications for solving the ALP

Few examples make use of Operations Research techniques for ALPs despite their common use in FLPs. One of the methods utilized to solve architectural layout design problems is MIP, which was widely used in FLPs. In conjunction to find optimal solutions, Kamol and Krung (2005) [112] firstly proposed MIP to solve ALPs by adapting more objectives than FLPs have. They formulated the architectural layout design problem as the multi-objective MIP using a MIP solver with a weighted sum approach. The problem objectives are the minimization of the absolute distance among rooms and the maximization of room spaces. Problem constraints are the connectivity, the unused grid cells, the fixed room location, the boundary, and the fixed border location, and the non-intersecting, overlapping, length, and ratio constraints. Kamol and Krung (2006) [113] presented a practical formulation of MIP based on the strong valid inequality constraints, which reduced the feasible region using LP relaxations to solve the medium size architectural layout design. Later, Kamol and Krung (2008) [114] used MIP formulation for the architectural layout to optimize room positioning, room sizes, and distances according to the architect's preferences subject to functional, dimensional, non-circular, and guided constraints using CPLEX solver [115].

As an early work by Ritzman et al. (1979) [116], they proposed goal programming, which is a multi-criteria decision analysis, for space planning problems to handle multiple objectives. Problem objectives are minimizing the deviation from square footage space standards; distances between rooms, unwanted moves and optimizing the equitable distribution of air-conditioned offices to the departments, fair sharing of rooms, and occupancy of departments. Glover and McMillan (1985) [117] developed a decision support system that generated bubble diagrams, solved non-linear programming formulation models, and utilized block plan improvement heuristics. Problem objectives are optimizing proximity strengths subject to spatial restrictions by allocating the functions and spaces within a layout.

2.4.5 Physically Based Modelling for the design of ALP

This is a recent subject in space planning that applied the physics of motion to space elements. In this approach, space units are moving according to the forces of repulsion or attraction. Arvin (2002) [118] presented how to model a variety of design objectives in a physically based space planning system as shown in Figure 2.15. Topological objectives are defined as adjacency and orientation whereas geometric objectives are defined as an area, proportion, and alignment. In Guo and Li (2017) [94], they used the physics of motion to define interaction rules for moving the agents for a layout design. Those rules are based on attraction, repulsion, swap, and compression forces.

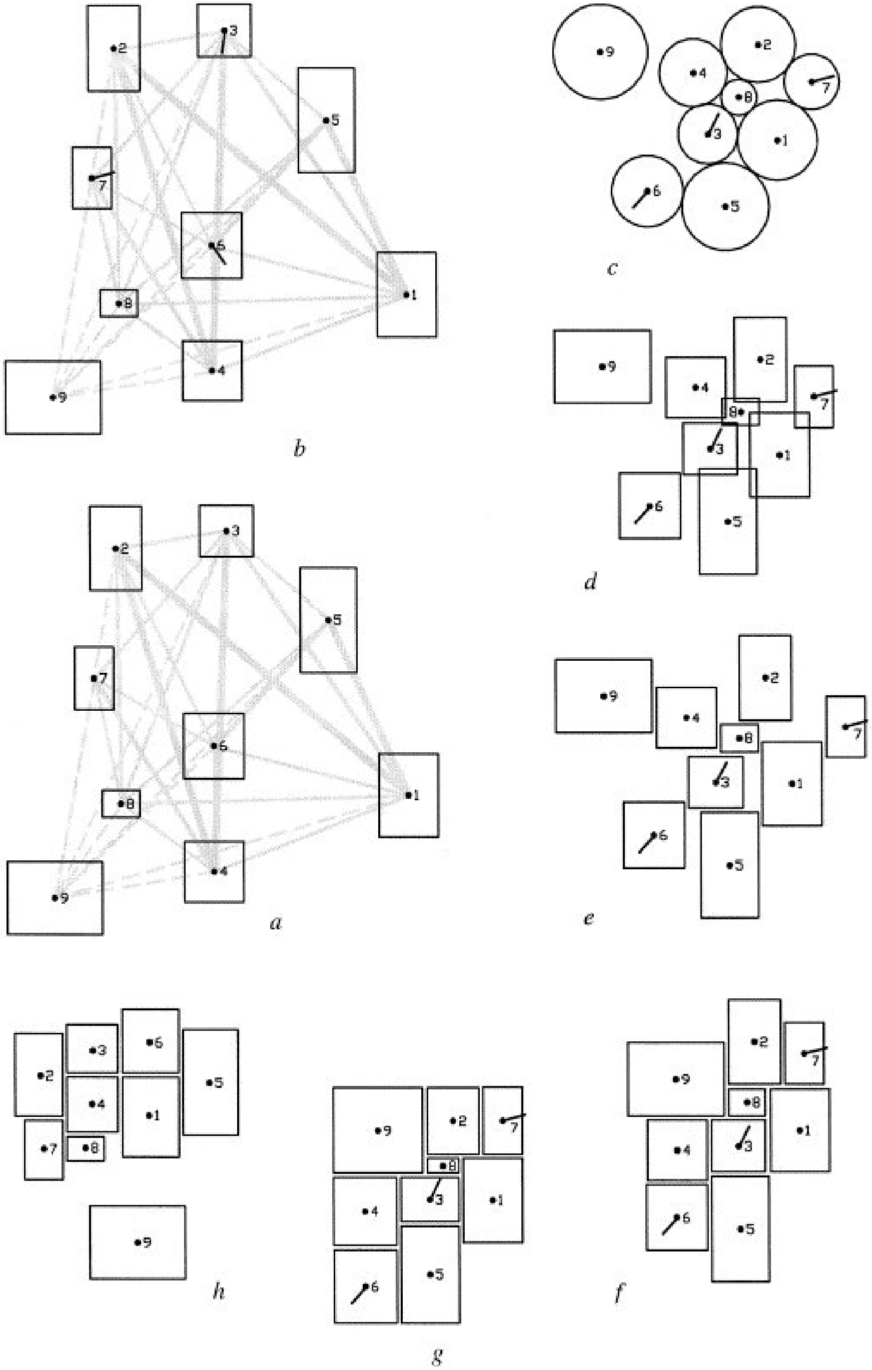

FIG. 2.15 Layout development by physically based modelling (Arvin, 2002) [118]

2.5 Hospital Layout Problems

The hospital layout problem, as a case study, is considered in both facility layout and architectural layout research. In some sources, the hospital layout problem is regarded as a pure engineering problem and in some other sources, mostly the architectural ones, human aspects of the hospital layout design are also included. In the reviewed hospital layout literature, we see that two major techniques are at the forefront of the researchers: optimization studies and analysis/simulation studies.

2.5.1 Optimization Studies for HLP

Related to optimization studies for HLPs, QAP and MIP formulations have been mostly utilized for solving hospital layout problems in the reviewed literature. The detailed review of QAP and MIP formulations implemented as a hospital layout case study can be found in Chapters 4.1 and 4.2 respectively. Other than those related to both QAP and MIP, there are also some other types of mathematical formulations as optimization studies for HLPs in the reviewed literature. Stummer et al. (2004) [119] investigated the trade-offs between travel costs incurred by patients and total costs associated with location-allocation hospital plans using a multi-objective tabu search. Liang and Chao (2008) [120] focused on a facility layout model to optimize adjacency and travel distances considering space requirements using the tabu search method. Motaghi et al. (2011) [121] considered quantitative relationships between activities for hospital layout optimization using a heuristic method (diamond algorithm). Arnolds and Nickel (2013) [122] aimed to ensure patient satisfaction with ward layout adaptations, formulated the problem with a mathematical model, and solved it using a CPLEX solver. Chraibi et al. (2016) [123] focused on material handling costs based on rectilinear distances, travel frequency, trip difficulty rating, baseline travel cost, and sequence of activities. The mathematical model is designed for an OT layout optimization in a hospital using the PSO algorithm. Rismanchian and Lee (2016) [124] formulated a goal-programming model to minimize distances travelled by critical and non-critical patients on patient flow, maximize design preferences and minimize relocation costs for assigning the emergency department units to locations using a CPLEX solver. Safarzadeh and Koosha (2017) [125] formulated a non-linear MIP model with fuzzy constraints and converted it to a linear MIP model for a multi-row hospital facility layout. They minimized handling costs and lost opportunity costs related to waste spaces using GA. Arnolds and Gartner (2017) [126] improved ICU and OT layouts through clinical pathway mining to minimize travel distances by formulating a math model and using a CPLEX solver.

Regarding the use of metaheuristics optimization algorithms on the HLPs, as more architectural problems, Gero and Kazakov (1998) [127] introduced also the GA algorithm to minimize layout cost comprised of travel distances and space relations for a case study of hospital layout. Gulec et al. (2013) [128] used an evolutionary design approach by a single objective GA to optimize the routing of the users in a health campus. Su and Yan (2015) [129] combined daylight simulations and an evolutionary design approach with a GA for the maximization of daylight illuminance and minimization of travel distances of nurses for a nursing unit layout optimization. As an example of a holistic approach, Sleiman et al. (2017) [130] proposed a framework that started with a spatial configuration and then a performative computational design of a building. During the space configuration, they proposed a new method using EA, namely an Early Design Configurator (EDC), to satisfy user requirements and geometric constraints. In the next step, design alternatives that are satisfied all requirements are selected, and performed energy and cost assessments by an Early Design Validator (EDV) for a healthcare building.

Some other OR techniques are observed in the HLP studies in the reviewed literature. Levary and Schmitt (1986) [131] improved a hospital facility layout planning using a group decision-making process, REL chart [132], from-to chart, and improvement heuristic. They aimed at increasing employee morale, work motivation, and performance through layout improvements in a clinical laboratory of a hospital with seven departments. Moatari-Kazerouni et al. (2015) [55] used From-To charts (REL charts) through interviews and exchanged pairs for layout improvement based on occupational health, safety, and transportation costs in a hospital kitchen area. Girija and Bhat (2013) [133] focused on delays in patient care by evaluating the patient flow through network diagrams, PERT charts, and CPM (critical path method) [103] in an emergency department. Lin et al. (2013) [26] evaluated the logistics relationship (movement of people and goods, move sequence) and non-logistical relationship (relation of product and personnel) among the units using a REL chart, and proposed the SLP approach [132] for the OT department layout improvement in a hospital. Recently, Gul et al. (2017) [134] proposed fuzzy PERT and fuzzy CPM to evaluate uncertain delays in patient flows in an emergency department.

There is also one study about physically based modelling applications on hospital cases in the literature. As it is discussed before, spatial configuration based on space relations can be modelled as physically based modelling using the physics law of motion. A novel study by Lorenz et al. (2015) [135] evaluated the adjacencies in hospital layout planning using this approach.

2.5.2 Analysis and Simulation Studies for HLP

With regards to space syntax analysis using hospital case studies, Peponis and Zimring (1990) [136] analysed the impact of configuration on wayfinding in a 100-bed homey hospital. Tzeng and Huang (2009) [137] analysed the influence of spatial configuration on wayfinding behaviours by performing space syntax axial-line mapping and isovist analysis in a hospital outpatient area. Morgareidge et al. (2014) [138] analysed the influence of spatial configuration on the effectiveness of visual surveillance, movement, and informal communication in an emergency department. Zwart et al. (2015) [139] analysed wayfinding, view of nature, daylight, visibility of the patient area from reception desks, privacy, and communication between medical staff and patients in a nursing ward. Neo et al. (2017) [140] evaluated the impact of spatial configuration on hand hygiene behaviour in inpatient wards and hand sanitizing stations of a hospital. Some other analysis and simulation studies are focusing on specific hospital case studies in the literature. Yi and Seo (2012) [20] analysed the influence of hospitals on walking behaviours based on observations of the routing pattern of nurses in an ICU department. Choudhary et al. (2010) [141] created a simulation model that predicts the effect of different layouts of hospital units on nurses' movement patterns and speed of travel distances. Khan and Callahan (1993) [142] created a queuing model to examine the operating characteristics of the system (waiting in line, length of wait) with statistical test in 200-bed hospital laboratory. Wurzer et al. (2015) [143] compared different hospital layouts based on patient routing characteristics with simulations such as process flows and agent-based simulations. Dan et al. (2016) [144] simulated the queuing pattern focusing on patient waiting time, patient satisfaction, and labour intensity in a pharmacy department. Vos et al. (2007) [145] developed an evaluation method for hospital layout design based on flows of patients and goods using discrete event simulation. Wurzer (2013) [146] concentrated on process modelling and agent-based simulation by mentioning some important issues for hospitals as such urban context, adjacency, separation of traffic, location, size and proportion, orientation and wayfinding, extensibility and adaptability, adequacy of planned concept, visibility, accessibility, wayfinding, space placement, dimensioning, movement, circulation and traffic. Baskaya et al. (2004) [147] investigated the impact of configurations on wayfinding by data analysis on an existing hospital. Karvonen et al. (2007) [148] focused on routing of patients using production flow analysis in new acute care hospital. Martin et al. (2011) [149] investigated the patient journey (delay in patient flow, patient waiting times, and overall length of stay) in the emergency department using qualitative and quantitative data analysis, UML activity diagrams. Kazanasmaz and Tayfur (2012) [150] classified and assessed the floor plans in terms of spatial quality focusing on the efficiency of primary and circulation areas in nursing units by developing fuzzy rules. In addition, recent hospital layout review papers can be found in Jamali et al. (2020) [151] and Benitez et al. (2019) [152].

Finally, to highlight the correspondence between the above-mentioned methods and hospital layout problems, performance indicators, focused problem types and corresponding case studies are presented in Table 2.2. In the reviewed hospital layout literature, the majority of the works prioritized "time" optimization in the hospital layout planning such as minimizing delay in patient care, travel distance of medical staff and waiting times, etc. The scarce number of papers took more attention to the performance indicators related to "hygiene" such as the risk of infection or bacteria transmission and "safety/privacy/community" issues such as the need for visual accessibility of the patient areas. Some studies are focused on "wayfinding" simulation in hospital layouts. Related to the impact of configurations on the "work performance" in hospitals, one study [11] simulated human behavior in a hospital to observe the movement of nurses and see how the interruptions affected the work performance of the nurse.

TABLE 2.2 Overview of hospital layout problem type, solving method and case study for each reviewed paper

Author	Year	Published in	Problem Type	Performance indicators	Used method	Case Study (Hospital Type/ Focused Department/ Location)
Rosenberg et al.	1972	Journal of Medical Education	investigating the design criteria for education space	**space requirements**	some analysis methods	educational hospital
Elshafei	1977	Operational Research Society	location of clinics within a hospital department	delay, patient flows	QAP and improvement heuristic	Ahmed Maher Hospital in Cairo
MURTAGH et al.	1982	European Journal of Operational Research	facilities assigned to locations (benchmark problem)	**transport cost**	new heuristic method	whole hospital
Levary and Schmitt	1986	Comput. & Indus. Engng	facility layout improvement	**employee morale, work motivation, and performance**	group decision-making process, REL chart, interviews from the user group, improvement heuristic: CRAFT (pairwise exchange method)	The clinical laboratories in a Midwestern hospital consist of seven departments
Peponis and Zimring	1990	JOURNAL OF HEALTHCARE DESIGN	Analysis of the Impact of Configurations on Wayfinding	**wayfinding**	space syntax analysis	100-bed Homey hospital
Butler et al.	1992	IIE Transactions	facility layout and bed allocation	**distance between services for nurses**	SLP approach, QAP and system simulation and CRAFT constructive heuristic	general purpose hospital in the south-eastern United States

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TABLE 2.2 Overview of hospital layout problem type, solving method and case study for each reviewed paper

Author	Year	Published in	Problem Type	Performance indicators	Used method	Case Study (Hospital Type/ Focused Department/ Location)
Khan and Callahan	1993	European Journal of Operational Research	queuing problem	number of patients **waiting in line**, **length of wait**	analysing historical data of 200bed hospital's laboratory operations, queuing	hospital laboratory
Hahn et al.	2001	Journal of Intelligent Manufacturing	facilities assigned to locations	**travel distance**	QAP, random heuristic, perturbation combined with pairwise exchanges, cycling rotation of certain facility elements, cutting plane heuristic, simulated annealing, tabu-navigation search, robust tabu search, dual procedure branch and bound enumeration	Whole building / the problem handled as a benchmark problem for Klinikum Regensburg to be built in Germany
Baskaya et al.	2004	ENVIRONMENT AND BEHAVIOR	Investigating the Impact of Configurations on Wayfinding	**visual accessibility** at the entrance hall, **orientation** and **wayfinding**	data analysis on existing hospitals	Etlik Polyclinic in Ankara, Dicle University Polyclinic
Stummer et al.	2004	Health Care Management Science	location allocation opt.	total **travel costs incurred by patients**, the **total costs associated** with a location-allocation hospital plan (number of beds)	math model, MO tabu search	NA
Yeh	2006	Automation in Construction	architectural / facility layout opt.	**adjacency** of objects, **distance** between objects, **availability of space** for object location, **positions of objects in relation to others**	QAP, annealed neural network	A case study of a hospital building with 28 facilities
Karvonen et al.	2007	World Hospitals and Health Services: The Official Journal of the International Hospital Federation	ideal patient flow modelling, functional organisation and layout model	**transfer routes** for patients and also, e.g., **lift capacity** in the hospital, **lead times of care processes**	production flow analysis and optimization	new acute care hospital
Vos et al.	2007	Health Care Management Science	development of an evaluation method for hospital layout design from operations research perspective	**flows of patients and goods**	discrete event simulation	a new Dutch hospital

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TABLE 2.2 Overview of hospital layout problem type, solving method and case study for each reviewed paper

Author	Year	Published in	Problem Type	Performance indicators	Used method	Case Study (Hospital Type/ Focused Department/ Location)
Liang and Chao	2008	Automation in Construction	facility layout opt.	**space requirement** and **adjacency**	tabu search	A case study of 4-storey hospital building with 28 facilities
Tzeng and Huang	2009	Journal of Asian Architecture and Building Engineering	Investigating the Impact of Configurations on Wayfinding	**wayfinding**	space syntax analysis	whole building
Choudhary et al.	2010	Journal of Building Performance Simulation	assignment of rooms	**nurse's movement, speed of travel**	generalized linear model that predicts the effect of different layouts of hospital units on nurses' movement patterns	NA
Martin et al.	2011	International Emergency Nursing	investigation of patient journey through ED	delay in patient flow, **patient waiting times**, overall **length of stay** in ED	Qualitative and Quantitative Data Analysis, UML Activity Diagrams (Microsoft access)	Bendigo Health / Emergency Department
Motaghi et al.	2011	International Journal of Management of Business Research	layout opt.	(quantitative) **relationship** between activities	Activity Relation Chart, math model, heuristic method (diamond algorithm to calculate efficiency of initial settlement)	Shafa Hospital
Amaral	2012	Computers & Operations Research	corridor-allocation problem for double row hospital layout	**daily traffic, communication cost among facilities**	MIP,Heuristic approach: 2-opt algorithm, 3-opt algorithm	NA
Kazanasmaz and Tayfur	2012	METU journal	classification and assessment of floor plans in terms of spatial quality	**primary areas** per bed, **circulation areas** per bed	developing a fuzzy logic algorithm, analysis of existing hospitals	nursing units/Turkey's hospitals
Yi and Seo	2012	Health Environments Research and Design Journal	analysing the influence of hospital layout on nurse walking behaviour	**nurse traveling times**, **walking behaviours**, **visibility** of patients from nurses, routing	data analysis based on observations	Intensive Care Unit in university hospital in Atlanta
Girija, V.R., Bhat, M.S.	2013	Journal of Health Management	managerial decision making	**delay in patient care**	Network diagram, PERT, CPM (opt.)	Emergency department
Arnolds and Nickel	2013	Socio-Economic Planning Sciences	dynamic hospital ward layout problem with movable walls	**patient satisfaction**	decision support, mathematical modelling, IBM ILOG CPLEX 12.2 solver	patient wards, The fixed ward layout problem (FWLP), The variable ward layout problem (VWLP)

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TABLE 2.2 Overview of hospital layout problem type, solving method and case study for each reviewed paper

Author	Year	Published in	Problem Type	Performance indicators	Used method	Case Study (Hospital Type/ Focused Department/ Location)
Kong et al.	2013	BMC Infectious Diseases	spatial distribution of infection (MRS) within a hospital	risk of infection/ **bacteria (MRS) transmission** within the hospital	Hierarchical design approach, Statistical model to estimate unknown model parameters, Markov-Chain	The study was conducted in the Princess Alexandra Hospital (PAH), a 796-bed tertiary hospital in Brisbane, Queensland, Australia
Wurzer	2013	Mathematical and Computer Modelling of Dynamical Systems	hospital planning that involves dynamic entities by embedding them into static process	**Urban context, Adjacency, Separation of traffic, Location, size and proportion, Orientation and wayfinding, Extensibility and Adaptability, Adequacy of planned concept, Visibility, accessibility and wayfinding, Space placement and dimensioning, Movement, circulation and traffic**	Process modelling (Microsoft Visio), agent-based simulation	NA
Gulec et al.	2013	ITU journal	architectural layout opt.	optimal **route of users** (distance between two related spaces)	single objective genetic algorithm	health campuses
Helber et al.	2014	Flexible Services and Manufacturing Journal	allocation of departments in hospital	**space requirements**, **transportation** processes, **neighbourhood** of spaces	hierarchical modelling approach: QAP & fix-and-optimize heuristic	Hannover Medical School, a large and complex university hospital in Hannover, Germany
Morgareidge et al.	2014	Frontiers of Architectural Research	optimal site allocation in master planning and process improvement for existing ED and designing the new one	**operating cost**, **travel distances**, **visual surveillance**, **movement**, **and informal communication.**	discrete event simulation, space syntax (axial map to calculate connectivity and integration of the old and new layouts)	Case study of the Yuma regional medical center (YRMC) ED

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TABLE 2.2 Overview of hospital layout problem type, solving method and case study for each reviewed paper

Author	Year	Published in	Problem Type	Performance indicators	Used method	Case Study (Hospital Type/ Focused Department/ Location)
Lin et al.	2015	J Intell. Manuf.	facility layout improvement in OT department	**logistics** of the material goods, Safety and pollution**, ease to contact with the ward, frequency of the medical personnel contact, comprehensive analysis (both logistical and non-logistical)**	REL chart and closeness ratings, SLP (PQRST), fuzzy constraint theory to assess the two plans to select the optimal one.	OT department
Lorenz et al.	2015	IFAC-PapersOnLine	spatial configuration	**space relations**	Adjacency Matrix, Physically Based Modelling (Newton's Laws of Motion), Monte Carlo simulation	a case study of architect's office
Moatari -Kazerouni et al.	2015	International Journal of Production Research	facility layout improvement	occupational health and safety, **transportation cost**	From-to-charts, interviews, REL chart, risk estimation, layout improvement by exchanging pairs	Hospital kitchen area
Su and Yan	2015	Artificial Intelligence for Engineering Design, Analysis and Manufacturing	nursing unit layout optimization	maximization of **daylight illuminance** (+heating and cooling energy) and minimization of **travel distances of nurses**	Genetic Algorithm, Daylight Simulation (DIVA), thermal energy simulation, offline simulation	nurse station in Boston
Wurzer et al.	2015	IFAC	comparing different layout with simulations	**flow and patient routing**	hospital simulation/ space design tool, agent-based simulation	whole building
Chraibi et al.	2015	IFAC	Dynamic Facility layout problem	minimizing **total travelling costs**, minimizing **rearrangement cost**	Multi-Agent decision making system based on QAP and MIP for large-sized DOTLP	OT department
Zwart et al.	2015	Health Environments Research &Design Journal	Analysis of the Impact of Configurations on Wayfinding	**wayfinding, view on nature, daylight, visibility** of the patient areas from reception desks, **privacy and communication** between medical staff and patient, noise reduction	space syntax analysis	nursing ward of the Deventer hospital in the Netherlands.

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TABLE 2.2 Overview of hospital layout problem type, solving method and case study for each reviewed paper

Author	Year	Published in	Problem Type	Performance indicators	Used method	Case Study (Hospital Type/ Focused Department/ Location)
Acar and Butt	2016	Journal of Biomedical Informatics	nurse-patient workload assignments in hospital	**total workload balance, travel distances of nurses**	observation data collection, AHP decision making mathematical models (MIP), XPRESS solver (Simplex Solver) for optimization	29-bed Adult Medical/ Oncology Unit (GMU)
Butler et al.	2016	The Journal of the Operational Research Society	Product planning and capacity acquisition, Facility layout/capacity allocation	**distance between services**	MIP, system simulation	urban hospital in the south-eastern United States.
Cheng et al.	2016	Habitat International	spatial accessibility of hospital	**travel time**	A kernel density two- step floating catchment area method (KD2SFCA)	whole building in Shenzen, China
Chraibi et al.	2016	IFAC	multi-objective Operating Theater Layout (OTL)	**material handling costs**	mathematical model, PSO algorithm	Operating Theater
Dan et al.	2016	Procedia Computer Science	queuing problem	**patient waiting time, patient satisfaction, labor intensity**	Data collection/ analysis, Simulation, single-queue multi-server queuing pattern	Pharmacy department
Rismanchian and Lee	2016	Health Environments Research &Design Journal	assigning ED units to locations within the building	minimizing the **distances travelled by critical and non-critical patients**, maximizing **design preferences**, and minimizing the **relocation costs**	process mining, process models, goal programming, interviews and questionnaires, location-tracking technologies, and video analysis, have been used by researchers to track patient movement, CPLEX solver	Emergency department / S Hospital in South Korea
Schaumann et al.	2016	Annali dell'Istituto superiore di sanita	Human behaviour in healthcare facilities	**interruptions of the medical staff**	Human behavior simulation in healthcare facilities	NA
Gul et al.	2017	Sigma J Eng & Nat Sci.	managerial decision making	**delay in patient flow**	Fuzzy PERT, Fuzzy CPM	Emergency department
Neo et al.	2017	American Journal of Infection Control	predicting and optimizing hand hygiene behavior	hand hygiene compliance, frequency of use of hand sanitizing stations	data collection/analysis, and space syntax	patient wards and hand sanitizing stations (HSS)

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TABLE 2.2 Overview of hospital layout problem type, solving method and case study for each reviewed paper

Author	Year	Published in	Problem Type	Performance indicators	Used method	Case Study (Hospital Type/ Focused Department/ Location)
Safarzadeh and Koosha	2017	Applied Soft Computing	multi-row facility layout opt.	**handling cost** and lost opportunity cost related to **waste spaces**	a nonlinear mixed-integer programming model with fuzzy constraints, GA	NA
Arnolds and Gartner	2017	Ann Oper Res	Improving layout planning through clinical pathway mining	**travel distances**	mathematical model, Mean absolute deviation (MAD) between clinical pathway probabilities, Significant clinical pathways, Error of the layout planning problem (ELPP), Cross-validation	ICU, OT

2.6 Review of Computational Tools for Architectural Layout Planning

An early common architectural space planning technique is bubble diagrams, which involve drawing a plan with circles to roughly understand the relationships between various activities that can refer to a set of spaces. Once the relationships are defined and spaces are laid out next to one another, a more detailed layout should be drawn either by hand or using CAD techniques. Computational tools can simplify this process by allowing the automatic application of a clearly defined set of rules to the entire space in a reasonable time. For years, computational approaches have been applied to architectural space planning in the literature. In [84], the authors dealt with space layout planning, which is the assignment of discrete space elements to their corresponding locations while the space elements have relationships with each other with an evolutionary design approach by making use of the EDGE system (implemented in C on a Unix platform). They applied the model to an office layout problem. In [127], the authors formulated a space planning problem by using a genetic algorithm and tested the algorithm on a small-size hospital layout application by using EDGE. In [108], the authors developed the ARCHiPLAN tool (on IBM) to automatically generates topological solutions for space planning. In [153], Michalek (2001) developed an automated layout tool using computational design techniques for topology and geometrical optimization. Simulated annealing and evolutionary algorithms were used in the C++ programming language. Wong and Chan (2009) [87] presented an architectural layout design problem that is related to finding the best adjacencies between functional spaces among many possible ones under given constraints. They formulated the problem as a combinatorial optimization problem and solved it with an Evolutionary Algorithm (EA). They developed the EvoArch tool, to represent architectural space topology as a graph with nodes (spaces) and edges (their adjacencies). EvoArch converted these graphs into their adjacency matrices and conducts crossovers and mutations on these matrices. Das et al. (2016) [154] developed a space plan generator (SPG) in Dynamo to computationally generate vast numbers of layout options through generative design strategies. Dino (2016) [91] presented an evolutionary approach for 3D architectural layout problems and developed EASE by using evolutionary algorithms, not directly using and/or developing a CAD tool but presenting the results as concrete geometrical layout alternatives. Streamer [155] is a very broad project on hospital design. They also dealt with the configurational layout of hospitals as one early part of the project using computational design approaches and BIM applications. Recently, Laignel et al. (2021) [156] developed the Optimizer tool for the automatic generation of floor plans with a constrained-programming approach. There are also various review papers about the use of computational approaches to space planning like Liggett (2000) [157], Cagan et al. (2002) [158], Homayouni (2006) [159], Dutta and Sarthak (2011) [160], Du et al. (2018) [161], Xu et al. (2020) [162].

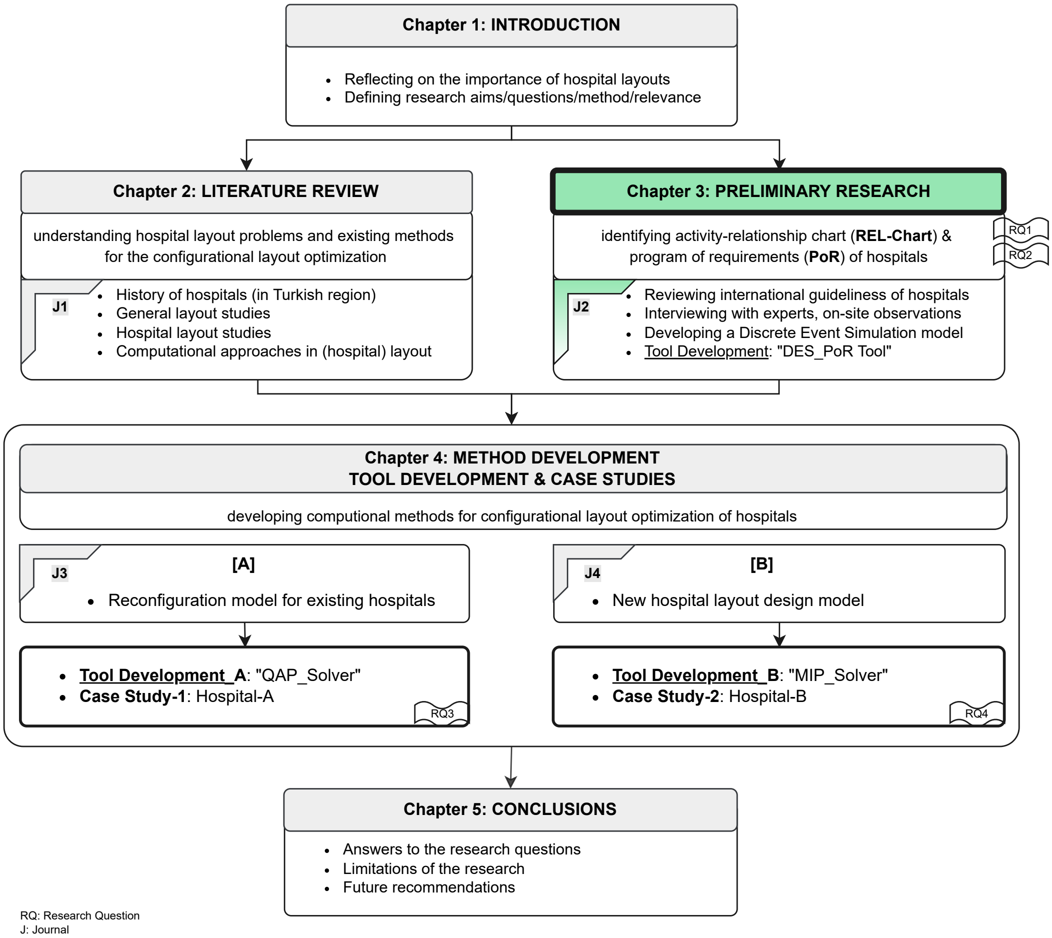
As result, very few numbers of studies made use of computational approaches in architectural space planning. In the reviewed literature mentioned above, there is an attempt to develop a computational tool that somehow automated/facilitated the space planning processes. Most of them are not used parametric CAD software. There is a limited number of tools available in the Parametric CAD platform to facilitate the space planning processes: DeCoding Spaces [163], SpiderWeb [164], and Syntactic [165]. The majority of the studies did not finally achieve concrete plans and only remained at topological or schematic layout levels.

Regarding the hospital layout tools, Jamali et al. (2021) [151] reviewed computerized hospital layout planning techniques. They also concentrated on algorithms applied to the QAP and graph theoretical applications on hospital layout in the literature. However, none of the mentioned methods applied to parametric CAD platforms, which are hot topics in computational design in architecture.

2.7 Literature Review Findings and Research Projections

Based on the understanding of the layout planning methods in terms of both layout in general and the case of hospital layouts, our significant research findings and research projections are listed as follows:

- The integration of OR tools (REL-Chart, From-to-Chart) into layout optimization studies especially in ALPs is very limited. REL-chart is mostly utilized in graph-theoretical studies.
- A systematic method for corridor generation (especially in hospital layout studies) is not considered in the reviewed literature. Corridor Allocation Problem (CAP) formulation is proposed in [166] but it is only considered as a matter of distancing between units.
- Graph theoretical approaches are capable of optimizing a configuration graph but they are limited in their capability for turning a graph into a geometrical plan layout.
- A systematic method for obtaining or even drawing adjacency/connectivity graphs is not observed in the reviewed hospital layout studies.
- The layout of a hospital, as a whole building especially in 3D, has rarely been considered in the reviewed literature. Rather, the majority of the works focused on the layout of the specialized department of a hospital such as the operation theatre or nursing units.
- The utilization of computational design tools in hospital layout planning is very limited in the reviewed literature. To the best of our knowledge, computational tools specialized in the configurational layout of hospitals are very scarce. Only recently in the streamer project [155], a BIM-based hospital layout generation tool is developed.
- Multi-level/hierarchical approaches for layout development are becoming a new trend.
- Since the complex processes of hospitals are directly affected their layout design, the use of (process) simulation techniques for the sake of layout planning is needed for matching the hospital layout with its operations.
- Graph theoretical methods are worth considering in hospital layout designs.
- The potential of making use of existing facility layout techniques on ALP can be a concern in hospital designs.


Chapter 1: INTRODUCTION
Reflecting on the importance of hospital layouts
Defining research aims/questions/method/relevance
Chapter 2: LITERATURE REVIEW
understanding hospital layout problems and existing methods for the configurational layout optimization
J1
History of hospitals (in Turkish region)
General layout studies
Hospital layout studies
Computational approaches in (hospital) layout
Chapter 3: PRELIMINARY RESEARCH
identifying activity-relationship chart (REL-Chart) & program of requirements (PoR) of hospitals
RQ1
RQ2
J2
Reviewing international guideliness of hospitals
Interviewing with experts, on-site observations
Developing a Discrete Event Simulation model
Tool Development: "DES_PoR Tool"
Chapter 4: METHOD DEVELOPMENT
TOOL DEVELOPMENT & CASE STUDIES
developing computional methods for configurational layout optimization of hospitals
J3
[A]
Reconfiguration model for existing hospitals
J4
[B]
New hospital layout design model
Tool Development_A: "QAP_Solver"
Case Study-1: Hospital-A
RQ3
Tool Development_B: "MIP_Solver"
Case Study-2: Hospital-B
RQ4
Chapter 5: CONCLUSIONS
Answers to the research questions
Limitations of the research
Future recommendations
RQ: Research Question
J: Journal

3 Preliminary Research

This chapter presents the desktop research and qualitative research performed for forming exemplary hospital design requirements, namely activity-relations chart and program of requirements. Here goes a summary of the contents of the chapter.

3.1 Background Information About Preliminary Research

As can be seen in the first step of the research methodology in chapter 1.6, before layout planning, a full program of requirements and spatial closeness, connectivity, and adjacency requirements in hospitals need to be identified as a part of a process referred to as 'space planning' [167]. To this end, preliminary research, using both qualitative and quantitative methods, has been done in this research.

If talking about the history of this section, in 2015, a Healthcare Architecture Research Group (see Figure 3.1) was established under the leadership of Prof. dr. ir. I. Sevil Sariyildiz, in Yasar University in Izmir, Turkey. Since its establishment, the team has organized many seminars and panel sessions with several experts (doctors, hospital architects) on the topic of Hospital Design to identify the hospital design problems in Turkey and to be able to get data about the ideal planning of hospitals. This team was divided into sub-teams that are focusing on different problems concerning the design of hospitals. For example, one of the sub-teams, called as SIM group, focused on healthcare interiors, and space perception of the medical staff and was granted within the scope of a scientific research project (grant no.BAP048) [168], [169]. Another group granted within the scope of a TUBITAK 1002 project (grant no.220K287), in which also the author (C. Cubukcuoglu) participated as a researcher, focusing on Indoor Environmental Quality (IEQ) and lighting aspects of the elderly institutional care centres [170]. Another researcher group member (I. Kahraman), who is also currently the head of the Izmir branch of the chamber of architects, focused on the sustainability and energy aspects of the hospitals by providing many collaborations with municipalities and the ministry of health. A series of scientific publications have been contributed by MSc students as part of computational design studios in which they participated, with the author and other research group members as advisors to the healthcare architecture works such as [171], [172].

FIG. 3.1 Yasar University Healthcare Architecture Research Group [173]

In this section, the infrastructure which is based on this research team, the results of expert interviews, and field studies on the reality of hospital design problems are reported. The results of this chapter are guidelines for the specification of the Program of Requirements (PoR) and Activity Relationship Chart (REL-Chart) with reasons for closeness/connectivity/adjacency requirements, a list of requirements, regulations, and standards related to layout. Typical units of a mid-size generic-purpose hospital are used as a demonstrator for making a synthesis of the studied requirements, standards, and regulations. The main deliverable of the chapter is a set of guidelines for preparing PoR and REL-Charts, based on findings and conclusions drawn from the studies.

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3.2 Forming a Typical Activity Relations Chart

Here we start with a review of international hospital design guidelines. Based on this review, we build our interview questions and gain an initial perspective for our field studies.

3.2.1 Reviewing International Guidelines Pertained to Its Layout

Most of the countries have hospital design standards that can be customized by regional factors. In addition to these strict written rules, some other rules can be followed in hospital design and guided by hospital designers in general. There are various literature studies about hospital design as can be seen in the Literature Review. However, studies on hospital design guidelines in the literature are very scarce. In this chapter, we reviewed previous publications on hospital design that can be defined as international guidelines on specific mid-size generic-purpose hospitals, which is the focus of this thesis. To get relevant data for creating a REL-chart for hospitals, these guidelines were reviewed from the point of the configurational layout aspect.

3.2.1.1 Hospital Types

A general classification of hospitals in terms of their ownership includes three types[3] (H. Varawalla and V. Desai [174]) listed:

- Government-owned - central / state / district / autonomous like army, railways etc.,
- Not for profit – Managed by Trusts / Societies,
- For-profit – Corporate Sector [private sector corporate hospitals].

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[3] The term typology is colloquially used amongst architects for referring to distinguishable types of spatial configurations and compositions of buildings. It is synonymous with the term building type.

The first type, government-owned state hospitals, is our main focus in this research. Because the number of state hospitals in Turkey is getting increased and these are the most needed ones in Izmir (Okunakol, personal communication, July 28, 2018).

In terms of typology, the types of hospitals (see Figure 3.2) are classified into two categories:

- Vertical planning,
- Horizontal planning.

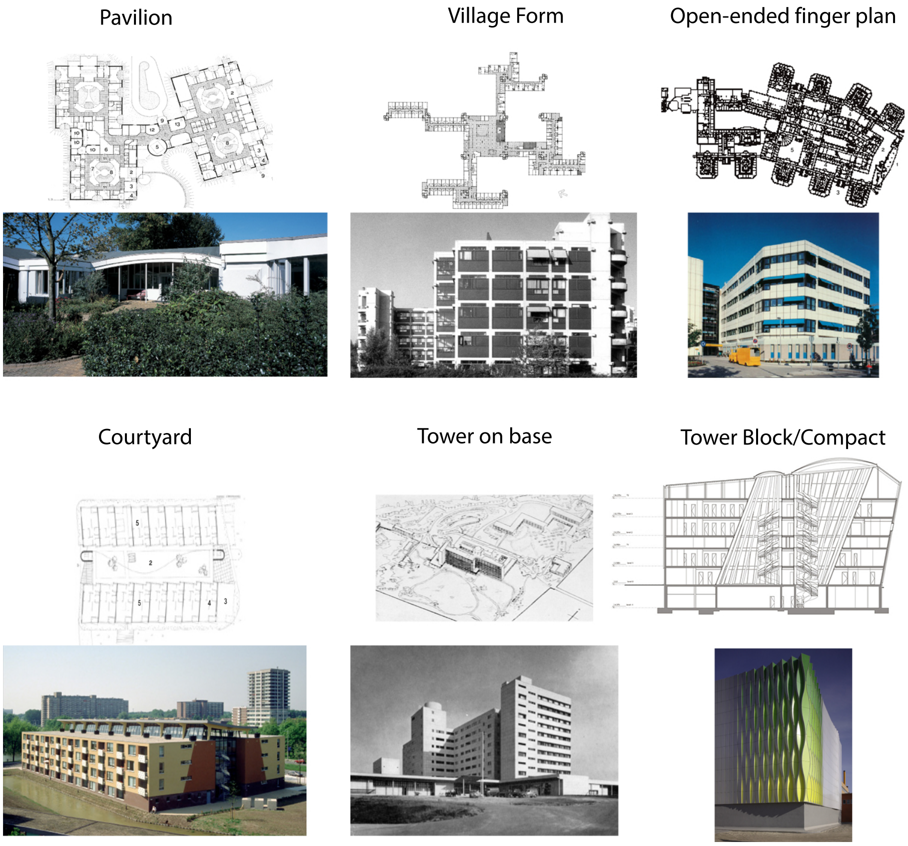

FIG. 3.2 Hospital Typology Examples (Mens et al. 2010 [21]; Wagenaar 2018 [175]; UNStudio, 2008 [176])

For vertical planning, there exist some design strategies related to its layout planning [177] as shown in the following items:

- The planning grid is generally structured by the design of the inpatient floors.
- In vertical healthcare facilities, it is planned to start from the top.
- The inpatient areas are located on the upper floors, to allow for a more pleasant, naturally lit environment in these areas.
- Diagnostic/therapeutic/interventional departments are located on the lower floors.
- The vertical circulation core is situated inside the building by the layout of the inpatient floors.
- The circulation flow conceptualized for the hospital is noticeably affected by the location of the vertical circulation core.
- The vertical circulation core is seen as the centre and the focus of all the major circulation paths of the hospital. Therefore, all surgical beds, operating theatres, and the intensive care unit (for example) can be located on the same floor to minimize vertical transportation. This design approach may be used as a justification to reduce the number of elevators, or the stairs' width in the hospital.

In addition, main vertical circulation elements in hospitals are defined as elevators, stairs and ramps. Elevators should be designed considering the hierarchy of circulation routes. Stairs are more affordable but should handle the design standards and ramps should be suitable for wheel chairs as in [178].

Horizontal planning (pavilion, village form, etc.) does not have as many well-established planning guidelines as vertical planning so horizontal planning is somehow more challenging. Pavilion-type horizontal hospital forms in which the various departments are far away from each other have some disadvantages in terms of walking distances; therefore compact or hybrid forms are more efficient in hospital planning [21].

3.2.1.2 Hospital Zoning

The different departments of the hospital can be grouped according to zones [178]. The following units can be grouped under the outermost zone, which is the most closely linked to the community and can be defined as departments that should be closest to the main entrance (Yurekli Yildiz, personal communication, September 30, 2018).

- primary health care support areas
- out-patient departments
- emergency department
- administration (especially business sections)
- admitting office, reception

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The second zone, which takes its workload from the departments in the outermost zone is listed as follows [178]. These can be defined as departments that should be the next closest to the entrance.

- diagnostic X-ray
- laboratories
- pharmacy

The Middle zone consists of units in between the outer and inner zones as follows [178]. In other words, operating theatres, the delivery department, and the nursery should have an outer zone (outermost zone, and second zone) on one side and an inner zone (inpatient departments) on the other, e.g., to provide ease of access from the emergency to x-ray and operating theatres [178]. The delivery department and nursery must be separated from the operating theatre but can be close to each other.

- operating department
- intensive care unit
- delivery unit
- nursery

The inner zone is located in the interior but with direct access to the public [178]. Inpatient departments should be in the interior zones and should take natural light (Yurekli Yildiz, personal communication, September 30, 2018).

- inpatient wards and nursing units

Service zone disposed around a service yard and generally includes the following units:

- dietary services
- laundry and housekeeping
- storage
- maintenance and engineering
- mortuary

Housekeeping and domestic service areas should be grouped around a service yard: laundry, kitchen, housekeeping, maintenance, storage, etc. The mortuary should be in a special service yard, with a discreet entrance; it should be away from the outpatient department, ward block, and nursery. The mortuary should, if possible, be located near the pathology department or laboratory. It should be easily accessible from wards and the emergency and operating departments. Separate access should be available for staff, relatives, and undertakers [178].

3.2.1.3 Hospital Main Units

Typically, in a mid-size state hospital, the main units can be defined as the outpatient department (OPD), inpatient department (IPD), intensive care units (ICU), operating theatre (OT), emergency (ED), diagnostic imaging (DI), administration (ADM), main entrance hall (ENT), supportive units (SUP) as in Figure 3.3.

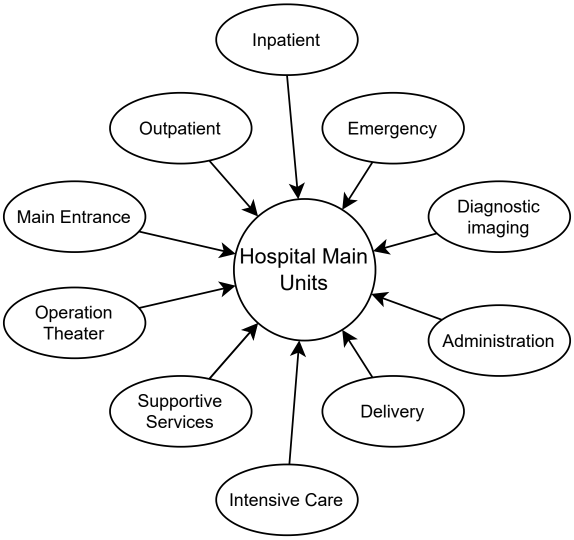

FIG. 3.3 Hospital Main Units

Outpatient Department

An outpatient department or outpatient clinic is part of a hospital implementing preventive & promotive health activities for outpatients who visit the hospital for diagnosis or treatment, but do not require a bed or to be admitted for overnight care. Therefore, the quality of OPD can reduce the load on inpatient services. OPD is the first point of contact or the face of the healthcare facility, meant for patients and attendants (Patijn, personal communication, August 14, 2017). Therefore, closeness to the main entrance is a must [179]. In exemplary hospitals in [21], outpatient clinics are on the ground floor. In a typical mid-size state hospital in Turkey, the most common OPD services are given in Table 3.1. (Yurekli Yildiz, personal communication, September 30, 2018).

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TABLE 3.1 OPD Services

OUTPATIENT - Polyclinics		
Emergency	Psychiatry	General surgery
Internal medicine & its minors	Family doctor	Plastic surgery
Paediatrics- new-born	Physiotherapy	Brain surgery
Dermatology	Algology	Cardiovascular surgery
Infectious diseases	Pathology	Paediatric surgery
Cardiology	Genetic	Thoracic surgery
Neurology	Radiological	Ear nose throat
Pulmonology	Nuclear medicine	Eye diseases
Urology	Orthopaedics	Obstetrics
Anaesthesia (no surgery)	…	…
…	…	…

As can be seen in Table 3.1, the emergency is one of the OPD services, however, it is also defined as one of the main units in a hospital that sees a patient 24/7 but does not operate on them. Sometimes, the emergency department may need a consultation from a specialist doctor and thus some specialist doctors are transported between their unit and emergency very often in a day. This situation requires ease of access between these specialist units and the emergency department. Gathering from our communications, the units that are often consulted by the emergency department are obtained and listed based on the consultation frequency in descending order given below.

- Internal medicine & minors
- General surgery
- Cardiology
- Neurology
- Orthopaedics
- Brain surgery
- Obstetrics (sometimes has a discrete emergency in the service)
- Anaesthesia
- Pulmonology
- Cardiovascular surgery
- Thoracic surgery
- Plastic surgery
- Paediatric surgery (sometimes has a discrete emergency in the service)

Inpatient Department

Inpatient wards are a key element of the hospital building and may occupy thirty-five to fifty percent of the hospital's built-up area [177]. The wards in a hospital are usually classified according to specialties: medicine, paediatrics, obstetrics-gynaecology, and surgery, which are the basic services offered by a district hospital. There are no radical differences between the requirements of medical and surgical wards and only minor differences between those of the other specialties [178]. Note that in some cases inpatient wards are distributed according to [177]:

- Ownership and Bed Mix of the hospital – corporate hospitals may have more single and double rooms than general wards. The bed mix of the hospital will decide the numbers in each category of beds.
- Age and Gender distribution – for separating floors or ear marked areas for paediatrics, male, and female categories of patients.

TABLE 3.2 IPD services

INPATIENT		
Services with wards		**Services without wards**
Medical Units (seeing patient, not doing operations)	**Surgical Units (both seeing patients and doing operations)**	**Fundamental Units (not seeing patient, not doing operations)**
Internal medicine & its minors*	General surgery	Biochemistry
Paediatric- new-born	Plastic surgery	Microbiology
Dermatology	Brain surgery	Pharmacology
Pulmonology	Cardiovascular surgery	Anatomy
Infectious diseases	Paediatric surgery	Physiology
Cardiology	Thoracic surgery	Histology
Neurology	Ear nose throat	…
Physiatry	Eye diseases	
Family doctor	Urology	
Physiotherapy	Orthopaedics	
Algology	Obstetrics	
Pathology	Anaesthesia (no surgery)	
Genetic	…	
Radiological		
Nuclear medicine		
…		

* Nephrology, Gastroenterology, Haematology, Oncology, Rheumatology, Endocrine, Geriatrics, Allergy-Immunology, Occupational diseases, Intensive care

Some inpatient services do not require wards such as biochemistry, microbiology, etc. The main categorization of the inpatient services is given in Table 3.2, by gathering information from our communications (expert interviews and site visits).

As can be seen in Table 3.2, some of the inpatient services require wards to admit the patients in the hospital. When talking about the ward's forms, wards are the most easily replicated areas of a hospital, whether on one-storey spread over a large site or stacked on top of the other in a multi-storey structure. The following in Figure 3.4 are commonly used ward forms in generic-type hospitals [178].

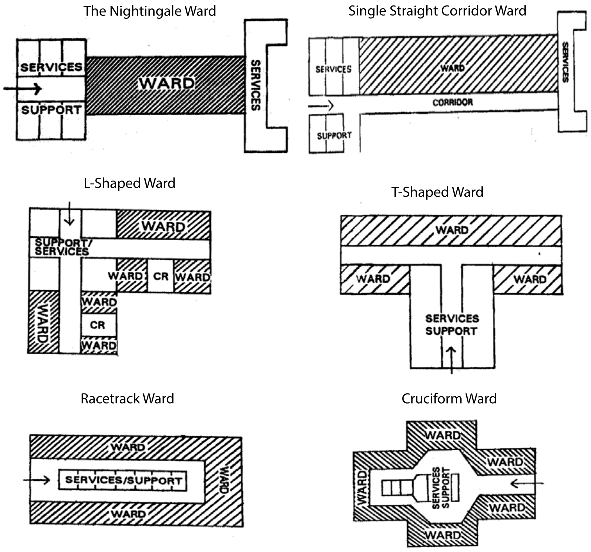


FIG. 3.4 Ward layout examples (WHO, 1996) [178]

There are several special planning and design considerations for patient wards and nursing units. It would be best if surgical wards and those for intensive care have proximity to operating theatres [180], [181]. It is better if this connection does not depend on the use of elevators, even though this cannot be always achieved [177]. All wards should be easily accessible from the hospital's main supply and disposal routes and have convenient communication with the diagnostic and treatment units [177]. All wards should be capable of being reached by visitors along simple logical routes from which they are not passing through sensitive areas where there are high risks of cross-infection [177] or private areas where medical staff should not be interrupted by visitors (Yurekli Yildiz, personal communication, September 30, 2018). Patient wards should not be used as the main route of access to another [177]. At least one nursing unit should be located in the ward area (on each inpatient floor). In comparison to other ward forms, a double corridor nursing floor provides a closer relationship between beds, nursing stations, and other services. Elevators are better in placing outside the nursing unit for freedom from noise and disturbances [182]. Some of the specialist units have their inpatient nursing floor. For example, the paediatric nursing floor is concerned with the care of children. The unit is generally noisy and should be located away from mainstream hospital traffic. If possible, it should be located adjacent to a terrace to be used as a play area [177]. The new born nursing floor is one of the areas of the hospital where patients are most inclined to infections. They should be located in the obstetrical nursing unit as close to the mothers as possible. They should also be close to the premature baby or neonatal intensive care unit [177]. The obstetrical nursing unit is responsible for prenatal care, aiding in the delivery room, care of the mother after delivery, and care of the new born. Ideally, the unit should be located on the same floor as the delivery suites and near them. It should also be adjacent to the nursery [177]. The neonatal intensive care unit (NICU) should be adjoining this unit because of the frequency and priority of the new born being transferred. The obstetrical inpatient unit should be easily accessible but should be separated from public traffic. Emergency and surgery departments require easy accessibility due to cases that might come in from emergencies or go to surgery. The psychiatric nursing unit is responsible for mentally ill patients' care and treatments. Physical barriers are needed due to communicable diseases, therefore isolation rooms should be provided and situated within the individual nursing units [177]. The oncology department has fewer relationships with other departments because most cancer patients are ambulatory. Direct exterior access to chemotherapy and radiation therapy can be needed for respecting patient privacy. Oncology needs access to emergency facilities, but it does not require direct access to the emergency. Chemotherapy should be connected to the pharmacy department for preparations of administered chemicals [177].

Delivery

The delivery department is very similar to the operating department in terms of its functional requirements and layout planning. In many hospitals, the two departments are fused into one, with shared staff and support areas, due to a lack of doctors, especially in rural areas [178]. Even though the integration of these two departments is not preferred due to the different sterile conditions, the two departments' proximity is desirable, especially when a delivery patient suddenly requires a transfer to the OT department. As expected, the nursery should be adjacent to the maternity wards to ensure protected transport of new-borns [178]. Also, operating theatre has a high spatial relationship with maternity wards [180].

Intensive Care Unit

Intensive Care Units (ICUs) are specialist nursing units that serve patients who are critically ill or require specialized care and equipment [177]. The number of beds in this unit should be between 1% to 2% of the total number of beds in the hospital. ICUs can be designed as one general ICU or specialized like many listed below:

- Intensive Coronary Care Unit
- Pulmonary Intensive Care Unit (PICU)
- Burns Care Unit
- Neonatal Intensive Care Unit (NICU)
- Critical Care of the Elderly
- Neurological Intensive Care Etc.

Many technical services are used in a typical intensive care unit, including a controlled environment, medical gases, compressed air, and power sources. Because these criteria are extremely similar to those in the operating room, it is preferable to put the intensive care unit near the operating room's recovery room (Figure 3.5) [178].

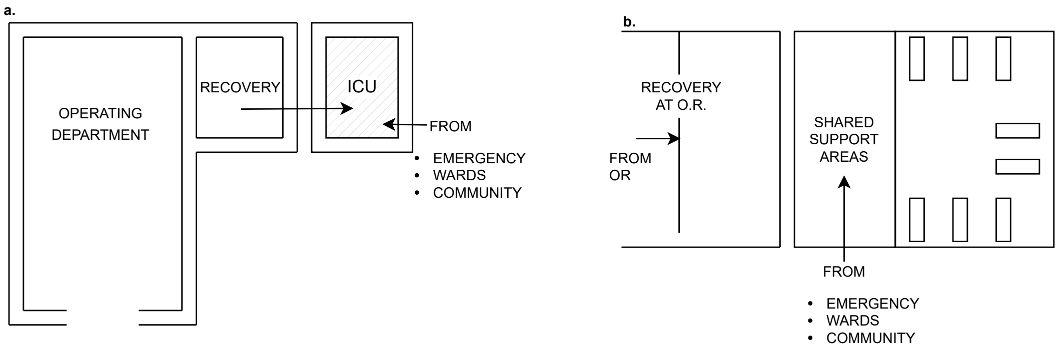


FIG. 3.5 Suggested placements of ICU and OT (WHO, 1996) [178]

Furthermore, the ICU should be designed to provide quick access from the following areas [177], [183].

- Emergency
- Operating theatre
- Medical imaging department (e.g. radiology)
- Functional testing facilities (e.g., catheter laboratory)

As most transfers to ICUs are either through the emergency department or from the operating rooms, ICUs should not be too away from nursing units in case inpatients may need to be transferred in an emergency [177]. ICUs also should be close to vertical transportation cores but should be away from heavy traffic and noise [177]. ICUs should be separated from public areas where visitors may interrupt medical staff for asking about their patients (Yurekli Yildiz, personal communication, September 30, 2018). Finally, fast and easy connections have to be established with the following services [183].

- Blood transfusion service
- Pharmacy and pharmacology services
- Technical support services
- Laboratory and microbiology service
- Physiotherapy service

Operating Theatre

Operating theatre (OT) requires a sterile area for carrying out surgical operations in a general hospital. The number of OTs required is related to the total number of hospital beds. As a general rule, one operating theatre is required for every 50 general in-patient beds and every 25 surgical beds [178]. It also depends on the total volume of the expected surgical operations (Aksu, personal communication, February 14, 2019). There are several space planning considerations for OTs in the guidelines. In general, surgical units have a central placement in the hospital ([184]; Patijn, personal communication, August 14, 2017). The suggested location of OT is on the same floor as the surgical inpatient wards or it should be connected to the surgical inpatient wards by the simplest route [178]. It should adjoin the central sterile supply department [178] and the intensive care unit [177], [178], [184]. It should be easily accessible from the emergency department and the delivery suite [178], [184]. It should be located in a cul-de-sac or should be away from heavy traffic [177], [178] (See Figure 3.6). Although the requirements of OTs can be met by an entirely internal placement, from the point of view of medical staff, some natural light can be a valuable asset [177] so windows are neither needed nor desirable [178].

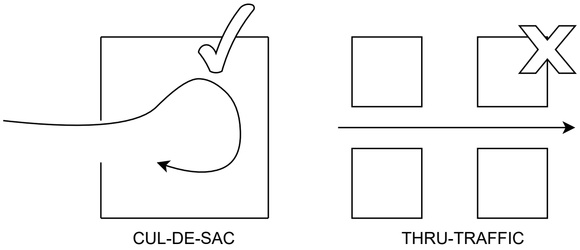
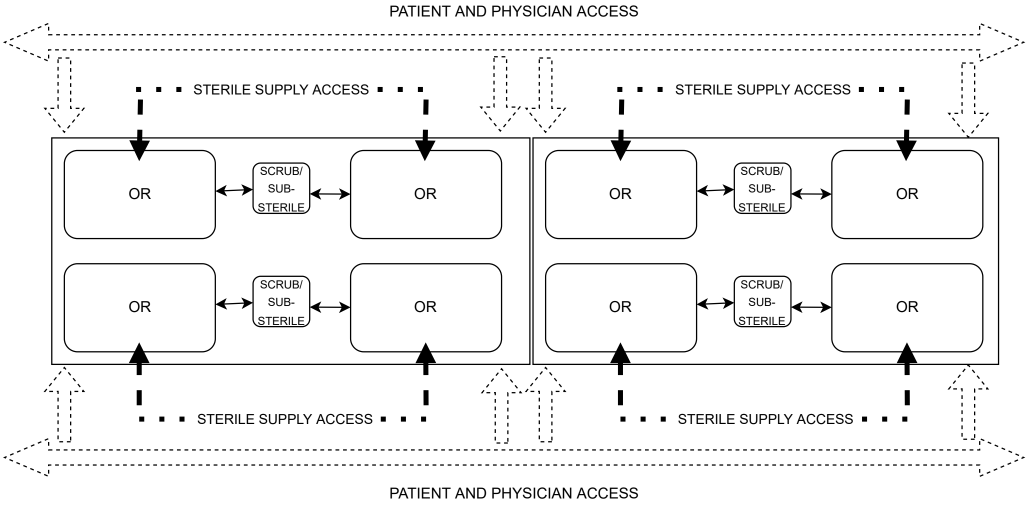


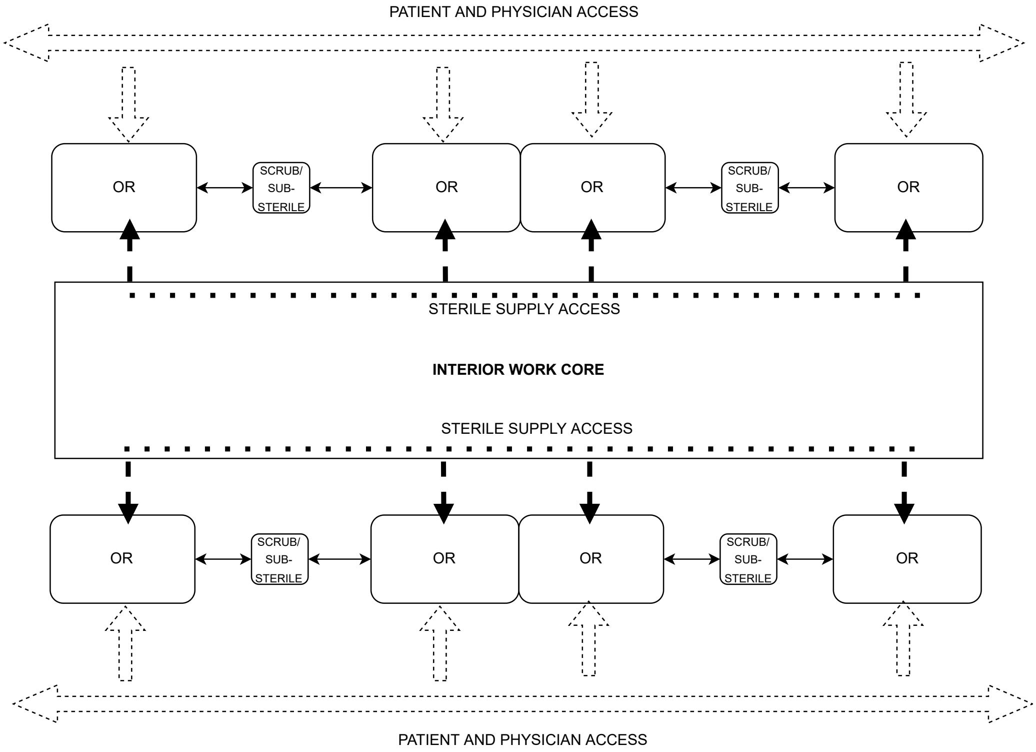
FIG. 3.6 Suggested location of operating department [178]

In addition to the placement of OT within the hospital, designing the internal layout of the OT is also a key task. Some strict standards differ from country to country but as a general rule, a surgical department could be split into zones following the cleanliness policy adopted by the individual hospital to reduce the risk of infection [177]. These zones are illustrated in Figure 3.7 and Figure 3.8.

The general zone includes waiting areas for relatives, catastrophe and triage areas, plaster rooms, offices, record rooms, laboratories, stores for non-sterile material, staff lounge refreshments, and toilet changing rooms. The clean zone includes the reception and holding area, anaesthesia rooms, delivery rooms, endoscopy rooms, stores for blood, medicine, parenteral solutions, etc., stores for tubed medical gases, the sterile service area, the general post-anaesthesia area, X-ray apparatus stores, and clean bed stores. The super clean zone includes scrub-up and gowning areas, operation rooms, sterile stores, sterile linen stores, and thoracic post-anaesthesia rooms [177], [178].



A diagram of a surgical suite's perimeter corridor concept



A diagram of a surgical suite's interior work core concept

FIG. 3.7 Diagrams for showing exemplary interior layouts of the Operation Theatre [177]

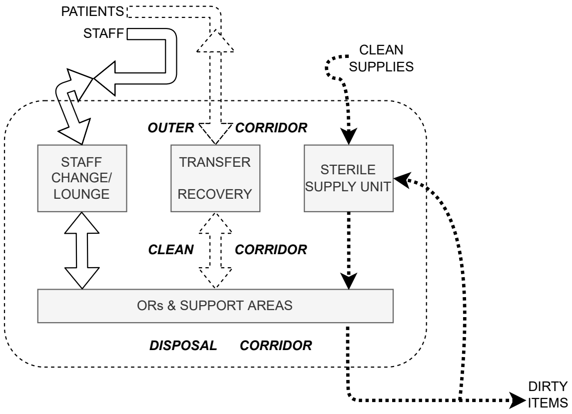


FIG. 3.8 Exemplary traffic flow in Operation Theatre [178]

Emergency

An emergency department (ED) is one of the main units in a hospital to treat patients who come without a prior appointment in a serious condition. EDs should be easily visible and accessible from the street and should have a discrete entrance for walk-in patients and ambulances. ED clinical areas should be on the ground floor and be close to the inpatient, ICU, diagnostic units, OTs, and pharmacy [180], [185].

Diagnostic Imaging and Laboratories

Radiology & Imaging

Radiology and imaging are a department in which diagnostic imaging is provided [178]. In these units, patients may receive more than one procedure per visit, so it is important to quantify the number and the average duration of procedures a patient undergoes. Patients can arrive at an imaging facility from different sources [177] as wheelchair patients may come from inpatient units or emergency and ambulatory patients may arrive with a scheduled appointment or without an appointment. Therefore, radiology and imaging units are interrelated with numerous departments. Diagnostic imaging, both x-rays, and ultrasounds should be available to inpatients and outpatients. There are many advantages to locating X-rays and ultrasounds in the same department due to shared equipment [178]. In small hospitals with a daily workload of 5-10 patients, the two can be in the same room [177]. Imaging units are frequently positioned adjacent to emergency or have direct access from the emergency because of the large proportion of emergency patients who need prompt radiological studies.

Some hospitals' emergency department has their imaging units inside the department. Imaging units also should be located on the ground floor or the first ground and it is required to minimize distances between rooms [184]. Women's diagnostic centres include mammography, ultrasonography, and bone densitometry to test for osteoporosis [177]. Ultrasound does not require any special building construction; the room must not be very dark [178]. But, the x-ray department should consist of a dark room in addition to the x-ray room and office/storage spaces [178] (See Figure 3.9).

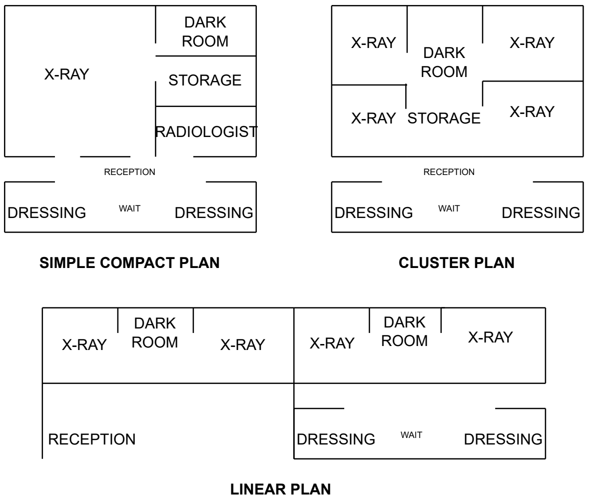


FIG. 3.9 X-ray imaging plan examples (WHO, 1996) [178]

Laboratory Services

The laboratory services should be located and designed to allow reception of deliveries of chemicals, and allow for disposal of laboratory materials and specimens [178]. Especially, pharmacy and outpatient departments must be accessible [177]. Due to the workload, which tends to double every 5-8 years, laboratory services may need future expansion [178] and according to [177] space requirements for laboratories tend to double every 10 years. Planning of laboratory areas therefore must be flexible, perhaps consisting of modules [177], [178].

Pathology

Pathology can be categorized under diagnostic units. According to [177], it should be easily accessible from the OPD, emergency, surgical inpatient wards, OTs, and ICU. Medical inpatient wards and other clinical departments can also become preferably reachable from the diagnostic units. For the ease of distribution of laboratory outputs like specimen containers, reports, and blood to the patient wards and other hospital departments, it should be connected to the main hospital routes. However, there should be no pass way crossing the unit which could be used as a connection between other departments or a general fire escape route. Regarding its relationship with the mortuary, the functionality of the mortuary is very much linked with that of the pathology unit, especially the histopathology departments' activities, and staff. The mortuary therefore should be easily accessible by the pathology personnel. The whole unit should be planned as a secure area with authorized access or at least with a minimum number of entrances to the unit.

Administration

The administrative department is orientated to the public but is at the same time private. Admission has a high spatial relationship with public facilities [180] and areas for business, accounting, auditing, cashiers, and records, which have a functional relationship with the public, must be located adjacent to the main entrance of the hospital. Other offices for hospital management can be positioned in more private areas [178].

Entrance Hall

Entrance halls can be defined as functional units in hospitals [186]. Only one main entrance and secondary entrances in the hospital have to be pointed out apart from each other for hygiene measures. Entrance halls should include waiting areas for visitors, a reception desk to supervise entrances and a closed area for admission for registration and initial tests. Short connections with emergencies separated from main corridors are needed [182].

Supportive Services

All service units other than the hospital main units mentioned above are called supportive services in this thesis such as worship places, central sterile supply, pharmacy, housekeeping, storages, kitchen and dining, parking area, bunker, mortuary, etc. Regarding the housekeeping facilities [177], the housekeeper's office should be located on the lowest floor and if possible near the central linen room providing different doors for clean linens and soiled laundry. The linen services are staff-intensive spaces and they should be easily accessible to a loading dock, materials management, and engineering/maintenance services, as well as close to elevators. Regarding the food services [177] in the hospital, receiving area should be located close to the loading and unloading dock for quick, safe food receiving. The kitchen should be located close to the servery, conference/meeting rooms, service

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elevator to patients' rooms, and auxiliary services, such as vending and catering. Floor pantries should be located near the service elevator core. The dining area for physicians and employees should be located near the kitchen. The staff spaces and supporting service areas are located near the elevator area on the wards. This allows for the segregation of clean and dirty utility areas from the inpatient area by preventing cross-traffic. In the central sterile supply department (CSSD), both sterile and non-sterile equipment for all hospital users are received, stored, processed, distributed, and controlled. Therefore, it is an important department in terms of infection control with its essential role of supplying sterile instruments to the wards or other hospital units like surgery. The department is divided into three zones as follows [177]:

- Decontamination zone: In this zone soiled instruments are received from other units for cleaning.
- Assembly/ Sterilization zone: Cleaned and inspected instruments are assembled here.
- Storage and distribution zone: Sterile instruments are stored here or delivered to the appropriate department.

Through the above, a distinct separation must be preserved between the soiled and sterile spaces. The technical staff working on the sterile side cannot pass through the non-sterile area or vice versa. According to [177], CSSD is placed adjacent to surgery or on another floor if it is placed directly above or below the surgical suites and linked by an elevator. Although the surgical and CSSD staff normally prefer an adjacent relationship, physical building often has an impact on the location of the central sterile supply [177]. In addition, storages have an essential role in storing medical supplies or records. The following compartments must be provided in the hospital storage area [177]: pharmacy storeroom, furniture room, anaesthesia storeroom, records storage, and central storeroom. For the smooth, rapid flow of supplies both to and from the central storage, adequate space and access should be provided for handling, unpacking, loading, unloading, and inspection. In a hospital planned with a functional central supply and delivery system, many of the traditional ancillary rooms could be eliminated from some departments and be replaced by systems of lifts, with sufficient parking space in the wards for trolleys. In the pharmacy department, medications are supplied to the whole hospital. There are three primary services of the hospital pharmacy [177]:

- Receipt and preparation of prescriptions
- Dispensing
- Clinical consulting

According to [177], an inpatient pharmacy (in the Western) is typically located near material management functions for convenience in receiving bulk items. It can also be positioned near inpatient units for dispensing medications or can be placed at a central location such as close to the lifts. Outpatient dispensing is provided in the hospital for outpatients requiring discharge medications and prescriptions. Outpatient dispensing should be conveniently placed for serving outpatients. Ideally, the pharmacy department should have secure access control. Entry points should be limited, if possible, to receiving and dispensing.

3.2.2 Interviewing with Expert People

According to Jamali (2020) [151], most of the hospital layout design studies have used different types of numerical data, containing information gathered from hospital event logs, but they have not adequately concerned with the integration of qualitative data into their investigations. For understanding the research query from a humanistic and idealistic perspective, we have made qualitative research that focused on obtaining data through open-ended and conversational communication with expert people on the hospital and its design. Thus, in this thesis, we conducted a series of interviews with experts as the main source of information to identify layout problems to be addressed and ideal planning for implementation in Turkey's hospitals. Rather than a stiff Q&A session with a long list of questions, a semi-structured interview with open-ended questions was prepared by creating a conversational space. Please see the prepared interview queries that mainly focus on attention to three titles as Basic Information, Identifying Existing Problems, and Ideal Planning in the following items in Table 3.3. As result, 9 professionals from both Turkey and the Netherlands were interviewed, counting hospital architects, hospital managers, and doctors. They are introduced in Section Consulted Experts ([187]–[190]). It is relevant to mention that 90% of the interviewed experts took attention to the themes: addressing logistical problems; long waiting times for patients and visitors; the importance of the design of waiting areas, and surgical units; the efficiency of the hospital for medical staff; functional relationships and logical connections of a lot of specialized units; flexibility for future expansion; privacy/community and daylight requirements in hospitals.

TABLE 3.3 Semi-structured interview questions

Basic Information

1. What are the main units in hospitals?
2. What are the sub-units in hospitals?
3. What are the specializations in hospitals?
4. How do general processes work in each main unit?

Identifying Existing Problems

1. What are the general problems in hospitals’ designs?
2. What are the layout problems in hospitals? Specifically, about
   a circulation areas (both vertical and horizontal)
   b connections between related units
   c waste flow
   d people flow (medical staff and users)
   e waiting times and adequacy of waiting areas
   f walking distances
   g interruptions
   h indoor way-finding
   i additional aspects: …

Ideal Planning

1. What are the units that have the strongest relations with each other in the hospitals?
2. What are the units that should be far from each other in the hospitals?
3. Which units need natural light or darkness?
4. Which units need privacy/community requirements?
5. How should be designed the circulation areas?
6. What should be the ideal planning for each main unit?

3.2.2.1 Consulted Experts ([187]–[190])

FIG. 3.10 Eşref Okunakol

Eşref Okunakol (Chief Physician)
Dr. Okunakol (Figure 3.10) graduated from Selcuk University Medical Faculty in Turkey in 1994. He worked in various positions in the healthcare sector such as in public hospitals Izmir general secretariat, head of administrative services, and in various hospitals as a general practitioner. He is currently working as a chief physician in the Atatürk Education and Research Hospital in Izmir, Turkey. He is also the vice president of Public Hospitals Services in Izmir. We can call him the main consultant of this thesis. We communicated with him many times during the whole Ph.D. process. Through his broad expertise in both managerial and medical positions in Turkey's hospitals, we have got plentiful information from him about the main requirements of hospitals and their ideal planning. He guided us in determining the subjects and case studies that we should focus on.

FIG. 3.11 Kübra Umar

S. Kubra Umar-Furtina (Physician)
Dr. Umar-Furtina (Figure 3.11 & Figure 3.13) graduated from Aegean University Medical Faculty in Izmir, Turkey in 1969; specialized as an ophthalmologist at Eye Hospital Rotterdam in 1975; worked as a specialist in her clinic hosted in Eudokia and then Ijsselland Hospital and some other clinics and hospitals in NL until her retirement. In August 2017, we communicated with her. With her broad expertise in both Turkey's and Netherlands' hospitals, we have learned many things from her about the functioning of both countries' hospitals and talked about Ijsselland Hospital's design (we can call it a good exemplary hospital in terms of its logical layout).

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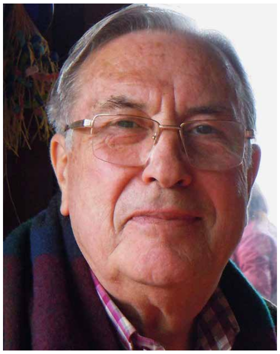

FIG. 3.12 Halit Umar

M. Halit Umar (Physician)

Dr. Umar (Figure 3.12 & Figure 3.13) graduated from Aegean University Medical Faculty in Izmir, Turkey in 1966; he specialized as a scientific researcher Pathological Anatomy in at Erasmus University Medical Faculty in 1974; worked in several hospitals in Rotterdam as a specialist doctor and also as a researcher at the Labs's in NL and Turkey until his retirement. In August 2017, we communicated with him. As he has plentiful experience in both Turkey and the Netherlands hospitals, by his broad expertise, we learned about the operational/logistical differences between both countries and got suggestions from him about hospital design.

FIG. 3.13 From our meeting with Dr. Umar-Furtina & Dr. Umar on the 10th of August, 2017

FIG. 3.14 Wytze Patijn

Wytze Patijn (Architect)

Patijn (Figure 3.14) is a Dutch architect. He was a professor of Architectural Design and dean of the Architecture Faculty at TU Delft and the director of the Architecture Office KuiperCompagnons in Rotterdam-NL. He was the chief State architect of the Netherlands and city architect of Delft – city. He has been the Architect/Head of the Design Research Department of the Municipality of Rotterdam Housing Department. He was the architect of the University Medical Center Groningen (UMCG) and was responsible for the new design developments and renovation for many years. On August 2017, we communicated with him. We have learned many things about Dutch hospitals' design principles and their operations. He provided us with his broad experiences with design criteria considered during the renovation of UMCG hospital.

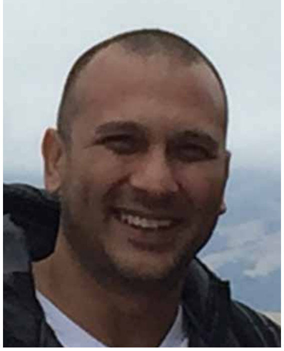

FIG. 3.15 Serden Gölpınar

Serden Gölpinar (Architect)

Serden Golpinar (Figure 3.15) is an international Architect and project manager. He has practiced in the architectural field for more than 18 years. He has worked as a *project manager in the USA* at various hospitals such as Kaiser Permanente, Riverside Regional Medical Center (Riverside) & Orange Country (Irvine), Las Encinas Hospital (Pasadena), Long Beach Memorial Medical Center (Long Beach), Lakewood Regional Medical Center (Lakewood), Aurora Charter Oak Hospital (Covina) and so on. Considering his broad expertise in hospital design, we communicated with him on the 8th of August, 2018. We have got various information about several US hospitals' design criteria from him and got different perspectives about hospital design and logical layout of the hospitals.

FIG. 3.16 Ezgi Yıldız Yürekli

Ezgi̇ Yildiz-Yürekli̇ (Physician)

Dr. Yıldız-Yurekli (Figure 3.16) graduated from Balıkesir University Medical Faculty in Turkey in 2014. During her medical education, she worked as a volunteer intern at various hospital emergency departments. She worked at Bingol State Hospital for one year. She is currently working as an assistant physician at Tepecik Education and Research Hospital to be specialized in internal medicine. On the 30th of September 2018, we communicated with her about Turkey's hospitals. Detailed information about step-by-step patients' journeys in hospitals was provided. We have learned many things about medical staff requirements and the ideal planning of hospitals.

FIG. 3.17 Uğur Aksu

Uğur Aksu (Hospital Manager)

Mr. Aksu (Figure 3.17) graduated in Business Administration in 2007, and later received his master's degree in Healthcare Management. He worked at various hospitals in Turkey in managerial positions. As of 15 July 2020, he has been working as the Assistant Manager of Tepecik Education and Research Hospital, Administrative and Financial Services. We communicated with him in February 2019 in his office. We have learned many things about existing hospitals in Turkey such as their functioning, main requirements, and departments' functional/spatial relationships, and also helped us to get information about the case studies.

FIG. 3.18 Dennis Keener

Dennis Keener (Hospital Design Manager)

Mr. Keener (Figure 3.18) is an international chief architect and medical planner at Bouygues Bâtiment International Hospital in France. On the 3rd of July 2019, a hospital design colloquium (Figure 3.19) was organized by the Chair of Design Informatics at TU Delft in collaboration with Architects and Healthcare Experts from Esteco / Bouygues Construction from France. During this colloquium, with his broad expertise in hospital space planning, we individually communicated with Dennis Keener. Mr. Keener presented BYCN hospital's design and built projects. He addressed their current design methodology and the way they see a use case on optimization techniques for macro space planning. We got also valuable feedback from him on this thesis.

FIG. 3.19 A Hospital Design Colloquium on the 3rd of July, 2019

FIG. 3.20 Rizal Sebastian

Rizal Sebastian (Architect)

Dr. Rizal Sebastian (Figure 3.20) holds a BSc degree in Architectural Design, MSc in Construction Management, and a Ph.D. in Architectural Project Management. He has over 20 years of professional experience as an architect, project manager, consultant, scientist, and research director. Currently, he is a full professor of applied science and the chair of the research group of Future Urban Systems at The Hague University of Applied Sciences in the Netherlands. He worked on several big projects one of which in Streamer project. STREAMER is an industry-driven collaborative research project on Energy-efficient Buildings (EeB) with cases of mixed-use healthcare districts in the EU. Considering his broad expertise in healthcare architecture, we communicated with him on September 2018 (See Figure 3.21). He presented hospital design requirements and pointed out the important themes in hospital design to be focused on in this thesis.

FIG. 3.21 Proficiency meeting with Dr. Rizal Sebastian on the 7th of September, 2018

3.2.3 Site Visits

In addition to the expert people knowledge, we visited various hospitals to observe operations and design aspects of existing hospitals through site visits. Three Dutch hospitals, namely Reiner de Graaf Gasthuis, Ijsselland Ziekenhuis, and Erasmus MC were analysed, which can be defined as good examples of what we can inspire from their logical layout design. Since the main focus of this dissertation is Izmir's hospitals, we also visited many hospitals in Izmir/Turkey to experience the patient journey in them to understand the problems caused by spatial configuration and to comprehend the existing design principles.

3.2.3.1 Reinier de Graaf Gasthuis

The Reinier de Graaf hospital has been providing care in Delft for about eight centuries. It has currently more than 2,600 employees, including more than 200 doctors and nearly 800 nurses. The bed capacity is 481. Through these properties, this hospital is a large hospital providing extra care for mothers and child care, elderly people, and oncologists. According to our site analysis, there is a spacious main entrance in the hospital, including a welcoming desk, canteen, an espresso bar, a shop, and seating units for visitors. Regarding the wayfinding elements, there are big signs, including all the departments' names with their particular levels' information (See Figure 3.22). In front of the vertical circulation elements, there are information signs about routes to facilitate spatial navigation in the hospital. Vertical circulation is provided by escalators as well as stairs and elevators, which are located nearby patient rooms. Way-finding elements are placed at the decision points as in Figure 3.23. Horizontal access-ways are positioned to take advantage of natural lighting as shown in Figure 3.24 and Figure 3.25.

FIG. 3.22 A general view outside the Hospital of “Reinier de Graaf Gasthuis”

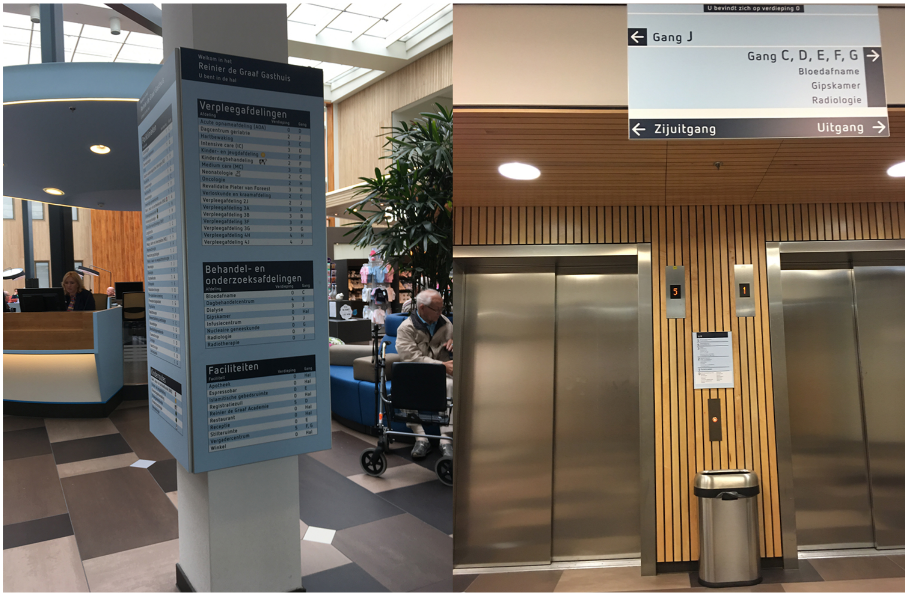

FIG. 3.23 Wayfinding design elements

FIG. 3.24 Vertical circulation elements

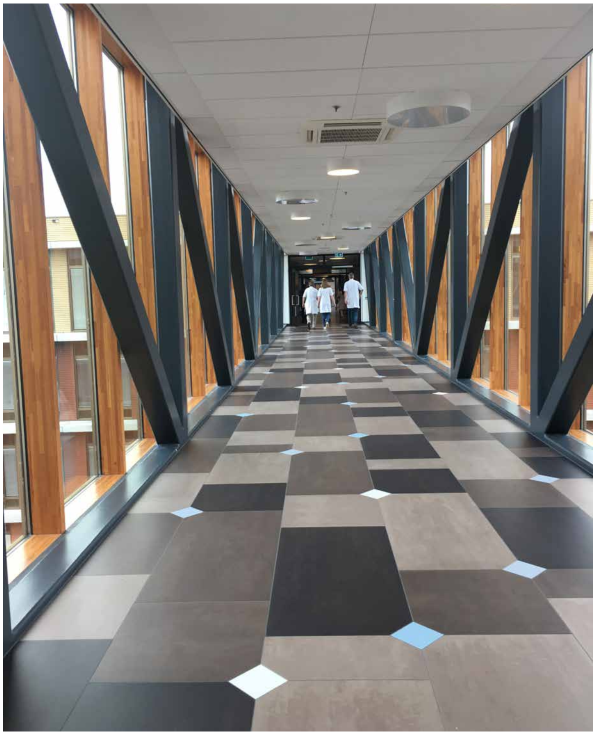

FIG. 3.25 Horizontal circulation areas

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3.2.3.2 Ijsselland Ziekenhuis

This hospital was designed in 1991 by the engagement of Bergweg Hospital and Eudokia Hospital in Rotterdam. There are more than 1550 employees, 110 medical specialists, and 200 volunteers for providing patient care in this hospital. It is a general regional hospital with 390 beds. It consists of more than 100 specialists and departments. Briefly, this hospital has two main entrances, which are located on two different sides of the long entrance hall on the ground floor (See Figure 3.26). This entrance hall enables main horizontal circulation to access polyclinics at ground level. It also provides access to patients' rooms through vertical circulation elements (Figure 3.28). There is a canteen located at the centre of the entrance hall. There is an efficient routing system for facilitating human movement within the hospital, such as there are short-cut horizontal accesses between corridors and the patient rooms (Figure 3.29). Wayfinding signs (Figure 3.27) are placed close to the elevators and stairs. All departments are shown level by level in these signs. We also observed that the hospital is designed by considering natural lighting requirements. For instance, the patients' rooms are orientated according to the direction of the sun light.

FIG. 3.26 Hospital main entrance

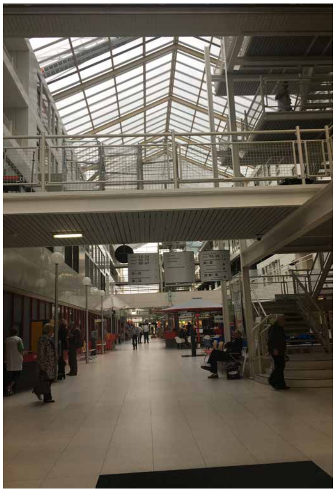

FIG. 3.27 Wayfinding design elements

FIG. 3.28 Vertical circulation elements

FIG. 3.29 Horizontal circulation elements

3.2.3.3 Erasmus MC Hospital in Rotterdam

The history of Erasmus Hospital dates back to the 1800s. It was called Dijkzigt Hospital in 1961 and integrated with Sophia Children Hospital in 1971 [191]. Erasmus MC is an academic hospital located in Rotterdam (See Figure 3.30). It had a major renovation and the construction was finalized in 2018 when a new hospital opened as Erasmus MC in the same year. According to recent data, the hospital has 39 operation rooms, 1.233 beds, 15000 m^2 clinical laboratories, 121 intensive care beds, 16 radiotherapy bunkers, 193 treatment places, and more than 300 clinical units [191]. According to our site analysis, there is a welcoming public area at the main entrance with shops, restaurants, and seating units (Figure 3.31). The wayfinding system is very similar to airports e.g. each patient has a day-ticket that shows the building code of the outpatient clinic based on the appointment. These codes are available in the routes throughout the hospital (Figure 3.32). The specialized units are located in a group based on clinical relationships [191]. The hospital is also designed according to the natural lighting requirements as having high ceilings and atriums (Figure 3.33). Even the basement floor is fresh and spacious with high windows of the atrium. Long and wide corridors are other characteristics of the new hospital.

FIG. 3.30 Overview of new Erasmus MC [191]

FIG. 3.31 Entrance Area [191]

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FIG. 3.32 Exemplary circulation area and wayfinding signs [191]

FIG. 3.33 Figure showing the high window in the basement [191]

3.2.3.4 Various Hospitals in Izmir, Turkey

Since the main focus of this dissertation is Izmir's hospitals, we visited many hospitals in Izmir/Turkey during the Ph.D. process. Therefore, rather than explaining each hospital separately, we will give a piece of general information about hospitals in the city of Izmir (Figure 3.34).

FIG. 3.34 A view of the coast of the city centre of Izmir [192]

Healthcare has historical importance in İzmir [193]. For example, Pergamon Asclepion was an important health treatment centre in ancient times. İzmir, which is located over the Aegean Sea, has the potential for health tourism due to having several thermal centres. Such cases are located in various places of Izmir, e.g. in Balçova, Bayındır, Bergama (Pergamon), Dikili, Menemen, Çeşme, and Seferihisar [193]. In addition, Izmir's calmness, serenity, mild Mediterranean climate and sunny weather, coasts, and ease of transportation are important privileges in the treatment processes and an important advantage for health tourism. In recent years, in terms of health facilities, the healthcare sector is developing in Izmir and the demand for hospitals is increasing due to immigration growth to Izmir within the country. There are various types of hospitals located in several parts of the city. The majority of the state (government-owned) hospitals are categorized as general-purpose hospitals at different health service levels (there are 3 levels in Turkey). Most of them take the name of the districts, for instance, Selçuk Hospital, Urla Hospital, Çiğli Hospital, and many more. Few ones are in the category of specialized state hospitals such as there are 7 education and research hospitals, 16 oral and dental health centres, 1 chest diseases hospital, 4 gynaecology and maternity hospital, 1 child hospital, 2 bone disease hospital, 17 eye diseases hospital, 3 oncology centres [194]. There are almost 20 private sector corporate hospitals in various places, as few examples, Ata Sağlık in Bornova, Özel Tınaztepe in Buca, Kent Hospital in Çiğli, Medical Park in Karşıyaka, Özel Sağlık in Konak, Medifema in Torbalı. In addition, a new concept of hospitals in Turkey appears that is called city

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hospitals. There is also one city hospital recently built in Bayraklı with a very large number of bed-capacity and clinical units. In our site visits, the focus was general-purpose state hospitals with mid-size bed capacity due to the general need in Izmir and in Turkey, suggested by our consultors. This situation affected our priority in selecting hospitals to visit in various places of Izmir, primarily in the districts of Urla, Konak, Torbalı, Karşıyaka, etc. Various hospitals in Izmir can be seen in Figure 3.35.

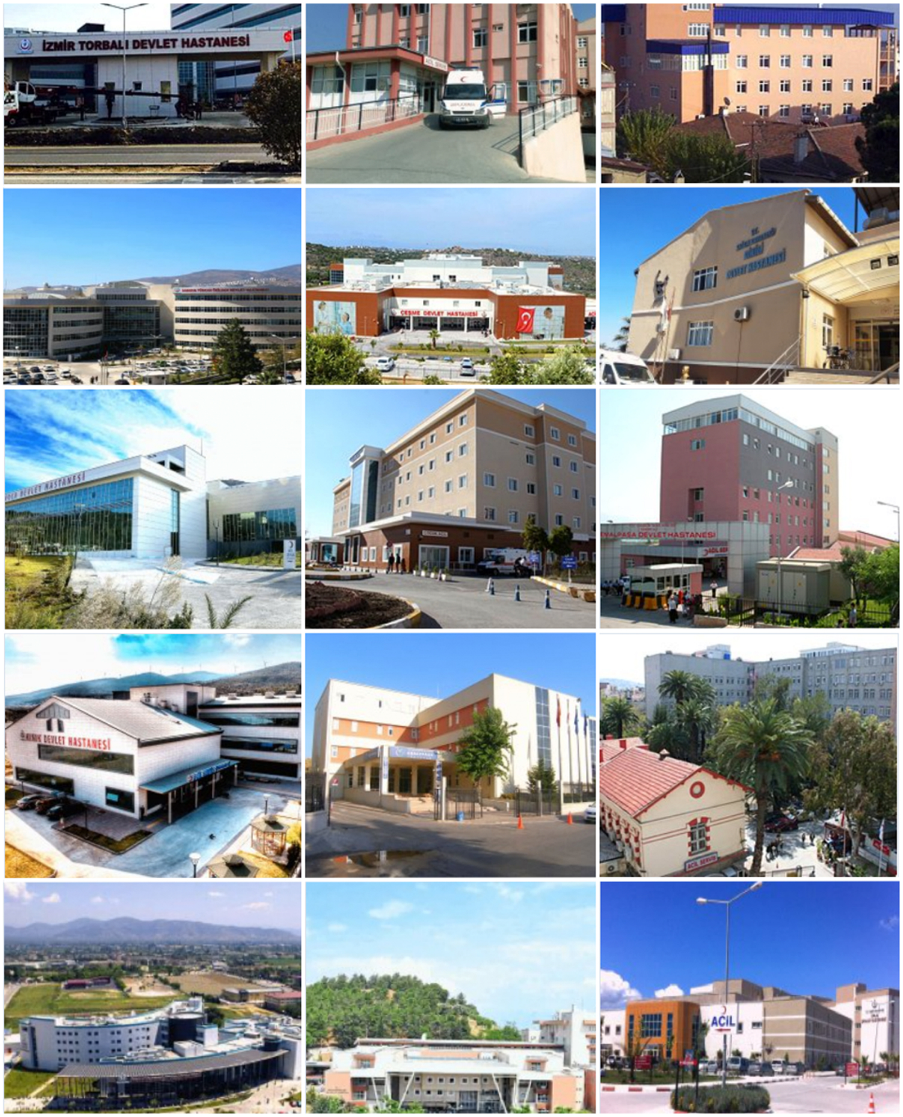
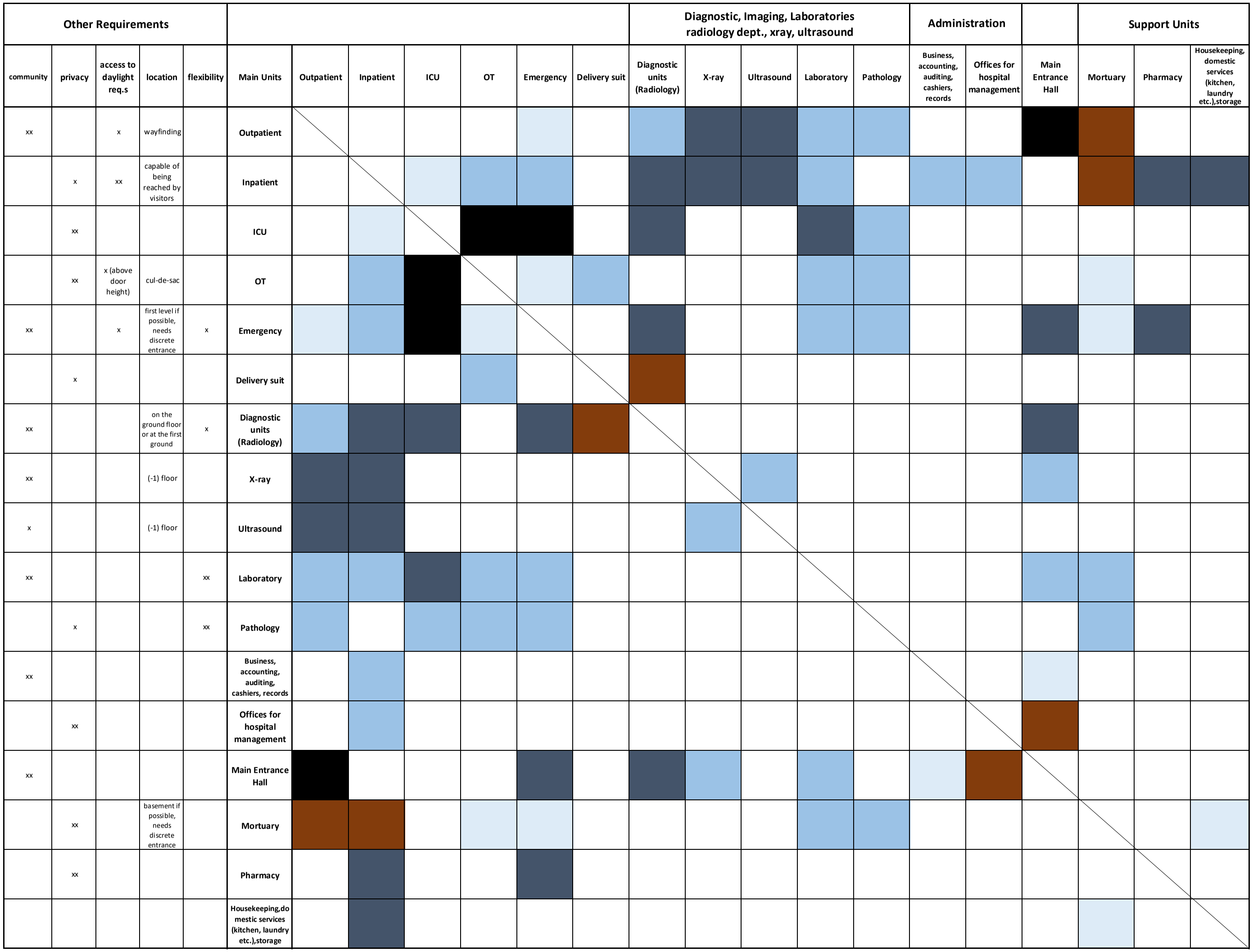


FIG. 3.35 Various hospitals in İzmir [194]

3.2.4 Activity Relationship Chart

Through the reviews of the above guidelines, personal communications, and on-site observations, the relationship chart between the hospital's main units is created which of each relation is weighted according to the adjacency and connectivity requirements. In addition to these requirements, privacy, flexibility, daylight, and some other specific location requirements for appropriate departments are also stated in the tables, thus these requirements are considered an effect during the layout arrangement of these units.

Related to the REL-Chart result in Figure 3.36, intensive care units (ICU) must adjoin the recovery room of the operation theatre. ICU requires many engineering services, in the form of a controlled environment, medical gases, compressed air, and power sources. These requirements are very similar to those in the OT. Mortuary must be away from inpatient wards but must be easily accessible. Housekeeping areas should be grouped around a service yard. Emergency patients require prompt radiological studies, however, in most cases emergency includes diagnostic units in the department. Suggested away-relationship between delivery suit and diagnostic is for pregnant safety. X-ray and ultrasound units should be in the same department. Laboratory and pathology units should be accessible to the mortuary for post-mortem examination. The Mortuary should be in a special service yard, with a discrete entrance. The privacy of the ICU is based on the heavy traffic and noise; it must exclude the traffic must be away from elevators. Diagnostic spaces are related to communal spaces, so they are next closest to the main entrance. The flexibility of the laboratory is required because the lab services come under great pressure to expand, as the workload tends to double every 5-8 years. Their growth will be even faster as the OPD is strengthened to integrate provisions for primary health. The plan for laboratory work benches must be flexible, perhaps comprising modules. Related to the security requirement of the pharmacy department, it should have secure access control, entrances should be limited and ideally, all entries should be under the pharmacist's visual control. ICUs don't have to be so close to the inpatients, in some cases, especially in research hospitals, ICU must be close to its service e.g. Pulmonary Intensive Care Unit (PICU) must be close to the pulmonology inpatient. Similarly, OT must be closer to the surgical units' inpatient wards than medical wards. To sum up, each closeness requirements come from different circumstances such as due to shared facilities or equipment, flow of people or materials, shared staff, privacy, community, and flexibility requirements, which are also shown in Figure 3.36 with customary codes for closeness ratings (Table 3.4).



Other Requirements												Diagnostic, Imaging, Laboratories radiology dept., xray, ultrasound					Administration			Support Units		
community	privacy	access to daylight req.s	location	flexibility	Main Units	Outpatient	Inpatient	ICU	OT	Emergency	Delivery suit	Diagnostic units (Radiology)	X-ray	Ultrasound	Laboratory	Pathology	Business, accounting, auditing, cashiers, records	Offices for hospital management	Main Entrance Hall	Mortuary	Pharmacy	Housekeeping, domestic services (kitchen, laundry etc.),storage
xx		x	wayfinding		**Outpatient**					░		▒	▓	▓	▒	▒			⬛	🟫		
	x	xx	capable of being reached by visitors		**Inpatient**			░	▒	▒		▓	▓	▓	▒		▒	▒		🟫	▓	▓
	xx				**ICU**		░		⬛	⬛		▓			▓	▒						
	xx	x (above door height)	cul-de-sac		**OT**		▒	⬛		░	▒				▒	▒				░		
xx		x	first level if possible, needs discrete entrance	x	**Emergency**	░	▒	⬛	░			▓			▒	▒			▓	░	▓	
	x				**Delivery suit**				▒			🟫										
xx			on the ground floor or at the first ground	x	**Diagnostic units (Radiology)**	▒	▓	▓		▓	🟫								▓			
xx			(-1) floor		**X-ray**	▓	▓							▒					▒			
x			(-1) floor		**Ultrasound**	▓	▓						▒									
xx				xx	**Laboratory**	▒	▒	▓	▒	▒									▒	▒		
	x			xx	**Pathology**	▒		▒	▒	▒										▒		
xx					**Business, accounting, auditing, cashiers, records**		▒												░			
	xx				**Offices for hospital management**		▒												🟫			
xx					**Main Entrance Hall**	⬛				▓		▓	▒		▒		░	🟫				
	xx		basement if possible, needs discrete entrance		**Mortuary**	🟫	🟫		░	░					▒	▒						░
	xx				**Pharmacy**		▓			▓												
					Housekeeping,domestic services (kitchen, laundry etc.),storage		▓													░		

FIG. 3.36 Activity Relationship Chart for A Typical Mid-Size Hospital

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TABLE 3.4 Customary codes for closeness ratings

⬛	Absolutely important	A	1
◼	Especially important	E	0.75
🟦	Important	I	0.5
⬜	Ordinary closeness	O	0.25
	Unimportant	U	0
🟫	Undesirable	X	-1

3.3 Identifying Program of Requirements of Hospitals

This sub-chapter has been published by Cubukcuoglu, C., Nourian, P., Sariyildiz, I. S., & Tasgetiren, M. F. (2020). A discrete event simulation procedure for validating programs of requirements: The case of hospital space planning. SoftwareX, 12, 100539. [195] The layout has been adjusted to fit the template of this thesis.

The previous chapter introduced the first part of our preliminary research to identify one of the most important inputs for hospital designs: a typical REL chart of mid-size hospitals through some qualitative methods. This chapter presented a computational model for creating another important input for hospital designs, which is the Program of Requirements (PoR) considering hospital layout design regulations (by referring to Turkey's standards in the presented case study).

A Discrete Event Simulation Procedure for Validating Programs of Requirements: The Case of Hospital Space Planning

Here we introduced a Discrete-Event Simulation (DES) tool developed as a parametric CAD program for validating a program of requirements (PoR) for hospital space planning. The DES model simulates the procedures of processing patients treated by doctors, calculating patient throughput and patient waiting times, based on the number of doctors, patient arrivals, and treatment times. In addition, the tool is capable of defining space requirements by taking hospital design standards into account. Using this tool, what-if scenarios and assumptions on the PoR about space planning can be tested and/or validated. The tool is ultimately meant for reducing patient waiting times and/or increasing patient throughput by checking the match of the layout of a hospital concerning its procedural operations. This tool is envisaged to grow into a toolkit providing a methodological framework for bringing Operations Research into Architectural Space Planning. The tool is implemented in Python for Grasshopper (GH), a plugin of Rhinoceros CAD software using the SimPy library (See Figure 3.37).

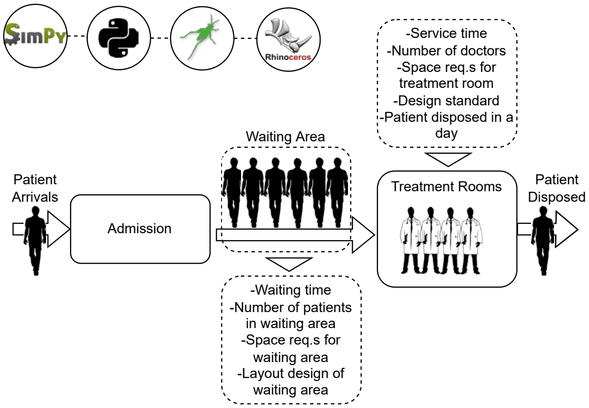

FIG. 3.37 Graphical Abstract: Relations between spatial and operational planning of hospitals

3.3.1 Introduction

3.3.1.1 Motivation and Problem Statement

Discrete event simulation (DES) is a method that mimics the operations of real and/or proposed systems as an ordered series of events. During the simulation, each event shows a specific change in the system's state at separate points in time. DES allows decision-makers to build complex models of operations, to quickly test what-if scenarios on their operations, and to explore alternative ways of implementing new strategies [196]. Space is almost always constrained and that indeed provides a sense of maximum efficiency/throughput. However, in addition to space, hospitals are the kind of buildings whose operations might be much more expensive than their building/space in their lifetime. The tool provides the means to simulate the volumes of operations in terms of flows of people and waiting for times etc. such that space planners and/or architects can ‘engineer’ the program of requirements before realizing it; i.e., to get a sense of scale and time-wise implications of decisions to provide the right amount of spaces for certain uses. DES has been widely used in hospital planning [197], [198] for modelling patient flow processes, estimating patient satisfaction, optimizing the healthcare human/physical resources, and reducing healthcare costs [199], [200]. In inpatient flow models, the most commonly considered inputs are patient admission schedules, admission rules, patient routing, flow schemes, facility, and staff resources; the most common outputs are patient throughput, patient waiting times, physician utilization, staff and facility utilization [201]–[203]. In particular, DES has been mostly utilized to model outpatient areas in the literature. Zhao and Lie (2008) [204] proposed the DES to model patient flow in the emergency department for resource utilization and reducing department crowding. Oddoye et al. (2009) [205] modelled a medical assessment unit (MAU) using the DES for evaluating the length of stay and bed utilization. Reynolds et al. (2011) [206] modelled the outpatient dispensing process by using the DES and evaluated the staffing levels and workload. Haji and Darabi (2011) [207] modeled Ear, Nose, Throat clinic and the appointment system using the DES for reducing outpatient waiting times. Al-Araidah, Boran, and Wahsheh (2012) [208] utilized the DES method for reducing delays in the ophthalmology outpatient department. Rau et al. (2013) [209] focused on the strategic capacity planning of an outpatient physical therapy service using the DES to reduce waiting times and length of stay. Weerawat, Pichitlamken, and Subsombat (2013) [210] built a DES model for an orthopedic outpatient area for the assessment of wait times to see doctors. Baril, Gascon, and Cartier (2014) [211] used the DES to model outpatient flows and appointment scheduling in an orthopedic clinic to reduce patient lead times and maximize the number of patients seen by the orthopaedist doctor. Best et al. (2014) [212] used the DES to improve patient flow, improve patient throughput and reduce the length of stay in emergency and acute care. Pan et al. (2015) [213] proposed a DES model to represent the patient and information flow in an ophthalmic outpatient department and aims at reducing patient waiting times. Baril et al. (2016) [214] utilized the DES for improving patient trajectories in a hematology-oncology department by reducing patient delays. Dan et al. (2016) [215] applied the DES to outpatient pharmacy queuing problem where the factors to evaluate queue system are average waiting time, the average length of the queue, average utilization of servers and length of busy time. Babashov et al. (2017) [216] developed a DES model of the patient journey for reducing the patient waiting times to consult or treatment in radiation oncology department. Shin et al. (2017) [217] implemented a DES model to characterize the patient flow in an emergency department with the aim of minimizing patient length of stay (LoS), number of handoffs, staff utilization levels, and cost. Recently, Moretto et al. (2019) [218] used the DES to improve service planning in orthopaedic and neurosurgical outpatient department. Baril, Gascon, and Vadeboncoeur (2019) [219] built the DES model to analyse ambulatory patient length of stay in an emergency department with a resource and staff planning. In [220], authors proposed a decision support framework for a clinician's schedule using the DES for an outpatient area of a hospital by assessing the patient waiting times for consultation.

The system is not meant to make decisions but to help the planners engineer their space plans. Hospital operations consist of a critically important sequence of medical activities and procedures where any delay in patient care may prove fatal. However, often it is unavoidable. Therefore, the fitness of the building for the planned operations of the hospital plays an important role in the layout design [221]. DES provides an explicit mechanism for testing the degree to which the building matches its operations [201], i.e. by simulating the patient flow patterns and thus hinting towards how estimated patient waiting times can be reduced by a functional/logical layout during the conceptual design phase of a hospital. In other words, DES provides an explicit way of modeling and understanding the functionality of the building, which can be used to inform the process of shaping the building accordingly.

Space requirements pertain to hospital design standards, such as minimum space area constraints and light requirements. Therefore, such requirements are among the important factors that should be fed to the layout design process (a.k.a. space planning). The area requirements generally differ based on several medical staff. For example, according to the hospital design standards of Turkey, outpatient waiting areas must be a minimum of 12 m^2 for 1 doctor, and a minimum of 24 m^2 for 2 doctors, and an additional 5 m^2 should be considered for each additional doctor [222]. On the other hand, space requirements must also handle people's expectations e.g. waiting areas must be large enough for the [estimated] number of visitors waiting in a queue.

The motivation for this paper can be summarized as follows:

- Hospital standards affect their design considerations (space requirements).
- Patient flow and waiting times can be estimated through DES.
- Space requirements differ from one context to another (country-specific regulations, the size of the program of requirements, etc.).
- Space requirements can be adjusted to reduce the waiting times (or a wider waiting area can be needed if patient waiting times are too high) using what-if scenarios in DES.
- DES provides a clear understanding of critical procedures within a building and thus can inform the spatial layout process.

3.3.1.2 State of the Art

There are some DES tools, namely Arena [223], and ExtendSim [224] that are mostly used in industrial engineering for system simulation [225]. Other recent DES tools are FlexSim [226], [227], SimEvents [228], [229], SIMUL8 [230], [231], MedModel [232], [233] and Manpy [234]–[236]. Specifically, MedModel focuses on healthcare simulations. Similar to the DES_PoR tool, Manpy is another Python-based open-source tool, which is developed on top of SimPy. However, they do not present straightforward ways of interaction with CAD software applications commonly used in architectural practice.

Utilizing DES in architectural design was suggested by [237], especially for early-stage conceptual design. Their approach integrates DES simulation into a hospital space planning tool. In addition, [221] presented an evaluation method using Discrete Event Simulation for the assessment of hospital layout design from the viewpoint of operations management to test if the building design provides for the efficient operation of patient care.

3.3.1.3 Contributions

The primary contribution of the paper is that users of this tool will be able to utilize the abovementioned functionalities in a Parametric Modeling environment, called Grasshopper (a plug-in of Rhinoceros CAD software). Using this tool, architects/decision-makers/designers can practically define space requirements to design a hospital considering hospital design standards. Rapid integration of meter square information to the model plays an essential role to define the program of requirements during the conceptual design phase in this tool. Providing real-time Discrete-Event Simulation at the same time, the tool can give feedback on the performance indicators (patient waiting times, patient throughput), which is translatable into the likely functional/logical performance of the hospital plan layout patterns. Furthermore, the outputs of this tool can be used in architectural design optimization models as an input to be minimized or maximized.

We applied the tool to a hospital in Izmir, Turkey (to be a newly built hospital in Seljuk). Therefore, minimum space requirements for each hospital department are taken from Turkey's hospital standard using an assumed building program. The DES part of the tool was applied to outpatient departments. In this part, patient throughput and patient waiting times are taken as outputs, which can be also defined as performance indicators of our tool. The number of staff is considered as an input, which also affects the spatial configuration and space area of the outpatient departments. The mutual interaction between the operational planning of the hospital and its spatial planning is central to our approach. Throughout this work, we show how DES models can be used as design decision-support tools to create a bridge between architecture and hospital management. Specifically, the tool can help answer these questions:

1. How to test the match of the layout with the operational planning of the hospital to reduce the patient waiting times and increase the patient throughput in a day?

2. How do scale and adjust the program of requirements (PoR) of hospitals through DES and hospital standards that are affected by hospital operational planning?

3.3.2 Software Description

The core functionality of this tool is to validate the program of requirements of a hospital referring to the patient-flow model by discrete-event simulation and hospital design standards and make this tool compatible with parametric design models created in GH algorithmic modeling for Rhinoceros CAD software. The first functionality is to simulate patient flows in the outpatient area. An outpatient department consists of many subsections with distinct specialties, and thus it has some special properties distinct from other departments in a hospital in its operations, and so it is a commonly modeled area by DES in the literature for capacity planning [198]. The outpatient department is typically the most active area in terms of human flow with many types of uncertainties in patient arrivals, treatment patterns, and service time. Waiting times can be defined as the time that patients arrive in the clinic and wait until doctors call them for treatment. And they are depending on both the operational and space planning of the hospital. For the patient-flow modeling with DES, Simpy library [238] is used in the GH_CPython [239] component that implements CPython (the standard implementation of Python3.7) codes inside Grasshopper (GH). Therefore, GH_CPython scripting is used in this tool. Figure 3.39 shows a screenshot from the GH interface. The component named DES_PoR tool in this figure is run a python code, which is available in Code 3.1. The number sliders at the left part are defined as input values of this component and the panels on the right side of the component are the outputs of the simulation and PoR values. Users can change these number sliders and simultaneously see the change in output values during the decision-making and planning processes for hospital space planning.

Besides, both waiting areas and treatment rooms have strict hospital design standards as described above. Therefore, we formulate another desired functionality as an automatic generation of area requirements based on hospital design standards. It is straightforward to adjust input parameters (e.g. staff planning) in the proposed tool and to quickly see the change in performance indicators e.g. area requirements. Simply, this tool is easy to use by architects/designers since it is compatible with GH. Users of this tool can write scripts inside the GH_CPython component and update the model according to the needs of the focused hospital. For example, in our case study, the hospital is planned as 16 outpatient departments with a discrete waiting area for each of them. Components are also adjustable which means if one more input is needed, users can add it easily e.g. this situation can happen if the number of doctors varies in each outpatient area.

To sum up, this tool facilitates the conceptual [digital] design phase of hospital space planning through computational tools. The intent here is not to present a fully working space planning tool, but rather to support architects/designers as a decision-support tool in the early design-decision making process and to highlight the use of hospital management tools in spatial design. The components of this tool are illustrated in Figure 3.38.

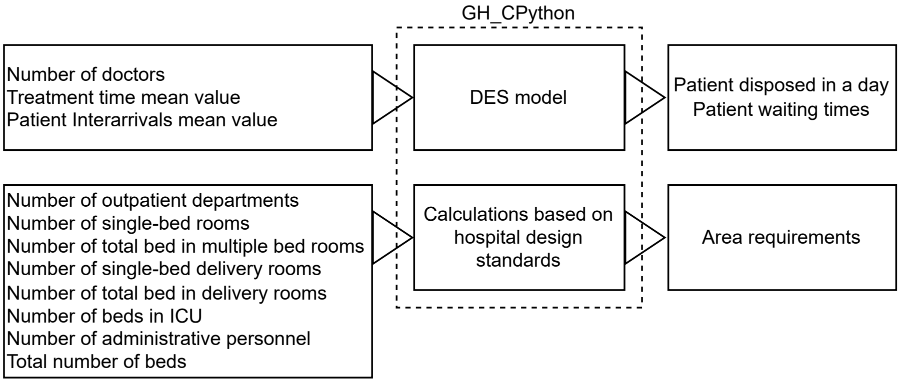

FIG. 3.38 Components of the tool

As a test case for the tool, we consider hospital standards pertaining to its spatial planning as follows [222]:

- Outpatient rooms must be min 16 m^2.
- Outpatient waiting areas must be
  - min 12 m^2 for 1 doctor
  - min 24 m^2 for 2 doctors
- additional 5 m^2 for each additional number of doctors.
- There must be min 6 elevators in 60-200 bed hospitals.
- There must be min 9 elevators in 201-350 bed hospitals.
- One-bed patient rooms must be min 9 m^2.
- Patient wards must be min 7 m^2 per bed.
- One-bed delivery patient rooms must be min 12 m^2.
- Delivery patient wards must be min 10 m^2 per bed.
- ICU units must be min 12 m^2 per bed.
- Neonatal ICU units must be min 6 m^2 per bed.
- Administrative offices must be 8-12 m^2 for each personnel.
- Bunker area = (number of beds) + (number of beds*20%)

Snippets of GH_CPython code for the DES model and calculation of area requirements are shown in Code 3.1 and the pseudo-code of this tool is given in Code 3.2.

CODE 3.1 GH_CPython code snippet

```
import random
import numpy as np
import simpy
TotalBeds_Num=SingleBedRoom_Num+MultipleBedRoom_BedNum+SingleBed_DeliveryRoom_
Num+MultipleBed_DeliveryRoom_BedNum+ICU_BedNum
#area calculation of treatment rooms & waiting areas in each outpatient department
if NUM_DOCTORS == 1:
  Outpatient_Dept_Area = (16 * NUM_DOCTORS) + 12 #treatment rooms + waiting areas
elif NUM_DOCTORS == 2:
  Outpatient_Dept_Area = (16 * NUM_DOCTORS) + 24 #treatment rooms + waiting areas
elif NUM_DOCTORS > 2:
  Outpatient_Dept_Area = (16 * NUM_DOCTORS) + 24 + (5 * (NUM_DOCTORS - 2))
#treatment rooms + waiting areas
RANDOM_SEED = 50 #seed number of simulation
SIM_TIME = 480 #simulation time in minutes: 8 hours
```

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```
data_wait = []
data_patientdisposed=[]
#create outpatient components
class Outpatient(object):
  def __init__(self, env, num_doctors, treatmenttime):
     self.env = env
     self.doctor = simpy.Resource(env, num_doctors)
     self.treatmenttime = treatmenttime
  def treat(self, patient):
     yield self.env.timeout(random.expovariate(1/TREATMENTTIME))
#create patient arrivals
def patient(env, name, pr):
  print(‘%s arrives at the outpatient department at %.2f.’ % (name, env.now))
  arrivetime=env.now
  with pr.doctor.request() as request:
     yield request
     print(‘%s enters the outpatient department at %.2f.’ % (name, env.now))
     entertime=env.now
     yield env.process(pr.treat(name))
     print(‘%s leaves the outpatient department at %.2f.’ % (name, env.now))
     print(‘%s waiting time %.2f.’ % (name, entertime-arrivetime))
     data_wait.append(entertime-arrivetime)
#create treatment process
def setup(env, num_doctors, treatmenttime, t_inter): #t_inter means that one patient arrives in each t_inter minutes
  outpatient_department = Outpatient(env, num_doctors, treatmenttime)
  #create 4 initial patients
  for i in range(4):
     env.process(patient(env, ‘patient %d’ % i, outpatient_department))
  #create more patients
  while True:
     yield env.timeout(np.random.poisson(t_inter)) #simulate patient arrivals in a poisson process with a lambda value of 7
     i += 1
     env.process(patient(env, ‘patient %d’ % i, outpatient_department))
     data_patientdisposed.append(i)
#run the simulation
random.seed(RANDOM_SEED)
env = simpy.Environment()
env.process(setup(env, NUM_DOCTORS, TREATMENTTIME, T_INTER))
env.run(until=SIM_TIME)
```

```
#get the outputs of DES from a,b
a=data_patientdisposed #number of patients disposed (treated) from the system
b=data_wait #number of waiting times
#calculate space requirements of hospital units
c=Outpatient_Dept_Area*OutpatientDept_Num #total area of all outpatient dept.s
d=(SingleBedRoom_Num*9)+(MultipleBedRoom_BedNum*7) #One-bed patient rooms must be
min 9 m2.Patient wards must be min 7 m2 per each bed.
e=(SingleBed_DeliveryRoom_Num*12)+(MultipleBed_DeliveryRoom_BedNum*10) #One-
bed delivery patient rooms must be min 12 m2.Delivery patient wards must be
min 10 m2 per each bed.
f=ICU_BedNum*12 #ICU units must be min 12 m2 per each bed.
g=Administrative_Num*random.randint(8,12) #Administrative offices must
be 8-12 m2 for each personnel.
h=TotalBeds_Num+(TotalBeds_Num*0.2) #Bunker area = (number of beds) + (number of
beds*20%)
#There must be min 6 elevators in 60-200 bed hospitals.
#There must be min 9 elevators in 201-350 bed hospitals.
if TotalBeds_Num >= 60 and TotalBeds_Num <= 200:
 MIN_ELEV = 6
elif TotalBeds_Num > 200 and TotalBeds_Num <= 350:
 MIN_ELEV = 9
i=MIN_ELEV
#get the outputs of PoR from c,d,e,f,g,h,i
```

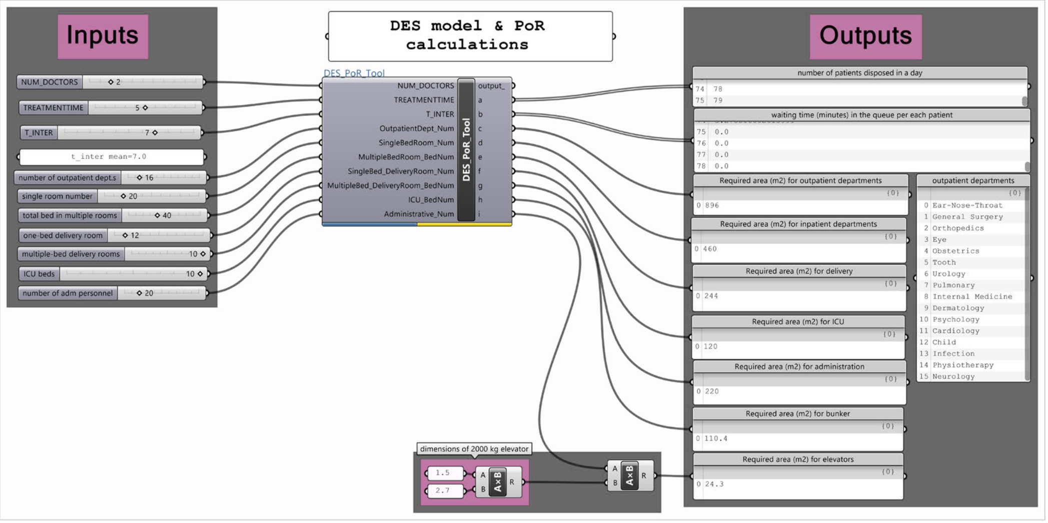
CODE 3.2 The procedure implemented in the DESPoR tool

```
Begin
  Put the simulation settings
  Create DES model
      Create patient arrivals
      Create a treatment process using GH inputs
      Run the simulation
  Get the outputs of DES
  Calculate space requirements for each unit
      Formulations using GH inputs and hospital design standards
  Get the outputs of PoR
End
```

3.3.3 Illustrative Examples

The presented method has been implemented as a computational tool and is currently being tested with a sample hospital. Since we were considering Turkey's hospital standards, we selected a hospital in Izmir as a case study, which is going to be newly built in Seljuk. There are 16 specialties in the outpatient department and 2 inpatient departments as surgery and medicine.

We construct a DES model based on the procedures for patients to be treated by some doctors in outpatient departments in a hospital. In the DES model shown in Figure 3.39, input values are taken the same for all outpatient departments. The number of doctors is input for every outpatient department as part of the resource planning process in this paper. In the literature [204], [209], [240], [241], the patient inter-arrivals to an outpatient department have typically been modeled as Poisson arrivals and the treatment time durations, which refers to the duration of consultation with the physician for this case, have been mostly modeled as exponential. Therefore, in this paper, we assumed that the interarrival times are followed by a Poisson process with 5-minute mean value, and the treatment times are exponentially distributed with a 7-minute mean value. We took 5 replications with 5 different seed numbers for the simulation. The minimum, maximum, average, and standard deviation of the waiting time results in each replication have been recorded in Table 3.5.



NUM_DOCTORS 2
TREATMENTTIME 5
T_INTER 7
t_inter mean=7.0
number of outpatient dept.s 16
single room number 20
total bed in multiple rooms 40
one-bed delivery room 12
multiple-bed delivery rooms 10
ICU beds 10
number of adm personnel 20

dimensions of 2000 kg elevator
1.5
2.7

number of patients disposed in a day
74 78
75 79

waiting time (minutes) in the queue per each patient
75 0.0
76 0.0
77 0.0
78 0.0

Required area (m2) for outpatient departments
{0}
0 896

Required area (m2) for inpatient departments
{0}
0 460

Required area (m2) for delivery
{0}
0 244

Required area (m2) for ICU
{0}
0 120

Required area (m2) for administration
{0}
0 220

Required area (m2) for bunker
{0}
0 110.4

Required area (m2) for elevators
{0}
0 24.3

outpatient departments
{0}
0 Ear-Nose-Throat
1 General Surgery
2 Orthopedics
3 Eye
4 Obstetrics
5 Tooth
6 Urology
7 Pulmonary
8 Internal Medicine
9 Dermatology
10 Psychology
11 Cardiology
12 Child
13 Infection
14 Physiotherapy
15 Neurology

FIG. 3.39 A screenshot of the DES tool as an editable Python script inside the Grasshopper interface. The tool can be combined with procedural workflows in this environment to give or take variable outputs and/or inputs.

TABLE 3.5 Simulation results for each replication

	Rep.1	Rep.2	Rep.3	Rep.4	Rep.5	Min	Max	Avg.	Std. Dev.
Total waiting time in a day (minutes)	13.07	29.38	49.56	24.57	11.87	11.87	49.56	25.69	15.29

According to the simulation results (Table 3.5), the minimum waiting time is obtained as 11.87 minutes in replication-5 with a seed number of 50. In this case, there are 72 patients treated in a day in each department. When the number of doctors is increased to 3, patient waiting time is reduced to 1.57 minutes. Then, the area required for the outpatient area is changed from 896 to 1232 m^2. On the other hand, when the number of single-bed rooms in the inpatient department is changed from 20 to 30, the area required for the inpatient department is increased from 460 to 550 m^2.

When the mean value of treatment time is taken as 12 minutes and the number of doctors is taken as 3 in each outpatient department, the total waiting time of patients is 89.5 minutes so 1232 m^2 is needed for all outpatient departments in the hospital. After simulating with 4 doctors, waiting time is reduced to 3.5 minutes, and the required area for outpatient departments is increased to 1568 m^2. The latter case requires 336 m^2 more area for the outpatient department with 86 minutes less waiting time. Furthermore, when the number of doctors is taken as 5, the maximum estimated waiting time becomes zero. This case has great advantages from the point of waiting time, however, the outpatient area is very large (1904 m^2), which may not be handled with space available constraint, which is 1800 m^2 in this case. Therefore, decision-makers could be recommended to plan 4 doctors in each outpatient department. As an example of sizing an inpatient department, when the number of single rooms is 20 and the number of beds in multiple rooms is 40, the required area is 460 m^2 for patient wards. If the number of single rooms is increased to 30 and the number of beds in multiple rooms is reduced to 30, then the area requirement amounts to 480 m^2. In the second scenario, the area requirement is slightly larger than the first one. It could be concluded that it would be more advantageous to select the second scenario for inpatient departments as it has 10 more single inpatient rooms; because single-patient rooms reportedly have a better effect on the patient healing process than multiple-bed rooms. This is how the tool allows for checking different scenarios during the decision-making process of hospital space planning.

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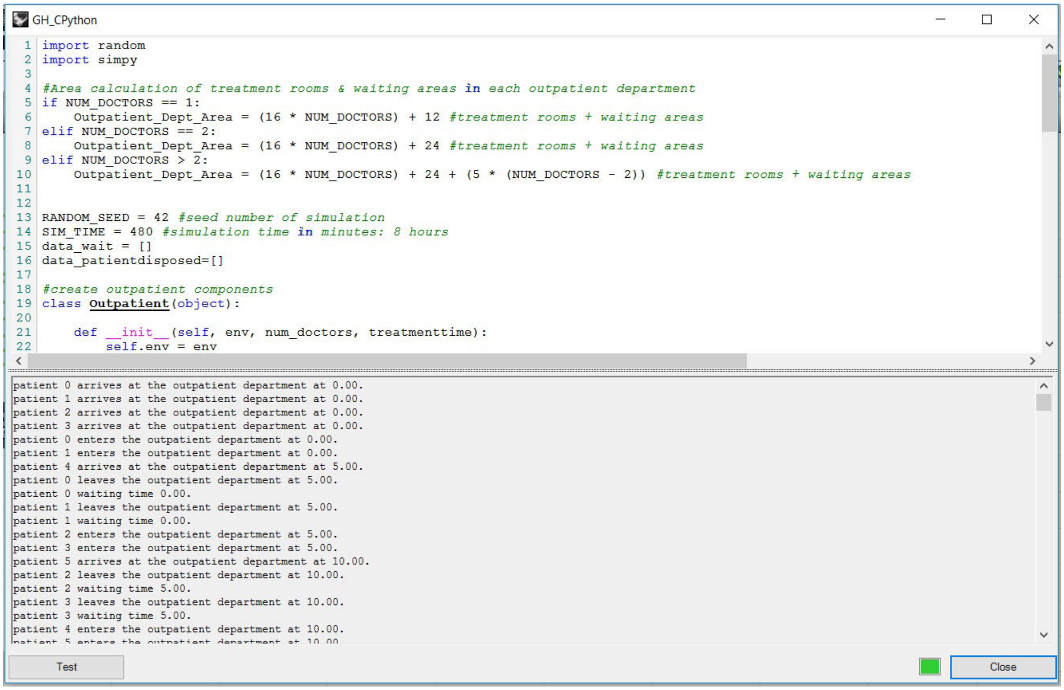
3.3.4 Impact

This tool is designed to handle two main research questions introduced in Section Contributions. Since this tool is created in a procedural modeling environment, it can be utilized to test the match of the building layout with the operational planning of the hospital in computational design workflows. Specifically, what-if scenarios on hospital planning can be tested through an interactive input-output connection over this tool. During such tests, changes in (patient-focused) performance indicators can be interactively observed by a decision-maker/architect by changing the decisions regarding input parameters. Our tool enables both identifying and validating building programs based on performance indicators obtained by the DES model and hospital design standards. In particular, it helps to answer the existing research question introduced by [221]. This tool represents a step towards closing the gap between these two worlds by representing a more practical way from the point of architectural design practitioners. The tool is a plug-in of Rhino CAD software, i.e. the de facto standard environment of choice for computational design in architecture, and at the same time portable to open environments because it is a Python script also implemented in a Jupyter notebook. This tool can be used in space planning of hospital designs in practice (as a Rhino/Grasshopper plugin) as well as in research studies (as a Python script). The script and some exemplary results are shown in Figure 3.40. It is envisioned to be an extensible and open-source tool for hospital planning. As it is freely available in the public domain (https://github.com/CemreTUDelft/DES_PoR_Tool), users can extend the tool for their own needs or integrate focusing on different case studies (types of hospitals) and system models (e.g. queue model) or different users (e.g. administrative people flow). In addition, users of this tool can estimate the flow rates between each space with the help of the DES. More flows between spaces require more closeness between their locations. Therefore, these flow rates are significant parameters to identify closeness ratings between each space, which also helps to create relationship charts (REL-charts) to be used during the space planning process. To the authors' knowledge, currently, there does not exist any publicly available DES model and building PoR test tool for hospitals in GH, especially for computational design and space planning.



```python
import random
import simpy

#Area calculation of treatment rooms & waiting areas in each outpatient department
if NUM_DOCTORS == 1:
    Outpatient_Dept_Area = (16 * NUM_DOCTORS) + 12 #treatment rooms + waiting areas
elif NUM_DOCTORS == 2:
    Outpatient_Dept_Area = (16 * NUM_DOCTORS) + 24 #treatment rooms + waiting areas
elif NUM_DOCTORS > 2:
    Outpatient_Dept_Area = (16 * NUM_DOCTORS) + 24 + (5 * (NUM_DOCTORS - 2)) #treatment rooms + waiting areas


RANDOM_SEED = 42 #seed number of simulation
SIM_TIME = 480 #simulation time in minutes: 8 hours
data_wait = []
data_patientdisposed=[]

#create outpatient components
class Outpatient(object):

    def __init__(self, env, num_doctors, treatmenttime):
        self.env = env
```

```
patient 0 arrives at the outpatient department at 0.00.
patient 1 arrives at the outpatient department at 0.00.
patient 2 arrives at the outpatient department at 0.00.
patient 3 arrives at the outpatient department at 0.00.
patient 0 enters the outpatient department at 0.00.
patient 1 enters the outpatient department at 0.00.
patient 4 arrives at the outpatient department at 5.00.
patient 0 leaves the outpatient department at 5.00.
patient 0 waiting time 0.00.
patient 1 leaves the outpatient department at 5.00.
patient 1 waiting time 0.00.
patient 2 enters the outpatient department at 5.00.
patient 3 enters the outpatient department at 5.00.
patient 5 arrives at the outpatient department at 10.00.
patient 2 leaves the outpatient department at 10.00.
patient 2 waiting time 5.00.
patient 3 leaves the outpatient department at 10.00.
patient 3 waiting time 5.00.
patient 4 enters the outpatient department at 10.00.
patient 5 enters the outpatient department at 10.00
```

FIG. 3.40 The script and some exemplary results

3.3.5 Conclusions

This paper introduced a new plug-in tool for grasshopper algorithmic modeling (GH) in the Rhinoceros CAD program. This tool is envisioned as a part of a larger suite of tools to bridge the gap between Operations Research and Architectural Design, specifically for computational space planning of hospitals. A discrete event simulation (DES) is implemented in this tool for patient-flow modeling. Outputs of the DES model facilitate the validation of the match between space planning elements such as PoR and REL charts and the operational logic of the building. For future work, hospital standards of different countries will be added to the model. Different users such as nurses can be added to the model. DES model can be improved considering different types of scenarios, such as patient flows in an emergency. Eventually, this tool can be generalized for other types of complex buildings such as airports.

3.3.6 Limitations

We focus on the outpatient department in this paper. In intensive care units or inpatient departments, patient flow logic is different. Treatment processes are different. Also, outpatient departments are working 8 hours a day. The simulation runs for 8 hours. Other departments' operations run 24 hours a day. Therefore, the DES is specialized for outpatient, where the waiting times are the most important in these places.

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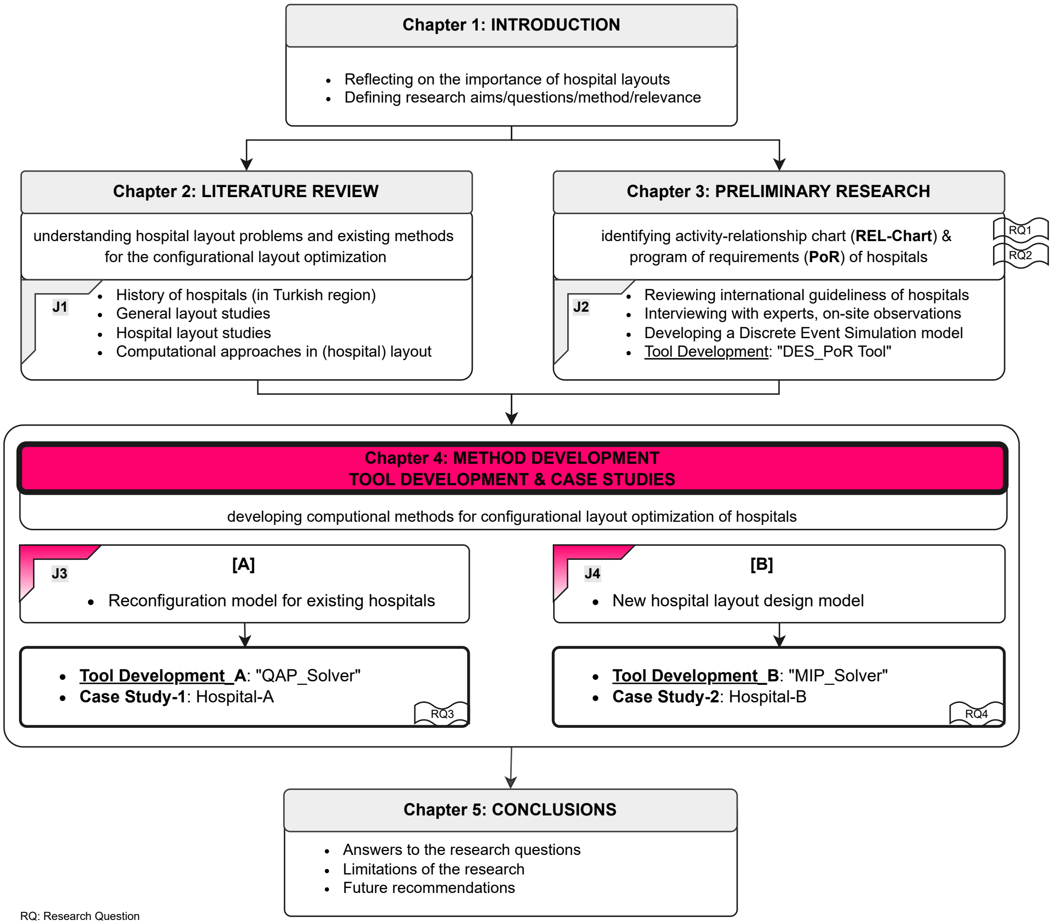

RQ: Research Question
J: Journal

4 Method Development & Case Studies

As mentioned in the dissertation outline in chapter 1, there are two parallel tracks of work reported in this dissertation on hospital layout design: track A (reconfiguration of existing hospitals) and track B (designing new hospital layouts). While developing the methods and tools in each track, we focus on hospitals in Izmir, Turkey that should be improved or newly designed. In track A, there is something there and we need to redesign it; in track B, there is nothing there and we need to design it from scratch. The core concept of the reconfiguration track is assigning hospital departments to the locations of the existing building such that the assignment cost is minimized. The assignment cost is defined as the sum, over all pairs, of the flow between a pair of facilities multiplied by the distance between their assigned locations. On the other hand, the core concept of the designing from the scratch case is assigning hospital departments to the faces of a hypothetical mesh surface such that the closeness of the interrelated spaces is minimized. In the second model, various types of constraints are defined considering adjacency, privacy, flexibility, and daylighting requirements. In addition, as a holistic approach, following the configuration of the hospital departments, corridors are designed in between the hospital departments in a way that assigns edges of the hypothetical mesh surfaces to the corridors. In the corridor model, wayfinding and work-related interruptions objectives are formulated. In the reconfiguration case, existing corridors/vertical circulation routes are kept and included in the model as pathways to be calculated the geodesic distances between existing locations. In both models, there is a discrete representation of the spaces however, their solution methodologies are differentiated. Due to the nature of the problems, in the first track, Quadratic Assignment Problem formulation and a heuristic optimization algorithm were proposed. In the second track, Mixed Integer Programming formulations and an Operations Research solver are suggested.

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The models presented in this dissertation have been programmed as a design toolkit that is available in CAD software and implemented in real-world case studies. The preliminary research presented in chapter 3 is required to get adequate hospital inputs to develop both models. They are not case-based models but for the test and validation of the layout results, each of the models applied to real-world case study hospitals, namely Hospital A and Hospital B chosen in Izmir, Turkey. The models are created considering Turkey's hospital design codes and standards and specific to mid-size general hospitals, however, the models can be modified later according to the different country's regulations with another extensive preliminary research. Finally, the workflow of two proposed models with case studies is illustrated in Figure 4.1. As shown in this figure, the workflow follows the stages of "build, evaluate, theorize, and justify" as suggested in [242], [243], [9] and we call the whole methodology as **HOPCA (Ho**spital Layout Design **Op**timization using **C**omputational **A**rchitecture**)** in this dissertation.

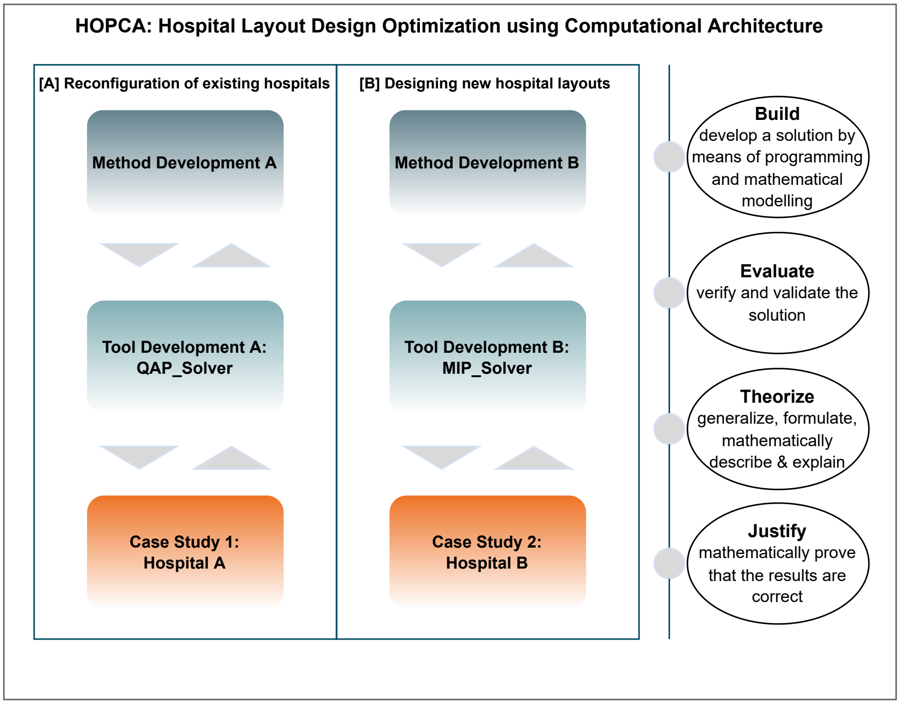

FIG. 4.1 Method Development Stages

4.1 Discretization of HLP

In this dissertation, the hospital buildings are designed with the idea that they are large human settlements with a wide range of systems for accommodation (for inpatients), transportation (of materials, waste, equipment), and communication (for visitors, patients, and medical staff). Because of these complex characteristics, as well as the obvious spatial complexity of modern hospitals, conceptually we can think of a hospital as an ‘Indoor City’. Our high-level goals for creating healing environments with proper layout designs must thus be meticulously translated and adapted to the design of such an indoor city (as an abstract configuration). To deal with these huge environments, we handle the problem as a topological layout problem for formulating an otherwise “wicked problem”. Such a representation provides some conveniences and advantages. Since connectivity has a great impact on the efficient functioning of complex buildings (See Figure 4.2) and must be clearly defined during the layout design process, a discrete representation of space is more adequate and effective than Euclidean space, especially in finding more realistic spatial distances. In the Euclidean (geometric) approach, the straight line can be defined as the distance between two locations, however, in real built environments, direct access is mostly spatially obstructed with doors, walls, or atriums. It is obvious that if two rooms are on the opposite side of an elevator, their access to one another is not through their straight line but a possibly much longer path. It is therefore suggested that a discrete network spatial representation is more suited for hospital layouts due to involving human actions as it facilitates the consideration of actual walkable distance.

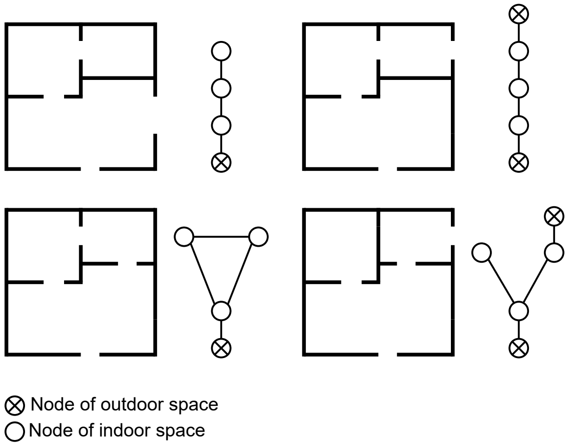

FIG. 4.2 Representing the differentiation of the human path due to changing connectivity in topology

Thanks to the neighborhood concept in topology, topological models allow us to establish semantic relationships between spaces. For example, we understand our location with the things such as being in Building X or near Room Y; instead of thinking about our actual coordinates (x,y) where we stand. Furthermore, topological layouts facilitate the gradual concretization of abstract graphs, which corresponds to Activity REL-Chart, towards geometrical floor plans (See Figure 1.8). Our approach, therefore, entails consideration of the discrete optimization techniques for the configuration of hospital layouts by making use of multi-disciplines including Architecture, Mathematics, Industrial Engineering, Computational Intelligence & Optimization, and Social Sciences. Here we start to explain our proposed models.

4.2 Track A: Reconfiguration of Existing Hospital Layouts

This sub-chapter has been published by Cubukcuoglu, C., Nourian, P., Tasgetiren, M. F., Sariyildiz, I. S., & Azadi, S. (2021). Hospital layout design renovation as a Quadratic Assignment Problem with geodesic distances. Journal of Building Engineering, 44, 102952. [244] The layout has been adjusted to fit the template of this thesis.

Hospital Layout Design Renovation as a Quadratic Assignment Problem with Geodesic Distances

Hospital facilities are known as functionally complex buildings. There are usually configurational problems that lead to inefficient transportation processes for patients, medical staff, and/or logistics of materials. The Quadratic Assignment Problem (QAP) is a well-known problem in the field of Operations Research from the category of the facility's location/allocation problems. However, it has rarely been utilized in architectural design practice. This paper presents a formulation of such logistics issues as a QAP for space planning processes aimed at the renovation of existing hospitals, a heuristic QAP solver developed in a CAD environment, and its implementation as a computational design tool designed to be used by architects. The tool is implemented in C# for Grasshopper (GH), a plugin of Rhinoceros CAD software. This tool minimizes the internal transportation processes between

interrelated facilities where each facility is assigned to a location in an existing building. In our model, the problem of assignment is relaxed in that a single facility may be allowed to be allocated within multiple voxel locations, thus alleviating the complexity of the unequal area assignment problem. The QAP formulation takes into account both the flows between facilities and distances between locations. The distance matrix is obtained from the spatial network of the building by using graph traversal techniques. The developed tool also calculates spatial geodesic distances (walkable, easiest, and/or shortest paths for pedestrians) inside the building. The QAP is solved by a heuristic optimization algorithm, called Iterated Local Search. Using one exemplary real test case, we demonstrate the potential of this method in the context of hospital layout design/re-design tasks in 3D. Finally, we discuss the results and possible further developments concerning a generic computational space planning framework. Graphical abstract of the study can be shown in Figure 4.3.

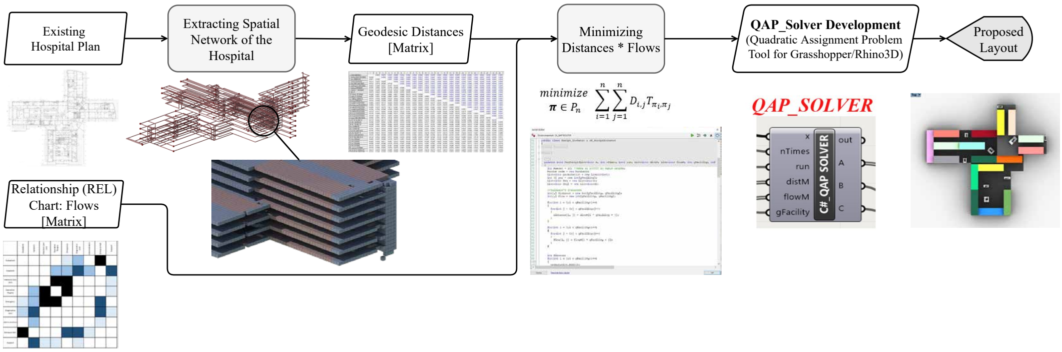

FIG. 4.3 Graphical abstract

4.2.1 Introduction

The term Space Planning refers to the processes aimed at arranging a spatial configuration having logistics-related objectives, ergonomics, and intended user experience of a building [245]. The spatial configuration of a building is an abstract representation of the particular ways in which the spaces inside a building are related to one another. Mathematically, spatial configurations are represented as graphs, which are typically labeled but may or may not be assumed as directed and weighted. Conventionally, if the graph in question is weighted and directed, it is called a network.

4.2.1.1 Problem Definition

Hospitals consist of a wide range of functional units, each serving different activities such as clinical, nursing, administration, service (food, laundry, etc.), research, and teaching. There are also numerous types of user groups and materials, moving or being transported between those various functions within the hospital. The flow rates of these movements in between the functional spaces can be modeled as a graph/ matrix indexed by the indices of the functional units, we can consider this as a graph describing the functional requirements. On the other hand, in an existing spatial configuration, how the spaces are inter-related can be modeled as a dense graph/ matrix encoding the distances between spaces of interest, computed concerning the [temporal] length of geodesics or optimal paths; we may refer to this graph as the spatial configuration graph. Therefore, one of the challenges of space planning can be seen as matching these two graphs such that the distance between pairs is small when the flow rate between them is large and vice versa.

According to the literature, around 67% of health and care employees are not able to perform their jobs efficiently due to the unsuitable layout of the working spaces [24]. Especially nurses sometimes spend more time walking than the activities related to patient care in a day [14] because of the spatial connectivity problems of the interrelated spaces. In one study, it has been observed that 28.9% of the nursing staff's time was wasted on walking [15]. Previous studies also show that the layout type of the nursing unit has an impact on the walking time of nursing staff, e.g. [16] established that nursing staff in the radial unit walked 4.7 steps per minute while the other staff working in the rectangular unit walked 7.9 steps per minute, which is significantly more. The poor placement of the clinics combined with the increasingly overwhelming volume of traffic between them was causing delays and heavy congestion in hospitals [246]. All these examples show that spatial configuration has a great impact on the efficient functioning of hospital buildings in terms of walking distances and transportation processes. Therefore, providing efficient transportation processes by minimizing the walking distances between interrelated spaces should be the major concern in hospital layout planning.

The use of Quadratic Assignment Problem (QAP) is highly desirable to deal with layout planning problems in hospitals. It is a well-known problem in the field of Operations Research. Most of the facility layout problems (FLP) are formulated as QAP to minimize transportation costs. The requirements for design in the production industry are parallel to those in hospital design. Therefore, facility-planning methodologies, which are widely used in industrial engineering, are needed in dealing with hospital layouts.

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4.2.1.2 Related Literature

QAP is developed by Koopmans and Beckmann (1957) [57]. It is one of the most difficult computational problems in the NP-hard class. Hence solving them optimally in a reasonable time is a very challenging task. Although exact problem-solving might be intractable, there exist heuristics algorithms capable of solving the QAP even in large sizes with nearly optimal solutions in a reasonable time.

QAP in General

Several solution techniques for the QAP have been suggested in the literature. In early works of QAP for FLPs, Kaku et al. (1988) [247] proposed a heuristic approach (exchange-improvement routine) for multi-story layout design. Kaku (1992) [248] proposed a procedure that combined a constructive heuristic and exchange improvement for loop conveyor and linear-track layout cases. Rosenblatt (1992) [249] developed a hybrid method that combined branch and bound framework with heuristics for equal-sized departmental layouts. A novel study by Li and Smith (1995) [250] proposed a sample test-pairwise exchange heuristic procedure (STEP) for dynamic facility layout. Urban (1998) [251] presented two heuristics (multi-greedy algorithm and GRASP) for dynamic facility layout design. Ulutas and Sarac (2006) [251] addressed QAP with relocation cost thus handling a dynamic facility layout problem by developing a heuristic algorithm, called modified sub-gradient (MSG). Ramkumar et al. (2009) [252] proposed a new heuristic (iterated fast local search) for equal area layout.

Moreover, Huntley and Brown (1991) [253] combined a genetic algorithm (GA) and simulated annealing (SA) for an equal-area layout. Yip and Pao (1994) [254] proposed a hybrid technique that combined GA and SA for equal-area layout design. Bland and Dawson (1994) [255] addressed QAP for large-scale layouts using a hybrid heuristic algorithm that combined SA and TS. Chiang and Chiang (1998) [256] proposed TS and SA for facility layout. Kochar et al. (1998) [257] proposed a meta-heuristic using a genetic algorithm, called HOPE, for unequal area single and multi-row layouts. Chiang (2001) [258] addressed a modified version of QAP with binary variables by proposing a TS algorithm for interdepartmental layout. Solimanpur et al. (2004) [259] used ant colony optimization for inter-cell layout. Nourelfalth et al. (2007) [260] used metaheuristics (Ant Colony Optimization with EGD local search) for equal-area layout. Jaramillo and Kendall (2010) [261] proposed a TS heuristic using different construction algorithms for machine layout. Moslemipour and Lee (2012) [262] developed a SA approach for dynamic layout. Pourvaziri and Pierreval (2017) [246] presented SA algorithm for dynamic facility layout design based on a QAP formulation. For an extensive review of solution techniques for the QAP, refer to recent survey paper by Singh and Sharma (2010) [263].

QAP in Hospital Layout Planning

A relatively limited body of research has been published concerning layout planning in hospitals.

Elshafei (1977) [264] firstly proposed QAP for locating the clinics within a hospital department using an improvement heuristic to optimize the traveling distances of patients and delay in patient flows. Murtagh et al. (1982) [265] used QAP formulation for assigning 19 clinics to predefined locations to minimize transport costs by developing a new heuristic. Butler et al. (1992) [266] formulated a QAP for bed allocation in a general-purpose hospital to minimize the distance between services taken by nurses using a constructive heuristic (CRAFT). Hahn et al. (2001) [267] proposed QAP for assigning the facilities to locations to minimize travel distance taken by all pairs in a hospital comparing the results of several heuristics and metaheuristics solution methods. Yeh (2006) [268] studied a case study hospital with 28 facilities considering various space planning aspects such as the adjacency of objects, the distance between objects, the availability of space for the location of objects, and the positions of objects in relation to others. Facility layout design formulated as QAP and solved by simulated annealing with an annealed neural network. Chraibi et al. (2015) [269] minimized total traveling cost and rearrangement costs in a dynamic facility layout problem of the Operating Theatre (OT) department of a hospital. Recently, Helber et al. (2016) [23] have proposed a hierarchical modeling approach. The first stage is formulated as QAP for assigning elements to locations using a fix-optimize heuristic by considering transportation processes, locating some units on specific locations, and ensuring the direct adjacency of two specific units. The second stage is detailed positioning within a location considering space requirements in a large hospital facility. Zuo et. al (2019) [200] proposed a QAP formulation for an emergency department of a hospital using a multi-objective tabu search algorithm by focusing on a real-case study.

As a result, most works focus on individual departments’ 2D layout optimization in the hospital such as OT planning and nursing units. Considering the whole set of hospital departments in a 3D layout optimization is scarce in the literature. There is only one study in [23] that focuses on whole hospital departments with a practical case study. Most of the application papers considered rectilinear distances (a.k.a. Manhattan distances), not geodesic distances. To the best of our knowledge, none of the works considered the combination of the QAP with the graph-theoretical aspect of computing spatial geodesic distances (walkable, easiest, and/or shortest paths for pedestrians) inside the building in real-case scenarios.

4.2.1.3 Utilization of QAP in Computational Design

QAP is first developed for facility layout planning but it is also useful for spatial layout planning in architecture. There are different facility layout programs like CRAFT [270], COFAD [271], CORELAP [272], and BLOCPLAN [273]. However, these tools have rarely been utilized in architectural design practice. Considering spatial layout planning as a fundamental aspect of architectural design that affects the functional performance of hospital buildings, we argue that a systematic approach to ensure the effectiveness and efficiency of a layout schema should be an integral part of any architectural design process, particularly in the case of critically complex building such as hospitals. The idea of bridging the gap between both the parametric CAD platforms and the layout design is not entirely new. There is a limited number of tools available in Parametric CAD platforms to facilitate the space planning processes, namely DeCoding Spaces, SpiderWeb, and Syntactic [163]–[165]. To the best of our knowledge, none of the tools proposed the QAP approach in layout planning and none of them utilize the shortest paths for pedestrians. These three toolkits provide methods for formulating space planning problems and analyzing spatial configurations within the framework of Space Syntax theories. However, other than heuristic force-directed graph drawing solvers, none of these tool suites proffer an explicit formulation of the space planning problem as an optimization problem. Our proposed methodology formulates the problem of layout optimization as a Quadratic Assignment Problem, and proposes a measure of quality as the Logistic Cost Function, as to which a benchmark can be created for the improvements on the inner walking/transportation costs within a complex layout. Finally, the proposed solver reduces these costs to a minimum and finds a new spatial configuration.

4.2.1.4 Contributions

The main goal of this paper is to formulate and solve a 3D space planning problem methodology in the form of a Quadratic Assignment Problem (QAP), in the context of a re-design/renovation task, by considering the effect of geodesic distances through a network of circulation spaces in 3D. The QAP is a well-known problem in the field of Operations Research from the category of the facility's location/allocation problems. The methodology is first and foremost developed for hospital space planning; however, it can also be used in design and optimization for other types of complex buildings, especially to study reuse scenarios. The methodology is implemented and tested partly in C# language [274] for McNeel's Grasshopper3D [275] and partly in VEX language [276] for SideFX' Houdini [277]. The following steps are presented in this paper:

- Formulating a layout problem in architectural design as a QAP based on geodesic distances
- Introducing a practical CAD workflow for applying QAP solvers to 3D spatial layout problems
- Discretizing and modularizing the design space as a way of structuring the geodesic computation problem in 3D as well as relaxing and simplifying the unequal area QAP problem
- Estimating flows and entering the flow matrix as an input of the tool
- Calculating spatial geodesic distances and entering the distance matrix as an input of the tool
- Proposing a heuristic algorithm for solving the QAP
- Implementation of the model and heuristic optimization algorithm
- Running the solver, reflecting on the results, and comparing them to the existing state of an actual hospital

4.2.1.5 Gaps in the Literature

The detailed literature review is given in section 4.2.1.2. We have identified and summarised the following gaps in the literature concerning the layout optimization of existing hospitals:

- There is no complete methodology for a 3D layout problem with a QAP formulation, most papers are focused on 2D layout and focused on specific departments such as the operation theatre and the nursing units. However, we focus on the entirety of the hospital design problem
- There is no study on QAP that focuses on geodesic distances (especially in 3D). Most studies focus on rectilinear distances on a flat 2D plan.
- The combination of QAP with the graph theoretical aspects (wayfinding) in real-world test cases is unique.
- Modularization/Discretization of space layout problem both in terms of modularization of the departments and the walkable space in between the departments in 3D for solving a QAP.
- There is no implementation of QAP problem-solving in computational design methodologies.
- The Iterative Local Search algorithm is not entirely new, but it has not been implemented in the case of space layout of hospitals.

4.2.2 Problem Formulation

As explained in the literature review the Quadratic Assignment Problem is well-known in the field of Facilities Layout Planning but relatively unknown in architectural layout design. Interestingly, when the focus of the optimization task is on improving the configuration of an existing building, the Quadratic Assignment Problem arises naturally when we consider the efficiency of the spatial configuration of the building as a whole. QAP is a combinatorial optimization problem that aims at allocating a set of facilities to a set of locations such that the total transportation cost is minimized. Total transportation cost is a function of the flows between facilities and the distances between locations. The QAP has a discrete representation of areas since the facility departments can only be assigned to predefined network locations. Essentially, the problem of assignment here is an unequal area layout problem because each department has a different required amount of surface area as in Table 4.1. Our model makes this discretization regular by topologically abstracting the whole 3D walkable floor space of the building as a voxelated domain [278][279]. Voxels or (volumetric pixels/picture cells) are 3D regular units of space for partitioning a 3D volume into a Cartesian grid of cells. The design domain, in this case, is voxelated for two main reasons: 1) to modularize the units of space so that the problem of layout can be formulated as an assignment problem, and 2) to use the explicit topological relations between adjacent voxels for constructing a network model of space to compute the geodesic distances for the computation of the logistic cost function (the objective function). For creating this tessellation, we split the departments into pieces based on their surface area requirements considering structural grids of the building. Then, each piece of the department corresponds to the area of one pixel/voxel in 3D. Such a regular tessellation brings about two main advantages: on the one hand computation of geodesic distance becomes straightforward on the network generated from the voxels, and on the other hand, the problem of assignment is relaxed in that a single facility may be allowed to be allocated within multiple voxel locations, thus alleviating the complexity of the unequal area assignment problem. Each facility can be assigned to exactly one location and no location is assigned to more than one facility. Therefore, the number of facilities should be the same as the number of locations. The basic QAP model can be formulated as:

$$\min_{\pi \in P_n} \sum_{i=1}^{n} \sum_{j=1}^{n} D_{i,j} T_{\pi_i,\pi_j}$$

where π is a vector of integers denoting a permutation of facilities at a moment in time, T_{π_i,π_j} denotes the [transportation] flow between a permuted facility $\pi_i = k$, and another permuted facility $\pi_j = l$ and $D_{i,j}$ is the distance between location *i* and *j*. P_n denotes the set of all permutations $\pi^{(t)} : \mathbb{N} \to \mathbb{N}$, where the superscript denotes the iteration time. Note that the cardinality of P_n will be $n!$, and so a brute-forth search becomes intractable as soon as the problem gets large, i.e. an order of complexity of $\mathcal{O}(n!)$; which in the case of our example would be about searching within $64! = 1.2688693e+89$ possible permutations. Note that the objective function is measuring the expected travel distance for a typical building user; this is because the transition probabilities (e.g. those given as percentage values in Table 4.2) are dimensionless/unitless and the travel distance between every two nodes is multiplied by the probability of that transition.

4.2.3 Methodology

We have formulated the problem as a matter of reducing the logistic cost function by choosing the right permutation of facilities within a set of existing locations. Due to the physical nature of the costs (distances) and the dimensionless (unitless), the meaning of the flow rates, and the physical unit of the objective function is the same as the distances. This means that the distances between the departments in a 3D space must be computed. To do so, we propose the following methodology:

1. Estimate the flow rates as the transition probability between the departments for a pedestrian (the flow rates, in this case, are considered as given, see Figure 4.10);

2. Discretise the walkable space in between the departments and model the topology of the connectivity between the discrete spaces as a graph/network;
3. Compute the geodesic distance between the department locations in the discretized space and attribute the distances to the pairs of departments using the Floyd-Warshall algorithm;
4. Heuristically improve (minimize) the objective cost function by try-fitting various permutations of facilities over the locations using the Iterative Local Search algorithm

4.2.3.1 Flows

As stated above, the objective of the QAP is a function of flows between facilities and distances between locations as constant parameters and the only variable parameter is the permutation, hence it is called a combinatorial optimization problem. The flow information refers to any quantitative relationship score between any pair of items, typically the estimated volume of transporting materials or the probability of transition of medical staff in between facilities. We have considered the latter probabilistic interpretation in our formulation. This score can also be interpreted from given adjacency requirements of a hospital, which are typically recommended for ensuring effective logistics according to medical procedures, providing privacy or community, security, safety, hygiene, congruence of noise levels, etcetera. The so-called REL Chart table, e.g. the one used in this paper (Figure 4.10) is a matrix whose entries indicate the relative importance of closeness between two departments. Considering the central importance of this matrix in the formulation of the QAP problem or even only in assessing the quality of a particular assignment, it is important to compose this table with objective information. However, in practice, such tables are often composed following discussions of the board of directors of a hospital. Nevertheless, for a building that does not exist yet, figuring out such importance ratings is a daunting task. For an existing building, however, these relative importance ratings can be replaced with the measured or estimated probabilities of transition between pairs of departments objectively. Given the technical difficulty of measuring such probabilities in practice, estimating the probabilities according to the foreseen procedures is an alternative that is feasible using a Discrete Event Simulation (q.v. [195], [280]).

The number of spatial units must remain the same throughout the QAP solving, and so, we first split the departments into spatial units considering the size of the designated modules and their area requirements. Then we divide the predicted flow rates mentioned in the REL Chart equally between the dividend units. We added this description to the methodology section. The suggestion to set high intra-closeness ratings for encouraging closeness between the split parts is very logical and it is already implemented by setting high flow rates between the divided units (100% closeness). The numbers written in our REL chart are percentages [0,100] which are interpreted at the end as numbers in the range of [0,1] as transition probabilities. This makes it possible to have a physical interpretation of the objective cost function as an expected travel time as explained in the section Application. However, if we raise these numbers to values higher than 100 (or 1) this would disrupt the probabilistic interpretation and make it hard to explain and justify the results.

4.2.3.2 Spatial Geodesic Distance

To compute walking distances within a building, spatial geodesic (optimal paths on a network) are used in this method. In the mathematical field of graph theory, the geodesic distance between two vertices in a graph is the total sum of the costs attributed to the edges connecting them through an optimal path. For constructing such paths and computing geodesic distances, firstly, the set of all spaces (locations, corridors, and stairs) is discretized in a surface geometric model [279]. The spatial network of the indoor walkable space of the building is then extracted from this mesh, a multi-source graph-traversal search is run, and the distance matrix is obtained. The graph is constructed based on 6-neighborhoods of voxels (i.e. voxels connected to their top, bottom, left, right, back and front neighbors)[281]. Then multiple A* searches are run within the constructed graph to find the geodesic distance from every location to every other location. Note that the location points (as marked in red and shown in Figure 4.4 and 4.5) are exactly 64 voxels corresponding to the larger sets of voxels whose areas are equal to 100 m^2. These large areas are not included in the graph generated from the voxels because the model only needs to have the distance from their access points to other access points.

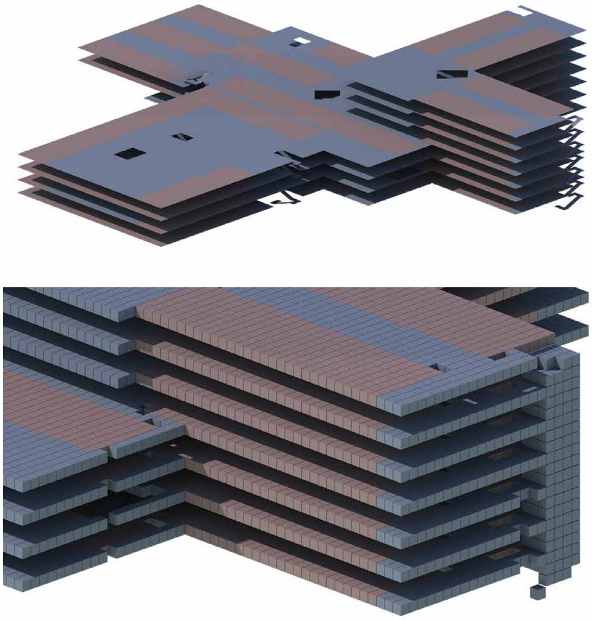

FIG. 4.4 the walkable space as a mesh (top) and its discretized voxel model (bottom); blue voxels: circulation areas & red voxels: location areas

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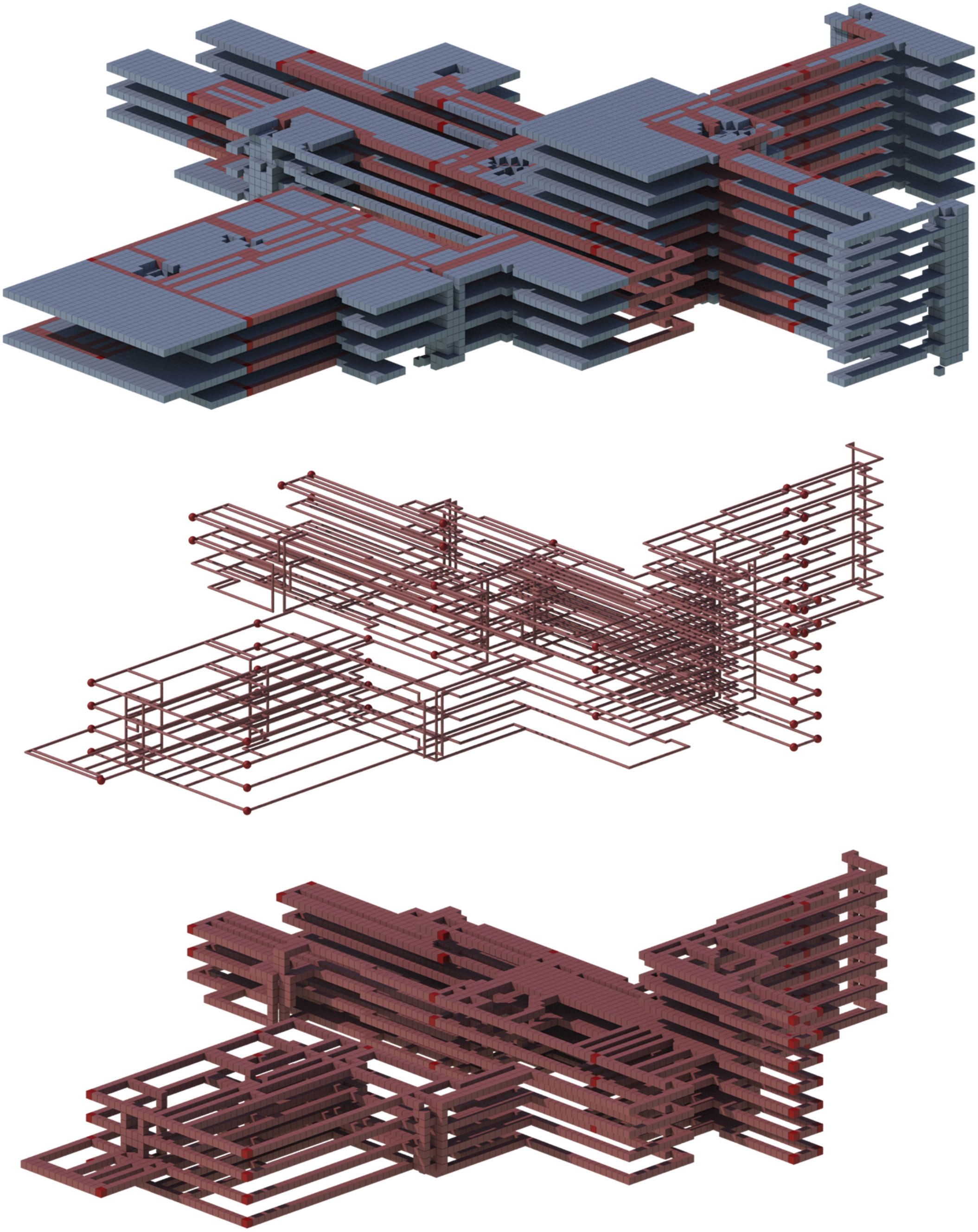

FIG. 4.5 Extracting “spatial network” of the building (top), continuous version of paths (middle), a discrete version of paths (bottom), (red dots are location points)

4.2.3.3 Heuristic Problem Solving

As stated before, QAP is an NP-hard problem. Therefore, heuristic optimization algorithms are seen as remedies for tackling this complex problem in large instances. In this tool, we selected Iterated Local Search algorithm (ILS) [282]–[285] for problem-solving. Recently, the performance of an ILS algorithm in [286] has been tested on QAP instances arising from real-life problems as well as on several benchmark instances from the QAPLIB [287]. Inspired by [286], [288], we utilize the ILS algorithm for the space planning tool presented in this paper. Details of the algorithm that is considered in this paper are given in the sub-sections below.

Solution encoding

The encoding scheme in our algorithm corresponds to a sequence of integers that represents facilities in a feasible solution (permutation).

Initial solution

In the Iterated Local Search (ILS) algorithm, the initial solution $\pi^{(0)}=\left[\pi_1,\pi_2,..,\pi_n\right]^T$ is constructed randomly, which is a permutation of the integers between 1 and , where is the number of facilities.

Perturbation scheme

In the ILS procedure, the initial solution is perturbed with swap and insertion neighborhoods to escape from local minima. In this paper, random swap and insertion neighborhoods are employed. The swap operator exchanges two facilities in a solution, whereas the insertion operator removes a single facility from a solution and inserts it into a random position in the solution. As an example, to a swap operator, suppose that we are given a current solution $\pi^{(0)}=\left[5,4,2,1,3\right]^T$. Two facilities are randomly selected and they are exchanged. As an example, we randomly choose the facility $\pi_4^{(0)}=1$ and $\pi_2^{(0)}=4$ to swap them. Thus, we end up with a solution as $\pi^{(1)}=\left[5,1,2,4,3\right]^T$. In addition, as an example of an insertion operator, we apply forward or backward insertion with an equal probability. Suppose that we are given a current solution $\pi^{(0)}=\left[5,4,2,1,3\right]^T$. Assume that we randomly choose $\pi_3^{(0)}=2$. Then, we remove it from the solution and insert it into the fourth position as a forward insertion to generate a new solution $\pi^{(1)}=\left[5,4,1,2,3\right]^T$ whereas in the backward insertion, we remove $\pi_3^{(0)}=2$ from the current solution and insert into the second position as $\pi^{(1)}=\left[5,2,4,1,3\right]^T$.

Local Search

After the "perturbation" of the current solution, we apply a "local search" based on the swap neighborhood. In the swap local search, the perturbed solution $\pi^{(1)}$ goes under a swap local search procedure. The iteration counter is fixed at 1 at the beginning, we select two facilities randomly and simply swap them. If the new solution obtained after the swap neighborhood is better than the current solution, it is replaced with the current solution, and the iteration counter is again fixed at 1, otherwise, we keep the current solution as it is. And the iteration counter is increased by 1. The swap local search is repeated until the iteration counter is reached at the number of facilities n. The pseudo-code of the swap local search is given in Algorithm 4.1.

ALGORITHM 4.1 Swap Local Search

Input Notation	[Data-Structure] Data Type	Input Name: Notes
$\left[D_{i,j}\right]_{n\times n}$	Matrix of float	**Distance Matrix:** a matrix whose entries represent the network distance between locations i&j
$\left[T_{k,l}\right]_{n\times n}$	Matrix of float	**Flow Matrix:** a matrix whose entries represent the [transportation] flows between facilities k&l
π	Array of Integer	**Current Permutation:** labeling of locations as to facility indices/labels, passed by reference
Output Notation	**[Data-Structure] Data Type**	**Output Name: Notes**
π	Array of Integer	**Next Permutation:** labeling of locations as to facility indices/labels
$f(\pi)$	float	**Best fitness:** the best fitness value found by the algorithm

Problem: Given a distance matrix D on n locations and a transportation flow matrix T on n facilities, desired a permutation π of locations such that the fitness $f(\pi)=\sum_{i=1}^{n}\sum_{j=1}^{n}D_{i,j}T_{\pi_i,\pi_j}$ is minimized.

```
Procedure SwapLocalSearch $(\pi, f(\pi))$
    iteration=1
    while ( $iteration \leq n$ ) do
        Find two facilities, $\pi_a$ and $\pi_b$, randomly
        Swap $\pi_a$ and $\pi_b$
        Generate a new solution as $\bar{\pi}$ with swapped $\pi_a$ and $\pi_b$
        if $f(\bar{\pi}) < f(\pi)$ then do
            $\pi = \bar{\pi}$
            iteration=1
        else
            iteration=iteration+1
        end if
    end while
    return $(\pi, f(\pi))$
End Procedure
```

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The general framework of the ILS algorithm is given in Algorithm 4.2. Briefly, the initial solution is constructed randomly. Then, a swap local search is applied to the initial solution. A loop based on the termination criterion is started. Repeatedly, perturbation and swap local searches are applied to the current solution until a termination criterion is satisfied. If we need to implement a fixed-department constraint, we can define a set dubbed f and we can add a condition to the Swap procedure and change it to:

if $(a \notin f \wedge b \notin f)$ *then Swap* π_a *and* π_b

ALGORITHM 4.2 The General Framework of the Iterated Local Search Algorithm

Input Notation	[Data-Structure] Data Type	Input Name: Notes
$\left[D_{i,j}\right]_{n\times n}$	Matrix of float	**Distance Matrix:** a matrix whose entries represent the network distance between locations i&j
$\left[T_{k,l}\right]_{n\times n}$	Matrix of float	**Flow Matrix:** a matrix whose entries represent the [transportation] flows between facilities k&l
$\pi^{(0)}$	Array of Integer	**Initial Permutation:** labeling of locations as to facility indices/labels
Output Notation	**[Data-Structure] Data Type**	**Output Name: Notes**
$\pi^{(t)}$	Array of Integer	**Last Permutation:** labeling of locations as to facility indices/labels
f	float	**Best fitness:** the best fitness value found by the algorithm: $f=\sum_{i=1}^{n}\sum_{j=1}^{n}D_{i,j}T_{\pi_i,\pi_j}$

Problem: Given a distance matrix D on n locations and a transportation flow matrix T on n facilities, desired a permutation π of locations such that the fitness $f(\pi)=\sum_{i=1}^{n}\sum_{j=1}^{n}D_{i,j}T_{\pi_i,\pi_j}$ is minimized.

```
Procedure Iterated Local Search $\left(\pi^{(0)}, f\left(\pi^{(0)}\right), t_{\max}\right)$
$t=0$
$\pi^{(t)}=\pi^{(0)}$ #GenerateInitialSolution
Repeat
$\bar{\pi}=\mathrm{Perturbation}\left(\pi^{(t)}\right)$
$\pi^{(t)}=\mathrm{SwapLocalSearch}(\bar{\pi},\mathrm{f}\,(\bar{\pi}))$
$\mathrm{t}=\mathrm{t}+1$
Until $(\mathrm{t}<\mathrm{t}_{\max})$
Return $\left(\pi^{(t)}, f\left(\pi^{(t)}\right)\right)$
End Iterated Local Search
```

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4.2.4 Test & Implementation

The purpose of our implementation at this point was to test the algorithms. More specifically, the purpose was to verify whether the algorithms work as expected in terms of the correctness of the results and to validate whether the results are improved. We have implemented the method presented above partly using the C# programming language and developed a space planning tool, called QAP Solver as an add-on for McNeel's Grasshopper3D [275] software application and partly as a VEX add-on for SideFX' Houdini [277] for computing network geodesics and the corresponding distance matrix.

QAP Solver component implements Algorithm 4.2 for solving a QAP instance based on the given input data (flow and distance matrices). Inside the component, the first initial solution is generated randomly, and then the optimization algorithm is run after the Boolean toggle is set to "True" mode; this will trigger the generation of new permutations, for each of which the objective function of the QAP is evaluated and reported. In each generation, the component is capable of showing the change of decision variables (permutation) on a collection of number sliders by realizing a slider update procedure inside the component. In this way, users of the tool can see how well the layout is being improved over the generations in terms of the value of the fitness function and at the same time see the generations in real-time, as the number sliders that encode the permutation are used to pick and change the colors of rooms in the 3D model. In addition, the tool allows users to set the maximum number of trial times (t_max in Algorithm 4.2). The user is expected to connect as many number sliders as the number of facilities (functional units). All sliders should be connected to the QAP Solver component. The output of the component presents the result of the optimization as well as the amount of improvement in objective value. The permutation results are also shown on the number sliders, e.g. if the first slider has resulted as 2, then the second facility is placed to the first location, and so on. The QAP Solver component is shown in Figure 4.6 when working on a toy problem with three facilities to be assigned to three locations.

For computing the geodesic distances, we first extract a set of meshes representing the connective spaces such as corridors, stairs, and ramps [if any]; then we voxelate these spaces using openVDB [289]; then construct a network out of the voxels, and then calculate shortest paths from all locations to each other location, i.e. the same set of locations will be used as both origins and as destinations. Technically, the locations are first mapped onto their closest points/voxels on the network. The output of the process will be the matrix of distances $\left[D_{i,j}\right]_{n\times n}$ where n is the number of locations. This output is directly used in the QAP solver. The working principle of the QAP solver can be shown in the video available online (https://www.youtube.com/watch?v=Lv52qy1OjSw).

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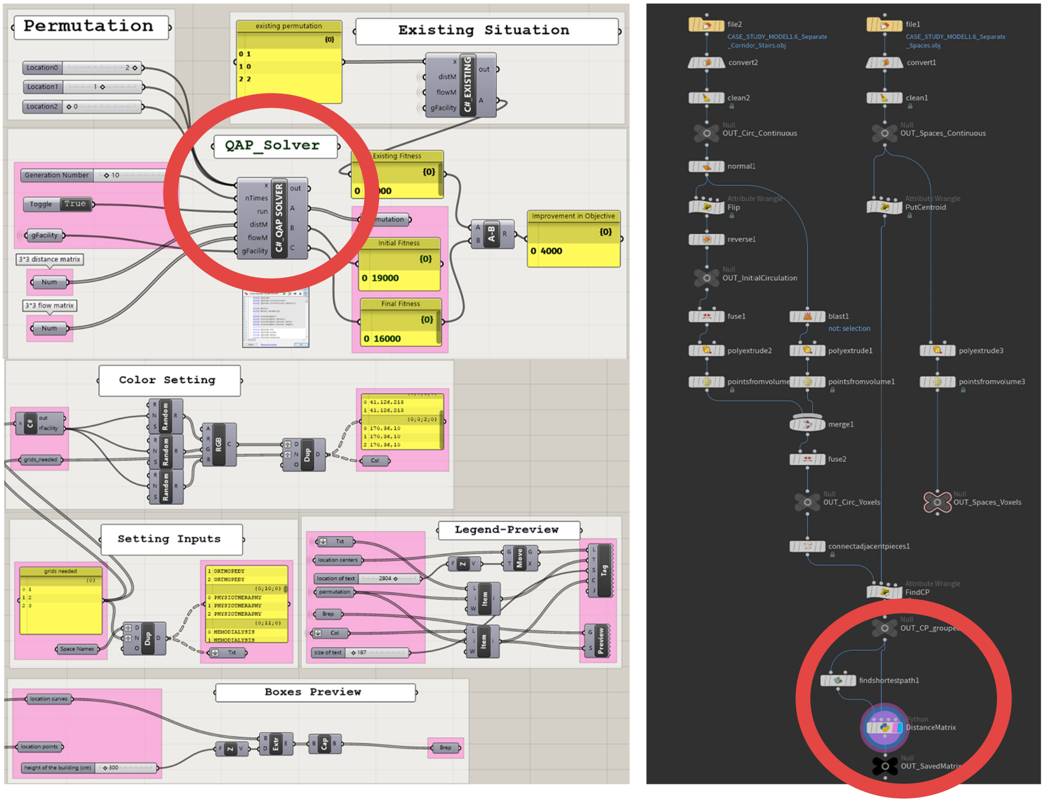

FIG. 4.6 QAP_Solver Component in Grasshopper3D (left) and the Geodesic/Network Distance Computing in Houdini (right)

4.2.5 Application

In this section, we articulate an outlook for using the QAP tool in space planning and design of existing hospitals in a larger context.

Due to the nature of the QAP method, it can be used in case of the following scenarios in redesigning a hospital building, i.e. a building with a set of facilities is to be moved to another or the same building with the same number of locations:

1. When we know the transportation flows [logistics of pedestrians or materials] between the facilities of a building;
2. When we can estimate the flows between the facilities of a building, e.g. by utilizing a simulation procedure such as Discrete Event Simulation [280]

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We illustrate the application of the proposed QAP method can be used in computational space planning in the context of an exemplary case study hospital (corresponding to the first scenario described above). All hospital departments are considered in the layout optimization problem; however, it would be also possible to perform a similar procedure on the inner spatial layout of only one department like the Operation Theatre layout or Intensive Care Unit layout, i.e QAP at a higher level of detail. The chosen hospital is a state hospital with a capacity of 250-beds for the in-patient wards. It is a 9-story building including basement and ground floors. In this model, we excluded the locations placed on the basement and the 7th level of the building in the existing situation; because, the 7th level has only a terrace area, which is not suitable for placing any facility; and the spaces located in the basement have some specific features and their locations cannot be changed. These spaces that are excluded from the model can be listed as a mortuary, a worship space, a bunker, parking lots, and storage. Furthermore, some of the functional units may require some specific locations due to a specific feature in hospitals, e.g. the emergency department and main entrance should be at the ground level of the hospital. The locations of these facilities are excluded in the model by making their locations constant proper locations. Based on this, there are 34 facilities considered in this case model for renovating the hospital layout.

Utilizing the QAP method is limited, theoretically, to equal-area layout problems. However, each functional unit differs concerning its space requirements in this case. Although this is arguably an inherent limitation of the methodology, we can relax the requirements such that this is no longer a limitation. Since each location is represented with [modular] discrete spaces (boxes in 3D), the number of needed boxes for each facility can also differ. As a new approach to adapting QAP to unequal departments, we can repeat each facility according to the area requirement in the flow matrix and distribute/divide the flows accordingly. For instance, assuming that each box has a capacity of 100 m^2 and that the cardiology department needs 300 m^2 then we can define this department 3 times in the flow matrix and then divide the row and the column corresponding to this space in the flow matrix by 3 and use the results in the new rows and columns. By this repetition, the number of facilities becomes the same as the number of locations, which is defined as 64 in the model; while this also entails that a single facility may not necessarily stay at a single location. This is obviously a limitation but at the same time, it might be beneficial in light of a higher level of satisfaction with the logistics requirements. Based on the structural system of the building, we define the locations as rectangular spaces, in line with the structural axes. This ensures that during the renovation the structural system does not have to be modified. Afterward, we tessellate each rectilinear floor space into four quadrangular faces. Each quad face refers to a square-like space surrounded by vertical column axes and horizontal beam axes of the existing building (as shown in Figure 4.7). A list of spaces with the number of needed rectangular boxes is given in Table 4.1 with nomenclature in Table 4.3. The flow matrix is given in Figure 4.10. For calculating the distance matrix, the spatial network of the building is given in Figure 4.5. The REL Chart table in Figure 4.10 is a matrix whose entries indicate the relative importance of closeness between two departments. Considering the central importance of this matrix in the formulation of the QAP problem or even only in assessing the quality of a particular assignment, it is important to compose this table with objective information. However, in practice, such tables are often composed following discussions of the board of directors of a hospital. Nevertheless, for a building that does not exist yet, figuring out such importance ratings is a daunting task. For an existing building, however, these relative importance ratings can be replaced with the measured or estimated probabilities of transition between pairs of departments objectively. Given the technical difficulty of measuring such probabilities in practice, estimating the probabilities according to the foreseen procedures is an alternative that is shown to be feasible using a Discrete Event Simulation [195]. The particular table added in the appendices of this paper, however, is a REL Chart produced by collating expert interviews, site visits, design guidelines/standards, and recommendations from the scientific literature.

Regarding the computational results, the proposed heuristic algorithm for the QAP is tested on an Intel Core-i7 computer, with 2 GB of RAM. Maximum trial time is taken as 50,000 iterations with a seed number 5. Permutations of the existing and proposed layout are given in detail in Table 4.2. Based on this table, existing fitness is 483751000 expected travel steps (roughly equal to 60 centimeters, i.e. the small voxel size in the model). After the optimization by QAP Solver, the new fitness is 411578400. The improvement in the objective value is 72172600 steps (adjusted to 721726.00 after dividing by 100 for converting flow percentages to probability fractions), which equals about 469121.90 meters of travel distance. To put this result in a more concrete context, let us assume that an average person can walk 5 kilometers per hour; then this number means that we have reduced the time spent walking in between the facilities by 469121.90/5000=93.82438 person-hours for a typical day. Note that as we explained in the definition of the unit of the objective function, this is the ‘expected travel distance’ (or the time spent on walking) for a typical building user on a typical day of operation. This means that the improvement can be attributed to the building as a whole rather than a person. The existing layout and the new layout result for the case study hospital model are visualized in Figure 4.8 and Figure 4.9.

Regarding the design results, the placement in inpatient areas is still located at the top levels of the building as expected due to the daylight requirements of patient wards. However, in the proposed layout, interrelated spaces with inpatients have

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moved to various locations. In the proposed layout, operation rooms are located closer to the patient wards and there exists the ease of access between these facilities with a vertical short connection. Critical patient flow processes and the shared equipment entail better access between intensive care units and operating rooms. In the new layout, intensive care units and operation rooms have a better connection since Intensive Care Units are the neighbor of the Operating Theatre at the upper levels of the building. In addition, delivery rooms have to get closer to Operation Theatre, which is an advantage for shared staff and facilities. The kitchen and dining hall were located at the last level of the building whereas they are located at lower levels in the proposed layout. This provides quicker food transportation from the kitchen to the medical spaces e.g. dining & kitchen area has horizontal access to outpatient and vertical access to inpatient. In the new layout, all departments related to maternity like Paediatrics Intensive Care Unit, Paediatrics Outpatient, Delivery Rooms, and Obstetrics departments are located close to each other.

Laboratories and diagnostic units are located adjacent to each other on the ground floor and become closer to the outpatient departments as expected. In addition, inpatient departments were placed in the areas that have one single corridor in the old layout. Whereas, these departments are mostly located in areas with a radial layout structure. Surgical outpatients like Obstetrics, Orthopedy, and Urology departments are located closer to the operating rooms in the new layout. Transportation processes between interrelated spaces became more efficient with the proposed approach.

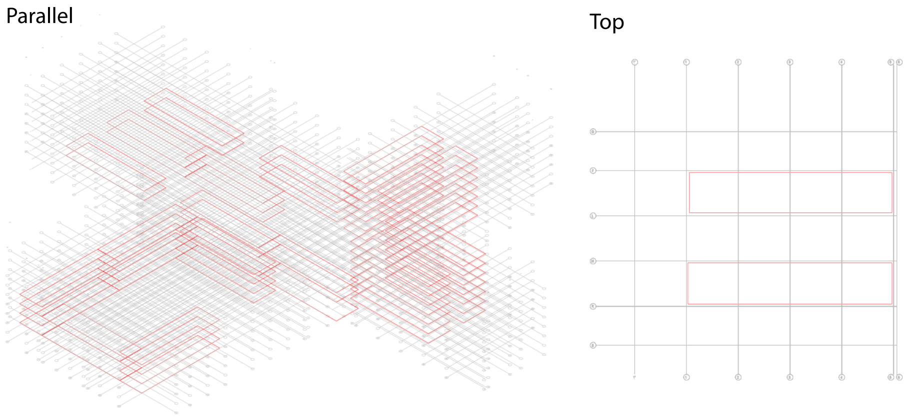

FIG. 4.7 Definition of rectangular location boxes' floor surfaces (consisting of 4 structural grid pixels based on building axes)

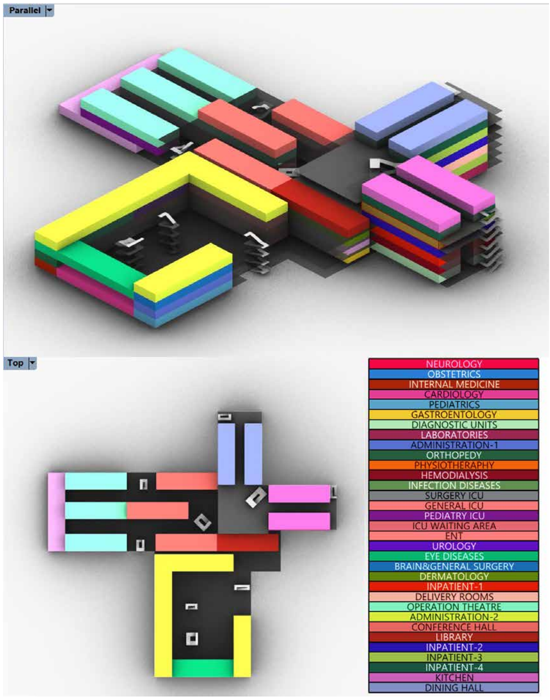

FIG. 4.8 existing layout

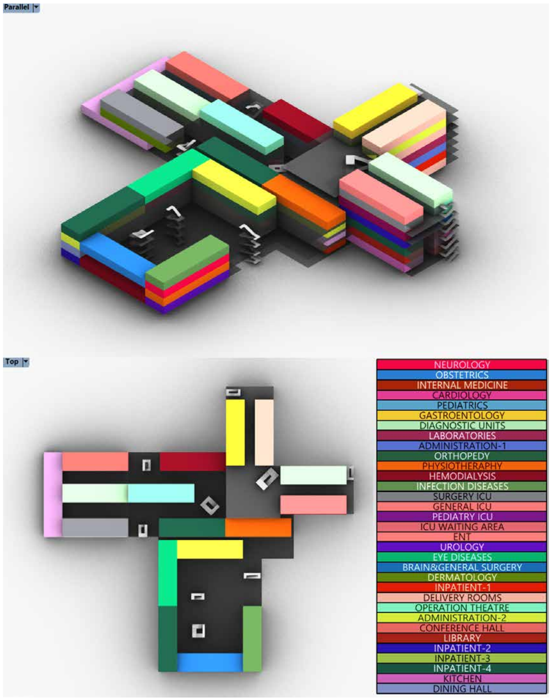

FIG. 4.9 proposed layout

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4.2.6 Conclusions

This paper introduces a new computational space planning methodology based on the well-known Quadratic Assignment Problem, presents a heuristic solver for it, and presents the test results of a hospital re-design case study. One of the novelties of the presented methodology is that it utilizes the spatial network of the existing building for computing geodesic distances, which are then used as inputs of the QAP model. Results show that objective value is reasonably minimized, and design results seem more logistically efficient. We have estimated an aspect of the operational cost of the building as the expected travel time of employees/users of the building using our objective cost function. It must be noted that this is a matter of ex-ante assessment and not a measurement, as measuring the actual travel time would require tracking the personnel inside the building and fall out of the scope of this paper. The time saving achieved with our methodology based on Operations Research has achieved an estimated reduction of around 90 person-hours for a typical operational day of the hospital. Due to its aggregate nature, such a reduction should be of interest to the management of the hospital as it implies not only a reduction of costs but also implicitly an increased comfort for the employees, users, and thus a higher-quality service. The contributions of the paper can be recapitulated as below:

- The obtained results, i.e. the new configuration and its corresponding logistic cost function, reveal a major difference made by reassigning the departments to alternative locations, hence validating the major contribution of the paper on improving existing layouts. The reduction of the logistic cost function, in this case, corresponds to a total reduction of around 93 person-hours of expected travel time between departments of the hospital for a typical day.

- We have considered the physical constraints pertaining to the size of the departments and assumed that the departments can be accommodated into modular/rectilinear spatial units (colored in the pictures). The newly found assignment can be visually inspected from the point of view of an architect/manager and it seems to be a feasible/logical assignment in terms of other constraints that are not taken into account in this formulation. If the configuration is deemed infeasible, the seed of the heuristic solver can be changed to find another configuration. The single configuration found as an example in this paper seems to be feasible. However, in practice, more experiments are needed to list layout alternatives and choose the one with the least transformation costs and/or the best suitability with respect to other architectural criteria.

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- The proposed methodology bases the reconfiguration problems on a completely discretized and modularized design space, and the proposed algorithm is reasonably fast, it would be theoretically feasible to dissect the spatial units into smaller units and generalize the method to broaden the application areas and the versatility of the method for incorporating more diverse validity constraints.

Integrating QAP into computational design workflows can, to say the least, provides awareness of the logistics performance of the building in terms of the expected walking time for personnel, and in that sense, it can even be used as an informative tool for conceptual design of new buildings as well as re-designing existing buildings.

4.2.7 Limitations & Future Work

The method presented in this paper is only suitable for reconfiguration of existing buildings, especially because it requires computing the distance between available locations for computing the main objective function. Even though most hospital buildings have a regular structural grid, it must be noted that our proposed way of dissecting departments into modular areal units is only feasible on such highly modular and regularly structured buildings. It must be noted that in our problem formulation we consider all facilities to be accommodatable in all available locations, while in reality there might be facilities that can only be accommodated in certain locations due to particular technical requirements. While this constraint is handled by excluding a list of fixed facilities, we have disregarded the exchangeability of other departments. Our methodology does not take the contiguity constraints into account explicitly as hard constraints, e.g. in cases where we split a facility into 2 or 3 facilities to fit it into our modularized spaces. We cannot enforce the new units to stay contiguous/adjacent to each other during the optimization process; however, by adding extra closeness ratings in between the split parts, we relax such constraints and add them to the objective function effectively. Moreover, this limitation can also be considered in another way: the obtained results, which may not strictly entail the initially conceived contiguity, can be used to reflect on the program of requirements and consider revising it, e.g. considering two Cardiology departments if a significant expected travel-time saving can be made by splitting it into two departments. This can be observed from the objective function. In future work, limitations of the proposed workflow to the existing buildings can be addressed by modifying the problem formulation, for instance by a Mixed-Integer Programming formulation of the hospital layout problem. More advanced optimization algorithms for solving the QAP can be proposed e.g. populated version of the proposed algorithm. The geodesic distances computed on the voxelated corridors are currently

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more accurate than Euclidean distance but still quite simplistic in that they do not consider the cost of waiting times for the elevators, nor do they differentiate between going downstairs and upstairs with distances on the same level. In general, instead of measuring distance in meters, it would be more general to measure distance in travel time/effort, to also account for path complexity for the visitors, for instance by using the Easiest Paths weighting [290] Corridor Allocation Problem (CAP) [291] can be added, which has the same fitness structure with the QAP but with an extra decision on locating the facilities on either side of a corridor. Finally, the proposed layout optimization tool can be potentially extended to solve a Multi-Objective QAP [292], [293] in further versions.

TABLE 4.1 A List Of Spaces With A Needed Number Of Boxes (Modular Units Of Roughly 100 M^2)

Facility Name	Number Of Boxes Needed
Neurology	1
Obstetrics	1
Internal Medicine	1
Cardiology	1
Pediatrics	1
Gastroenterology	2
Diagnostic Units	2
Laboratories	2
Administration-1	1
Orthopedy	1
Physiotherapy	2
Hemodialysis	2
Infection Diseases	2
Surgery Icu	2
General Icu	1
Pediatry Icu	1
Icu Waiting Area	1
Ent	1
Urology	1
Eye Diseases	2
Brain&General Surgery	1
Dermatology	1
Inpatient-1	2
Delivery Rooms	3
Operation Theatre	5
Administration-2	4

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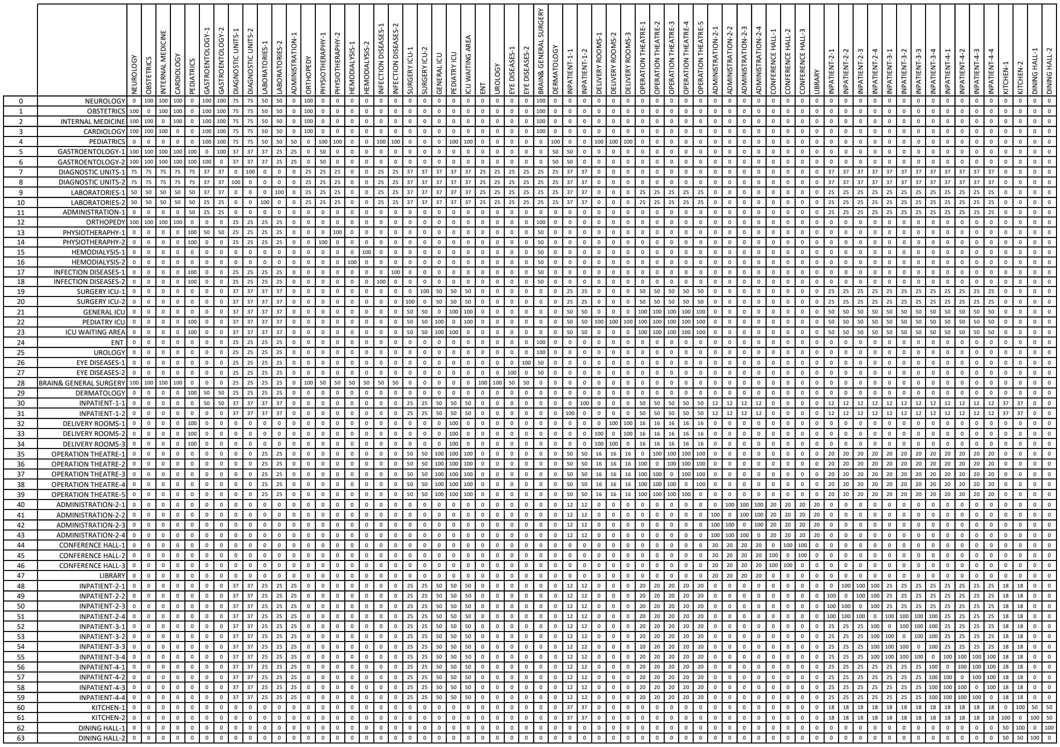
TABLE 4.1 A List Of Spaces With A Needed Number Of Boxes (Modular Units Of Roughly 100 M^2)

Facility Name	Number Of Boxes Needed
Conference Hall	3
Library	1
Inpatient-2	4
Inpatient-3	4
Inpatient-4	4
Kitchen	2
Dining Hall	2
Total Number Of Locations (Modular Units)	64



		NEUROLOGY	OBSTETRICS	INTERNAL MEDICINE	CARDIOLOGY	PEDIATRICS	GASTROENTOLOGY-1	GASTROENTOLOGY-2	DIAGNOSTIC UNITS-1	DIAGNOSTIC UNITS-2	LABORATORIES-1	LABORATORIES-2	ADMINISTRATION-1	ORTHOPEDY	PHYSIOTHERAPHY-1	PHYSIOTHERAPHY-2	HEMODIALYSIS-1	HEMODIALYSIS-2	INFECTION DISEASES-1	INFECTION DISEASES-2	SURGERY ICU-1	SURGERY ICU-2	GENERAL ICU	PEDIATRY ICU	ICU WAITING AREA	ENT	UROLOGY	EYE DISEASES-1	EYE DISEASES-2	BRAIN& GENERAL SURGERY	DERMATOLOGY	INPATIENT-1-1	INPATIENT-1-2	DELIVERY ROOMS-1	DELIVERY ROOMS-2	DELIVERY ROOMS-3	OPERATION THEATRE-1	OPERATION THEATRE-2	OPERATION THEATRE-3	OPERATION THEATRE-4	OPERATION THEATRE-5	ADMINISTRATION-2-1	ADMINISTRATION-2-2	ADMINISTRATION-2-3	ADMINISTRATION-2-4	CONFERENCE HALL-1	CONFERENCE HALL-2	CONFERENCE HALL-3	LIBRARY	INPATIENT-2-1	INPATIENT-2-2	INPATIENT-2-3	INPATIENT-2-4	INPATIENT-3-1	INPATIENT-3-2	INPATIENT-3-3	INPATIENT-3-4	INPATIENT-4-1	INPATIENT-4-2	INPATIENT-4-3	INPATIENT-4-4	KITCHEN-1	KITCHEN-2	DINING HALL-1	DINING HALL-2
0	NEUROLOGY	0	100	100	100	0	100	100	75	75	50	50	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	OBSTETRICS	100	0	100	100	0	100	100	75	75	50	50	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	INTERNAL MEDICINE	100	100	0	100	0	100	100	75	75	50	50	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	CARDIOLOGY	100	100	100	0	0	100	100	75	75	50	50	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	PEDIATRICS	0	0	0	0	0	100	100	75	75	50	50	50	0	100	100	0	0	100	100	0	0	0	100	100	0	0	0	0	0	100	0	0	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	GASTROENTOLOGY-1	100	100	100	100	100	0	100	37	37	37	25	25	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	GASTROENTOLOGY-2	100	100	100	100	100	100	0	37	37	37	25	25	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	DIAGNOSTIC UNITS-1	75	75	75	75	75	37	37	0	100	0	0	0	25	25	25	0	0	25	25	37	37	37	37	37	25	25	25	25	25	25	37	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	37	37	37	37	37	37	37	37	37	37	37	0	0	0	0
8	DIAGNOSTIC UNITS-2	75	75	75	75	75	37	37	100	0	0	0	0	25	25	25	0	0	25	25	37	37	37	37	37	25	25	25	25	25	25	37	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	37	37	37	37	37	37	37	37	37	37	37	0	0	0	0
9	LABORATORIES-1	50	50	50	50	50	37	37	0	0	0	100	0	25	25	25	0	0	25	25	37	37	37	37	37	25	25	25	25	25	25	37	37	0	0	0	25	25	25	25	25	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	25	25	25	25	25	0	0	0	0
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11	ADMINISTRATION-1	0	0	0	0	50	25	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	25	25	25	25	25	0	0	0	0
12	ORTHOPEDY	100	100	100	100	0	0	0	25	25	25	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	PHYSIOTHERAPHY-1	0	0	0	0	100	50	50	25	25	25	25	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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15	HEMODIALYSIS-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	HEMODIALYSIS-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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18	INFECTION DISEASES-2	0	0	0	0	100	0	0	25	25	25	25	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	SURGERY ICU-1	0	0	0	0	0	0	0	37	37	37	37	0	0	0	0	0	0	0	0	0	100	50	50	50	0	0	0	0	0	0	25	25	0	0	0	50	50	50	50	50	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	25	25	25	25	25	0	0	0	0
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21	GENERAL ICU	0	0	0	0	0	0	0	37	37	37	37	0	0	0	0	0	0	0	0	50	50	0	100	100	0	0	0	0	0	0	50	50	0	0	0	100	100	100	100	100	0	0	0	0	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	0	0	0	0
22	PEDIATRY ICU	0	0	0	0	100	0	0	37	37	37	37	0	0	0	0	0	0	0	0	50	50	100	0	100	0	0	0	0	0	0	50	50	100	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	0	0	0	0
23	ICU WAITING AREA	0	0	0	0	100	0	0	37	37	37	37	0	0	0	0	0	0	0	0	50	50	100	100	0	0	0	0	0	0	0	50	50	0	0	0	100	100	100	100	100	0	0	0	0	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	0	0	0	0
24	ENT	0	0	0	0	0	0	0	25	25	25	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	UROLOGY	0	0	0	0	0	0	0	25	25	25	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	EYE DISEASES-1	0	0	0	0	0	0	0	25	25	25	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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28	BRAIN& GENERAL SURGERY	100	100	100	100	0	0	0	25	25	25	25	0	100	50	50	50	50	50	50	0	0	0	0	0	100	100	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	DERMATOLOGY	0	0	0	0	100	50	50	25	25	25	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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33	DELIVERY ROOMS-2	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	100	0	100	16	16	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	DELIVERY ROOMS-3	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	100	100	0	16	16	16	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	OPERATION THEATRE-1	0	0	0	0	0	0	0	0	0	25	25	0	0	0	0	0	0	0	0	50	50	100	100	100	0	0	0	0	0	0	50	50	16	16	16	0	100	100	100	100	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20	0	0	0	0
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41	ADMINISTRATION-2-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	12	0	0	0	0	0	0	0	0	100	0	100	100	20	20	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	ADMINISTRATION-2-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	12	0	0	0	0	0	0	0	0	100	100	0	100	20	20	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	ADMINISTRATION-2-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	12	0	0	0	0	0	0	0	0	100	100	100	0	20	20	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	CONFERENCE HALL-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	CONFERENCE HALL-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	100	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	CONFERENCE HALL-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	LIBRARY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	INPATIENT-2-1	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	0	100	100	100	25	25	25	25	25	25	25	25	18	18	0	0
49	INPATIENT-2-2	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	100	0	100	100	25	25	25	25	25	25	25	25	18	18	0	0
50	INPATIENT-2-3	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	100	100	0	100	25	25	25	25	25	25	25	25	18	18	0	0
51	INPATIENT-2-4	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	100	100	100	0	100	100	100	100	25	25	25	25	18	18	0	0
52	INPATIENT-3-1	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	25	25	25	100	0	100	100	100	25	25	25	25	18	18	0	0
53	INPATIENT-3-2	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	25	25	25	100	100	0	100	100	25	25	25	25	18	18	0	0
54	INPATIENT-3-3	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	25	25	25	100	100	100	0	100	25	25	25	25	18	18	0	0
55	INPATIENT-3-4	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	25	25	25	100	100	100	100	0	100	100	100	100	18	18	0	0
56	INPATIENT-4-1	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	100	0	100	100	100	18	18	0	0
57	INPATIENT-4-2	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	100	100	0	100	100	18	18	0	0
58	INPATIENT-4-3	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	100	100	100	0	100	18	18	0	0
59	INPATIENT-4-4	0	0	0	0	0	0	0	37	37	25	25	25	0	0	0	0	0	0	0	25	25	50	50	50	0	0	0	0	0	0	12	12	0	0	0	20	20	20	20	20	0	0	0	0	0	0	0	0	25	25	25	25	25	25	25	100	100	100	100	0	18	18	0	0
60	KITCHEN-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	18	18	18	18	18	18	18	18	18	18	18	0	100	50	50
61	KITCHEN-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	18	18	18	18	18	18	18	18	18	18	18	100	0	100	50
62	DINING HALL-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	100	0	100
63	DINING HALL-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	50	100	0

FIG. 4.10 The Flow Matrix used in the case study hospital

TOC

TABLE 4.2 The Existing Assignment Of The Case Study Hospital

Location Index	The Existing Assignment		The Proposed Assignment	
	Facility Index	Facility Name	Facility Index	Facility Name
0	44	Conference Hall-1	56	Inpatient-4-1
1	35	Operation Theatre-1	19	Surgery Icu-1
2	22	Pediatry Icu	29	Dermatology
3	7	Diagnostic Units-1	30	Inpatient-1-1
4	8	Diagnostic Units-2	61	Kitchen-2
5	3	Cardiology	15	Hemodialysis-1
6	4	Pediatrics	25	Urology
7	2	Internal Medicine	50	Inpatient-2-3
8	1	Obstetrics	48	Inpatient-2-1
9	0	Neurology	55	Inpatient-3-4
10	5	Gastroenterology-1	49	Inpatient-2-2
11	9	Laboratories-1	32	Delivery Rooms-1
12	6	Gastroenterology-2	2	Internal Medicine
13	10	Laboratories-2	54	Inpatient-3-3
14	15	Hemodialysis-1	60	Kitchen-1
15	16	Hemodialysis-2	47	Library
16	11	Administration-1	13	Physiotherapy-1
17	12	Orthopedy	63	Dining Hall-2
18	13	Physiotherapy-1	57	Inpatient-4-2
19	14	Physiotherapy-2	6	Gastroenterology-2
20	19	Surgery Icu-1	4	Pediatrics
21	20	Surgery Icu-2	17	Infection Diseases-1
22	21	General Icu	3	Cardiology
23	17	Infection Diseases-1	31	Inpatient-1-2
24	18	Infection Diseases-2	44	Conference Hall-1
25	23	Icu Waiting Area	52	Inpatient-3-1
26	30	Inpatient-1-1	23	Icu Waiting Area
27	31	Inpatient-1-2	59	Inpatient-4-4
28	26	Eye Diseases-1	1	Obstetrics
29	28	Brain&General Surgery	0	Neurology
30	27	Eye Diseases-2	41	Administration-2-2
31	25	Urology	9	Laboratories-1
32	24	Ent	26	Eye Diseases-1
33	36	Operation Theatre-2	45	Conference Hall-2
34	37	Operation Theatre-3	7	Diagnostic Units-1
35	38	Operation Theatre-4	12	Orthopedy
36	39	Operation Theatre-5	46	Conference Hall-3

>>>

TABLE 4.2 The Existing Assignment Of The Case Study Hospital

Location Index	The Existing Assignment		The Proposed Assignment	
	Facility Index	Facility Name	Facility Index	Facility Name
37	32	Delivery Rooms-1	11	Administration-1
38	29	Dermatology	40	Administration-2-1
39	33	Delivery Rooms-2	24	Ent
40	34	Delivery Rooms-3	62	Dining Hall-1
41	48	Inpatient-2-1	28	Brain& General Surgery
42	49	Inpatient-2-2	51	Inpatient-2-4
43	45	Conference Hall-2	35	Operation Theatre-1
44	50	Inpatient-2-3	10	Laboratories-2
45	47	Library	14	Physiotherapy-2
46	51	Inpatient-2-4	39	Operation Theatre-5
47	46	Conference Hall-3	16	Hemodialysis-2
48	52	Inpatient-3-1	37	Operation Theatre-3
49	53	Inpatient-3-2	22	Pediatry Icu
50	54	Inpatient-3-3	34	Delivery Rooms-3
51	55	Inpatient-3-4	36	Operation Theatre-2
52	56	Inpatient-4-1	38	Operation Theatre-4
53	57	Inpatient-4-2	20	Surgery Icu-2
54	58	Inpatient-4-3	43	Administration-2-4
55	59	Inpatient-4-4	53	Inpatient-3-2
56	60	Kitchen-1	8	Diagnostic Units-2
57	61	Kitchen-2	21	General Icu
58	62	Dining Hall-1	33	Delivery Rooms-2
59	63	Dining Hall-2	5	Gastroenterology-1
60	40	Administration-2-1	42	Administration-2-3
61	41	Administration-2-2	27	Eye Diseases-2
62	42	Administration-2-3	58	Inpatient-4-3
63	43	Administration-2-4	18	Infection Diseases-2

TABLE 4.3 Nomenclature

Notation	Explanation
QAP	Quadratic Assignment Problem
C#	C sharp programming language
GH	Grasshopper
CAD	Computer Aided Design
ILS	Iterated Local Search
FLP	Facility Layout Planning
STEP	A sample test-pairwise exchange heuristic procedure
GRASP	Greedy randomized adaptive search procedure
MSG	Modified sub-gradient
GA	Genetic algorithm
SA	Simulated annealing
TS	Tabu search
EGD	Extended great deluge
OT	Operating Theatre
2D	Two dimensional
3D	Three dimensional
OR	Operations Research
QAPLIB	A Quadratic Assignment Problem Library
CAP	Corridor Allocation Problem
A*	A-star
π	A vector of integers denoting a permutation of facilities at a moment in time
$T_{\pi_i \pi_j}$	The [transportation] flow between a permuted facility $\pi_i = k$, and another permuted facility $\pi_j = l$
P_n	The set of all permutations
$D_{i,j}$	The distance between location i and j
tmax	Maximum number of trial times
n	Number of facilities & locations
CRAFT	Computerized Relative Allocation of Facilities Technique
COFAD	COmputerized FAcilities Design
CORELAP	Computerized Relationship Layout Planning

4.3 Track B: Designing New Hospitals

This sub-chapter has been published by Cubukcuoglu, C., Nourian, P., Sariyildiz, I. S., & Tasgetiren, M. F. (2022). Optimal Design of new Hospitals: A Computational Workflow for Stacking, Zoning, and Routing. Automation in Construction, 134, 104102. [294] The layout has been adjusted to fit the template of this thesis.

Optimal Design of New Hospitals: A computational workflow for stacking, zoning, and routing

The paper proposes a generative design workflow for three major hospital layout planning steps to satisfy multiplex configurational requirements. The initial step is stacking through clustering functional spaces into floor plans, for which a spectral method is presented. Subsequently, a novel simultaneous process of zoning and routing is proposed as a Mixed-Integer Programming problem-solving task; performed on a quadrilateral mesh whose faces and edges are allocated respectively to the rooms and the corridors. The paper situates the workflow in the context of an Activity-Relations-Chart for a general hospital while demonstrating, explaining, and justifying the generated optimal floor plans. The conversion of the hospital layout problem to a Mixed-Integer Programming problem enables the use of existing Operations Research solvers, allowing for the generation of optimal solutions in a digital design environment. The comprehensive problem formulation for a real-world scenario opens a new avenue for the utilization of mathematical programming/optimization in healthcare design.

4.3.1 Introduction

The healthcare sector is one of the most challenging and fastest-growing industries in the world. Hospital buildings are the most complex buildings in the architectural design field [295], [296]. Thus, these facilities are requiring huge building programs for many different users while satisfying standards, architectural requirements, and engineering aspects [1]. These buildings are having a large impact on their environment [297]. In addition, their design requires expert knowledge and experience. Due to these facts, healthcare facilities are accepted as an important architectural public design type in the built environment of its design complexity. Especially in the early phase of the design process, their functionality should not be disregarded and their spatial configuration has a great impact on their functional performance. Otherwise, the unsuitable layout of the working spaces affected medical staff performance and can cause difficulties such as medical error, stress levels, or work concentration [244]. Hospital designs typically require systematic design methodologies and computational design tools to satisfy sophisticated adjacency/closeness requirements in response to programmatic necessities, project site specifications, and surrounding buildings, in addition to environmental requirements such as daylight.

Computational design techniques can alleviate the complexity of dealing with many such performance criteria practically. More specifically, by shifting the attention from the geometry of a layout to its topology and its network structure, spatial configurations can be directly analyzed, synthesized, and evaluated in computational design workflows. The importance of directly dealing with a topological abstraction of spatial configuration lies in the direct link between the network of walkable spaces (hereinafter referred to as spatial configuration) and the adjacency/closeness requirements that must be fulfilled in hospital design processes. This link exists because of the direct link between network structure and movement potentials and probabilities [9]. More specifically, computational design of spatial configurations can be practiced in procedural CAD environments and support decision-making in design processes with several advantages [9] as follows:

- Providing for objectivity in decision making by making decision bases transparent
- Providing for systematization of design processes;
- Creating new design tools by scripting;
- Customizing existing design tools;
- Allowing (semi) automation in the design process;
- Speeding up decision-making processes in conceptual design; and, most importantly,
- Facilitating evaluation of designs by enabling mathematical operations or computational simulations, and allowing for visual inspections (as enabling 2D and 3D models)

In this paper, we present a formulation of configuration design problems as a task combining room placement and corridor generation and present a configurational design methodology for hospital design for solving such problems. Briefly, the framework encompassing this methodology consists of stacking (Figure 4.11 a), zoning (Figure 4.11 b), and routing (Figure 4.11 c) steps; respectively deciding on how to divide the floors between functional areas, placing rooms, and embedding corridors at the same time. The methodology is intended to be modular, extendable, and easy to integrate with other computational design workflows and spatial decision support systems. All of the steps are implemented with a customized computational design tool that we developed especially for hospital designs. In the first step, the stacking problem is solved by graph-theoretical approaches. In zoning and routing parts, multi-level hospital layout problems and corridor design problems are addressed using Mixed Integer Programming Techniques (MIP).

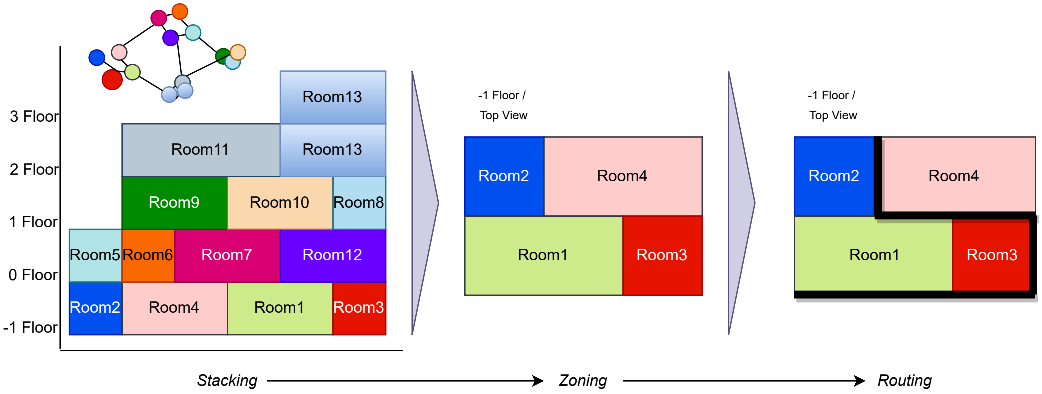

FIG. 4.11 (a) stacking, (b) zoning, (c) routing

4.3.1.1 Overview of Layout Planning as MIP

Hospital layout problems can be positioned into a sub-category of Facility Layout Problems (FLP). According to our literature review, hospital layout problems such as FLP have been solved by using Quadratic Assignment Problem (QAP) and MIP methods [298], [299]. However, we see that the [ordinary formulation of] QAP is better suited to layout design in renovation scenarios for the placement of the centers of departments [151]. This is because QAP is essentially about minimizing the sum of travel distances between points (a.k.a. the departments), whereas here we have the problem of first allocating locations/faces to the room surfaces; thus before having the rooms the QAP formulation is not straightforward to apply in a new design; this is because even after finding the locations of the room centres we still need to grow the rooms to certain sizes and deal with several constraints that are difficult to address in QAP. Therefore, in this paper, we refer to MIP methods that allow for the simultaneous layout of departments and corridors while dealing with such validity constraints as adjacency, cohesion, and alike. From an architectural point of view, this can only be possible if we can implement the MIP method on a discretized mesh model of the building envelope. We used quadrilateral meshes in the model because most of the real-world layout problems are either quadrilateral or can be tessellated as a quadrilateral mesh [300]. However, the same methods can be applied without loss of generality to other kinds of mesh tessellations (e.g. triangular, mixed triangular/quadrilateral, or polygonal) if needed in a design problem.

An optimization problem is called an Integer Program (IP) if any of its decision variables are restricted to be discrete (an integer as opposed to a more common float approximating a real number); if all variables are discrete, the model is a pure IP; otherwise, the model is called a mixed-integer program (MIP). It must be noted that the terms programming and optimization are used almost interchangeably in computational contexts, albeit the term programming is colloquially associated with the most well-known types of optimization problems in Operations Research. MIP optimization problems with a quadratic objective are called Mixed-Integer Quadratic Programming (MIQP) problems. Whereas problems without any quadratic or higher-dimensional terms are often referred to as Mixed Integer Linear Programming (MILP) problems; if there are nonlinear functions in the objective function and/or the constraints, it is called Mixed-Integer Non-Linear Programming (MINLP).

In the literature, MIP is widely considered a central formulation in facility layout planning [301]. In general, Peters (1996) [302] introduced a MIP model for facility layout design in flexible manufacturing systems by proposing a genetic algorithm (GA). Liu and Meller (2007) [303] proposed a MIP formulation based on a sequence-pair representation approach for unequal area facility layout design by presenting a GA-based heuristic algorithm. Bozer and Wang (2012) [304] formulated an unequal area facility layout problem as a MIP model in which binary (0/1) variables are used to prevent departments from overlapping with one another by proposing a heuristic procedure based on the graph-pair representation technique and a simulated annealing (SA) algorithm. Kosucuoglu and Bilge (2012) [305] proposed a mathematical programming approach including one MINLP and two MIP models for the facility layout of flexible manufacturing systems by using a GA-LP heuristic algorithm. Murray et al. (2012) [306] considered a double-row layout as a facility layout problem where rectangular machines of unequal size must be placed in two rows separated by a straight aisle of predetermined width using a tabu search heuristic. Kulturel-Konak and Konak (2013) [307] formulated a MIP to minimize the total material handling cost as a function of the distance and the amount of material flow between departments by proposing a hybrid GA/LP approach for unequal area facility layout design. Xiao and Seo (2013) [308] formulated a MIP for unequal area layout design to minimize the total material handling in a manufacturing system by using two-step heuristics comprised of both construction and improvement using simulated annealing. Hong et al. (2014) [309] developed a MIP model for solving the design problem of facility layout and automated material handling system (AMHS) for semiconductor fabrication facility by using a pairwise interchange method with a tabu search metaheuristic. Hammad et al. (2017) [310] proposed a general MIP formulation for the site layout planning problem, which is a well-studied layout problem that requires finding an appropriate physical arrangement of temporary facilities operating on construction sites using a cutting plane algorithm and exact location-decomposition algorithm. Lacksonen (2018) [311] used a MILP model to find the block diagram layouts with varying department areas using a branch and bound algorithm. Leno et al. (2018) [312] solved an unequal area facility layout problem with a MIP formulation by using an elitist strategy hybrid GA–SA algorithm. Recently, Wan et al. (2020) [313] dealt with a multi-row facility layout problem by using an improved multi-objective greedy randomised adaptive search procedure. Liu et al. (2021) [314] addressed a single-row facility layout problem by using CPLEX software [115] and a constrained improved fireworks algorithm. A recent literature review on facility layout planning can be found in [298].

There are, however, only a few examples that make use of MIP techniques for architectural layout planning (ALP) despite their common use in FLPs. In conjunction to find optimal solutions, Keatruangkamala and Sinapiromsaran (2005) [315] firstly proposed MIP to solve ALPs by adopting more objectives than classical FLPs have. They formulated an architectural layout design problem as a multi-objective MIP using a MIP solver with a weighted sum approach. The problem objectives are the minimization of the absolute distance among rooms and the maximization of room spaces. Problem constraints are the connectivity, the unused grid cells, the fixed room location, the boundary, and the fixed border location, and the non-intersecting, overlapping, length, and ratio constraints. Keatruangkamala and Nilkaew (2006) [113] presented a practical formulation of MIP based on the strong valid inequality constraints, which reduced the feasible region using LP relaxations to solve the medium size architectural layout design. In a later work, Keatruangkamala and Sinapiromsaran (2008) [114] used a MIP formulation for the architectural layout to optimize room positioning, room sizes, and distances according to the architect’s preferences subject to functional, dimensional, non-circular, and guided constraints using the CPLEX solver [115].

Recent hospital layout design reviews can be found in [151] and [152]. More specifically, regarding the MIP methods in hospital planning, we provide a short review here: Amaral (2012) [316] focused on the corridor-allocation problem for double-row hospital layout to minimize daily traffic and communication cost among facilities. It was formulated as a MIP with a quadratic objective (multiplication of flows and distances) using heuristic approaches (2-opt and 3-opt algorithms).

Helber et al. (2014) [23] proposed a hierarchical modeling approach that divides the whole problem into sub-problems, where the first stage was formulated as a QAP for assigning elements to locations using a fix-optimize heuristic, and the second stage was formulated as a MIP for detailed positioning within a site, considering space requirements, in a large hospital facility. They concentrated on transportation processes, fixing some units in specific locations, and ensuring the direct neighborhood of some pairs of units. Chraibi et al. (2015) [269] minimized total traveling cost and rearrangement costs in a dynamic facility layout problem (deciding the locations of the departments in a facility over multiple planning periods) for the operation theatre department of a hospital. They used both MIP and QAP formulations using a CPLEX solver. Acar and Butt (2016) [317] dealt with the nurse-patient assignment problem in a 29-bed oncology unit and formulated it as MILP and solved it with a simplex solver. Butler et al. (2016) [318] proposed a multi-level approach consisting of MIP formulation and system simulation for the capacity allocation problem of facility layout in a general-purpose hospital by considering distances between services. Safarzadeh and Koosha (2017) [125] formulated a non-linear MIP model with fuzzy constraints and converted it to a linear MIP model for a multi-row hospital facility layout. They minimized handling costs and lost opportunity costs related to waste spaces using GA. Recently, Wang et al. (2020) [319] proposed an MINLP model for bed allocation in a hospital in Shanghai by using an Adaptive Hyperbox Algorithm. Huo et al. (2021) [299] addressed a multi-floor hospital facility layout problem in a hospital in Shanghai, China, based on a double-row model in which all departments are arranged into two rows on each floor for minimizing the total movement distance of patients and maximizing the total closeness rating score by using a Non-Dominated Sorting GA-II algorithm.

To sum up, the works that utilize MIP in hospital layout design mostly consider transportation cost as an objective and often see the problem as a facility layout problem. They typically do not consider some specific architectural features required by hospital layout designs such as way-finding [320], daylighting [28], or privacy [321]. As stated in [151], the adaptation of FLP techniques to the hospital is not commonly known or used by architects. However, in practice, hospital layouts are designed by architects in collaboration with space programmers and doctors. Thus, we propose to utilize MIP techniques in hospital layout design by additionally considering architectural aspects of hospital design. In this paper, we present a hierarchical layout design methodology for hospital layout planning and consider MILP integrated with required architectural design features of hospital layouts. Unlike QAP, this methodology is also convenient for designing new buildings.

4.3.1.2 Related Works

In Peng et al. (2016) [300], the floor planning problem is solved by a simultaneous approach to creating rooms and corridors in one optimization problem formulated as a MIP model with linear objectives and constraints or a Mixed Integer Linear Programming (MILP) problem.

In [300], plan layouts are generated with a set of pre-defined room templates that have fixed areas and shapes as combinations of squares. However, in a hospital, each room can require different square meters generally due to restrictive hospital design standards. Therefore, our plan layout approach enables each room (hospital department) to have various areas and shapes.

While the corridor design procedure of our approach is inspired by the work of Peng et al. (2016) [300], we have followed a step-by-step procedure combining room layout and corridor layout in our approach. First, varying hospital-department shapes are assigned to mesh faces based on a MIP model, which considers area requirements and some architectural needs. Then, using the output of the room layout procedure, corridors are created between the hospital departments with another MIP model, which considers objectives and constraints related to the hospital logistics network.

In addition, unlike [300], we consider relationships between rooms in layout planning by using relationship charts (REL chart), which is a common tool in FLP in industrial engineering, and Graph Drawing algorithms.

Similar to our approach, some works utilize such a graph-theoretical coordinate system and use MIP models in layout planning [258], [315]. However, they do not focus on corridor design problems. In other words, the flow of pedestrians or materials in a building layout is disregarded not only in these papers but also in the majority of computational layout approaches. Besides, they are not based on a mesh model nor do they interact with CAD software used in architectural practice.

There are also some studies [322], [323] focusing on both packing the rooms and routing passageways with a hierarchical approach. Merrell et al. (2010) [322] have some additional similarities with our approach in terms of considering relationships between spaces using Bayesian networks trained based on a corpus of observed realistic floor plans (to form a plausible adjacency matrix). Even though their method seeks to comply with such machine-generated adjacency recommendations, it does not focus specifically on optimizing closeness criteria, because their focus is only on generating realistically looking buildings for computer graphics applications,

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whereas in our case, hospital design, optimization concerning closeness criteria are central to the whole problem. However, their flexible multi-level approach allows rooms to be placed within a boundary area without having unused cells. For room layout, they applied a stochastic optimization approach by sliding walls, swapping rooms, and creating a 2D layout. When generalizing the model from 2D to 3D, passageways are created using some rules e.g. wide passageways are placed between public rooms. Nevertheless, as mentioned earlier, they do not consider any logistics cost optimization in their approach. Unlike this, Wu et al. (2018) [323] proposed a hierarchical framework for the generation of building interiors based on a mixed-integer quadratic programming (MIQP) formulation focused on the geometric layout of rooms in a 2D plan. Their considered objective function is in a quadratic form, which means that it is non-linear. In this work, each room is represented as an axis-aligned polygon defined by points on the bounding area as a polygon that consists of a set of small rectangles. During the room layout step, the polygonal regions are generated by considering adjacency constraints. Then, aisles are generated by expanding the gap between two regions with a fixed width if needed. However, none of them uses a mesh model with a MIP approach for corridor generation. Their corridor design step is mostly based on intuition rather than a computational logic.

In general, there is a subtle point on why satisfying adjacency requirements is not good enough for a serious case like a hospital layout. The reason is twofold:

Unless there are literal reasons pertaining to ‘piping, noise, vibration and alike’, producing adjacency requirements can be somewhat subjective, arbitrary, and confusing tasks if meant as a replacement for closeness requirements, while closeness criteria can make objective sense. In a general case other than those mentioned above, from a logistics point of view, it is not easy or even necessary to state why two rooms must be adjacent, however, they may easily need to be close by. That could easily be achieved by placing them on the opposite sides of a corridor; whereas by requiring that the two be adjacent, we may not only make the problem unnecessarily complicated but also make it unrealistic due to the infeasibility of making planar layouts with many required adjacencies. Secondly, the emphasis on adjacency requirements may simply be procrastination from the corridor generation problem in small floor plans while in large and complex floor plans, there does always exist a part specifically about corridor generation. Access space in large and complex buildings is often so large that it may even take a significant part of the space.

4.3.1.3 Contribution

The main contribution of this paper is to combine and transform two major space-planning problems, i.e. room layout (zoning/packing) and corridor generation (routing) to the standard forms of MILP problems so that they can be solved using standard engineering optimization engines. In other words, the main contribution of the paper is the formulation of the hospital layout problem to multiple standard MILP problems, so that standard solvers such as Gurobi, CPlex, and OR-Tools can be utilized to solve them efficiently. As such, the study of the time complexity of these well-known algorithms falls out of the scope of the paper. Nevertheless, we can relate the time complexity of the brute-force search problems in each major sub-problem. The two major sub-problems formulated as combinatorial optimization problems in the paper are the **zoning** and **routing** problems, discretized on a Mesh $M(V,E,F)$:

- For the **zoning** problem (face-to-room assignment problem):
  - For n rooms, we shall have n^2 integer variables to find, for each of which we can have $|F|$ possible choices of integers, where $|F|$ is the size (number of pixel-like faces in each direction) of a hypothetical square grid of pixels whose integer coordinates are tested for the room sizes x_i, y_i, and $i \in [0,n)$. This means that for a brute-force test, there will be $\mathcal{O}\left(n^{2|F|}\right)$ choices to be made. This means that the problem quickly becomes intractable with brute force or naïve searches.
- For the **routing** problem (edge-to-corridor assignment problem):
  - The number of edges to be designated as corridors is unknown in advance, because one does not have a target total length for the corridors at the beginning of the search process. However, the problem, in this case, is formulated in such a way that a vector of decision variables with the size of the number of edges in the underlying mesh will be the main decision variable of a canonical MILP formulation, i.e. in the form of $\min_{\mathbf{x}} \mathbf{c}^{\mathrm{T}}\mathbf{x}$. Therefore, the complexity of the problem is on par with a canonical MILP problem. Similarly, if one was to make a naïve brute-force search to find the best configuration of edges for the corridors, considering the binary variables indicating the assignment of an edge to a corridor, it would take $\mathcal{O}\left(2^{|E|}\right)$. This also indicates that even with binary variables this integer programming problem becomes intractable whence the mesh is of considerable size.

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The binary ILP (the case of routing) is listed in Karp's list of 21 NP-Complete problems [324]. The MILP is also known to be an NP-Hard problem. However, the solvers, in practice, manage to approximate solutions in polynomial time.

4.3.2 Stacking

In this stage, we aim to find the number of levels (or parts) needed for a to-be-built hospital. Before this stage, the shape of the outer envelope should be determined, whether as systematically as exemplified in this paper or as conventionally proposed based on the so-called common 'typologies' formed according to construction-related constraints and preferences. The decision on how to dissect the entire configuration of a hospital into parts (vertically [See Figure 4.12], horizontally [See Figure 4.13], or a combination of the two) is taken 'intuitively', i.e. conventionally by considering area requirements, site-specific circumstances, construction-related considerations, and alike. As a systematic alternative, further, in the text, we shall introduce a mathematical method for taking stacking (Figure 4.14) decisions concerning 'accessibility' requirements that are typically given in the so-called Activity Relationship Charts (4.3.2.1). The latter method is based on the idea of forming clusters as to the closeness requirements between the departments (4.3.2.2).

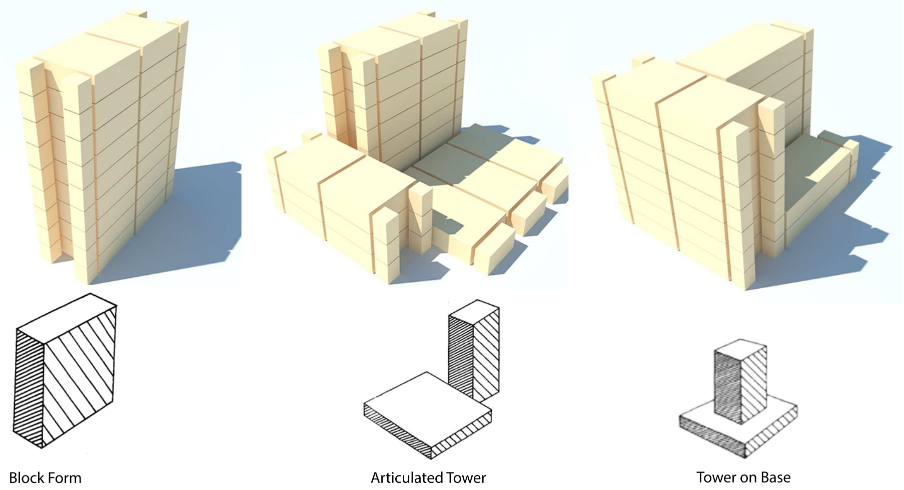
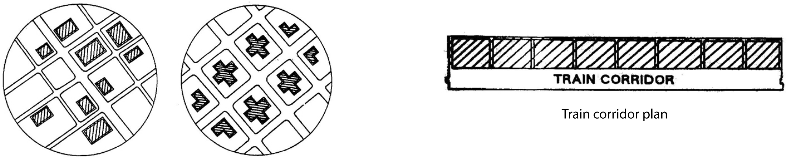
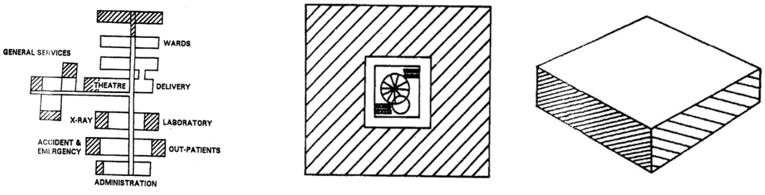


FIG. 4.12 Vertical Hospital Typology Examples [174], [178]



Village Form

Train corridor plan



Open-ended finger plan

Courtyard

Compact Form

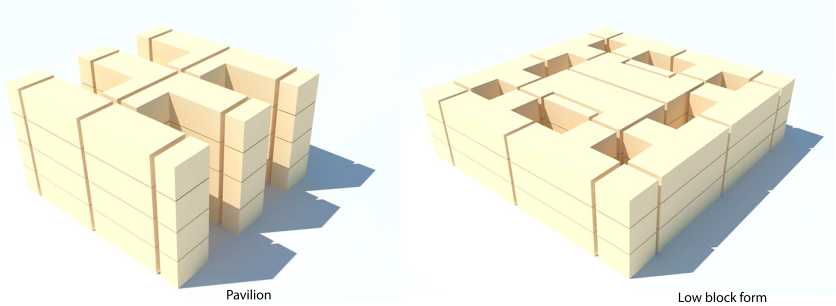


FIG. 4.13 Horizontal Hospital Typology Examples [174], [178]

Proposed Hospital at Shillong (all areas are in sq. and are carpet areas) **STACK PLAN**

Department	Basement	Lower Ground	Upper Ground	First	Second	Third	Fourth	Total
Public Areas			1152					1152
Casualty Department			1118					1118
Out-Patient Department				1313				1313
Radiology/Imaging & Diagnostics			1352					1352
Operation Theater Complex							2133	2133
Intensive Care Units							2444	2444
In-Patient Wing					6000	6000		12000
Central Sterilization & Processing Dept.							538	538
Clinical Laboratory				1287				1287
Kitchen & Dining			1269					1269
Administration				1356				1356
Building Services	6400		1100					7500
Parking		Parking						0
Sub-Total	6400	0	5991	3956	6000	6000	5115	33462
Add Vertical Circulation	1600	0	1498	989	1500	1500	1279	8366
TOTAL	8000	0	7489	4945	7500	7500	6394	41828

FIG. 4.14 Stack plan example of a vertical hospital in Shillong, India [174]

4.3.2.1 Activity Relationship Charts

In the stage of stacking, the floor levels of each main unit of hospitals are defined. In this paper, the main typical units for a middle-size general hospital are considered and listed with some accompanying sub-units as follows:

1. **Outpatient Department (OPD)**: consists of polyclinics or specialty units and waiting areas.

2. **Inpatient Department (IPD)**: consists of wards, nursing units, surgical and medical services, and the delivery suite that consists of delivery rooms and nurseries.

3. **Intensive Care Units (ICU):** are specialty nursing units designed, equipped, and staffed with specially skilled personnel for treating very critical patients or those requiring specialized care and equipment [177].

4. **Operating Theatre (OT):** consists of operation rooms, post-anesthesia recovery rooms, scrub-up, changing rooms, etcetera. This unit requires different entrances for materials, patients, and staff due to sterilization procedures.

5. **Emergency (EMG):** is one of the polyclinics. It welcomes ambulances or private cars with a distinct entrance. Triage and treatment areas are needed.

6. **Diagnostic units (DGU): labs and medical imaging units, typically consisting of:**
   - Radiology
   - X-ray
   - Ultrasound
   - Laboratory
   - Pathology

7. **Administration (ADM):**
   - Business, accounting, auditing, cashiers, records
   - Offices for hospital management etc.

8. **Main Entrance Hall (ENT):** consists of a welcome desk, waiting areas, shopping, café, and like.

9 **Support (SUP):**

- Housekeeping and linen rooms
- Storages
- Kitchen and dining
- Central Sterile Supply Department (CSSD)
- Mortuary: where dead bodies are kept, requiring a separate entrance.
- Pharmacy: supplies medicine for emergency and inpatient units.
- Parking
- Bunker

Each main unit is spatially related (meant to be close by) to each other due to many technical and non-technical relationships (see Figure 4.15, Table 4.4 and Table 4.5). Such closeness relations are typically expressed in terms of so-called closeness ratings in Activity Relationship Charts (ARC in short, a.k.a. REL-Charts), see e.g. Table 4.4 and Table 4.5 for a hypothetical hospital configuration. If we consider the main units as a graph, then the ARC can effectively be considered a weighted graph because of these relationships.

TABLE 4.4 customary codes for closeness ratings

■	Absolutely important	A	1.00
▩	Especially important	E	0.75
▒	Important	I	0.50
░	Ordinary	O	0.25
	Unimportant	U	0.00

TABLE 4.5 an exemplary REL-Chart for the main units of a typical middle-size hospital considered in this paper

	Outpatient	Inpatient	Intensive Care Unit	Operation Theatre	Emergency	Diagnostics	Administration	Entrance Hall	Support
Outpatient					░	▒		■	
Inpatient				▒	▒	▩	▒		▩
Intensive Care Unit				■	■				░
Operation Theatre		▒	■		■				░
Emergency	░	▒	■	■				▩	
Diagnostics Unit	░	▩						▩	░
Administration		▒						░	
Entrance Hall	■				▩	▩	░		
Support		▩	░	░		░			

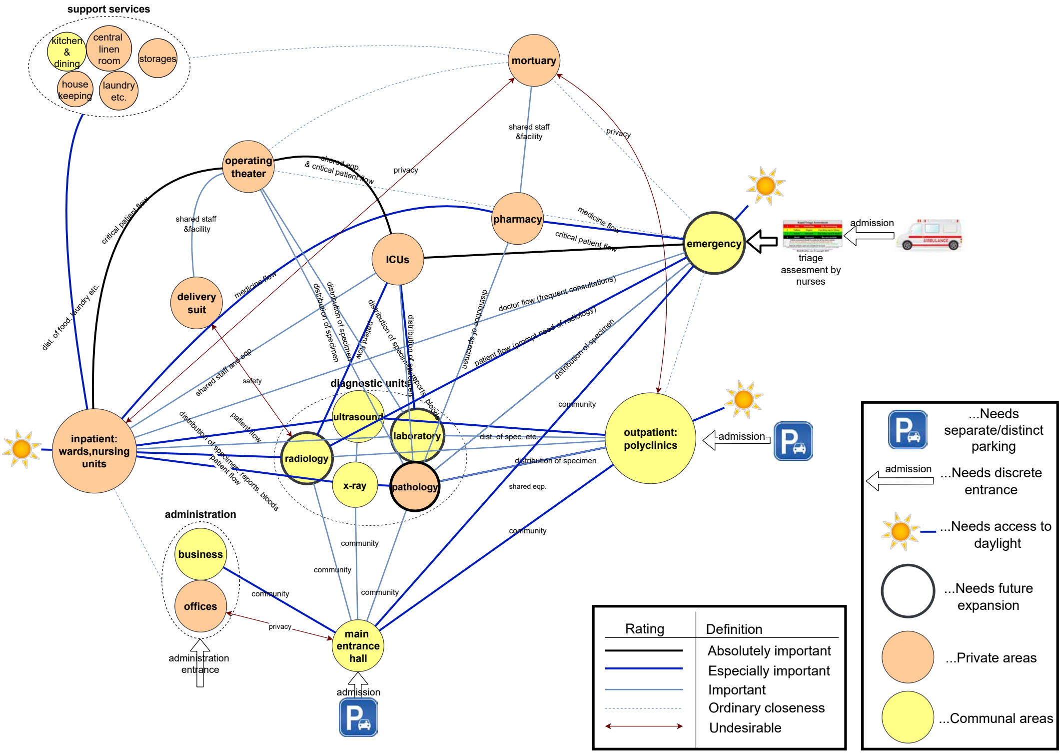


FIG. 4.15 a closeness diagram (graph) of the main and sub-units of a typical middle-sized hospital (drawn by the author after preliminary research using site visits, expert interviews, and literature review)

The typical reason for stacking on the horizontal floor is that horizontal access is often more efficient and thus preferred for critical or high-frequency connections in hospitals. Thus, we argue that in a systematic layout process, pairs of highly interrelated spaces within the same 'cluster' should be placed on the same level.

4.3.2.2 Stacking as Clustering

To find the clusters according to proximity requirements, we propose to perform a spectral clustering on the weighted configuration graph of the hospital. The idea of spectral clustering [325] is to find clusters on a dimensionality-reduced embedding of the graph in a so-called spectral domain (see Figure 4.16), i.e. the space of the most dominant eigenvectors of the weighted adjacency matrix that, roughly speaking, represent the steady-state of random walks on the graph in question.

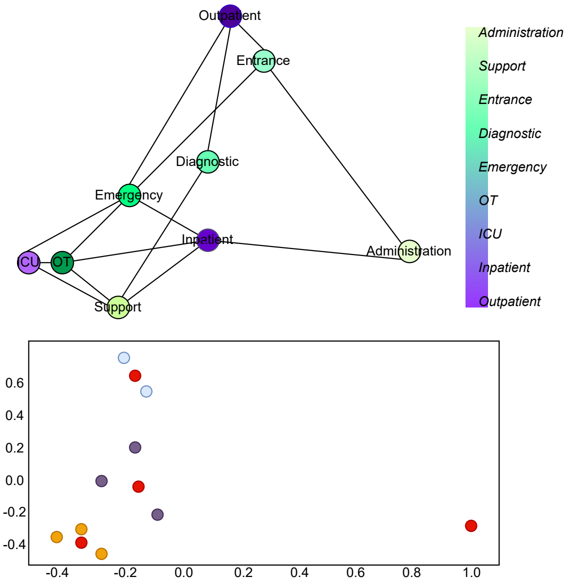


FIG. 4.16 a spectral embedding of the main units based on the REL-chart (weighted adjacency matrix, the same graph as shown in Table 4.5) and k-means clustering

The idea behind this process and its connection with closeness are explained in [326]. For clustering the main units within the spectral space (a.k.a. the frequency domain), we distinguish two different cases:

- If we know the required number of levels, then we perform spectral clustering based on the K-Means algorithm.
- If we are to find the number of required levels, then we perform spectral clustering based on the DB-Scan algorithm (not used here).

By clustering the entire space into horizontal clusters, we implicitly decide to provide (fast) vertical connections between spaces on different levels instead of locating them on one single huge horizontal area (which would lead to long walking distances and is not applicable when the site area is not enough). If some spaces need the same level requirements but they are in different clusters, then we can define them on the same level if the available space is sufficient. They can be also designed as two different building blocks located at the ground level. For example, two blocks on the ground level (main block: ground level of the main building and the attached block: added to the main block) can be defined. There should be a short connection between those two blocks and the attached block should have access to the vertical circulation of the main block. In addition, during the stacking stage, we should consider some special conditions. Some of the specialized spaces need certain levels due to some specific features. For example, most hospital design guidelines suggest that an emergency needs a distinct and separate entrance and that it should be placed on the ground level for quick access. Therefore, all spaces in the cluster that includes the emergency unit should be placed on the ground level.

As seen in Figure 4.16, the upper picture is a spectral drawing of the weighted adjacency matrix given in Table 4.4 and Table 4.5 and the lower picture is the output of k-means clustering with 4 by using the result of the spectral drawing. As a result, outpatient and entrance are in the first cluster; diagnostic units, emergency, and inpatient care are in the second cluster, intensive care unit and operation theatre are in the third cluster and administration is in the fourth cluster. The units that are in the same cluster can be located at the same level or these clusters can give an idea for a stacking task.

4.3.3 Zoning

In this stage, the zoning problem for each level is formulated based on MIP models introduced in [258], [315]. At this step, the building plot (e.g. input problem domain) is discretized into a quad mesh to define the structural system [axes] of the building and to decide the positions of the rooms on the mesh faces. Therefore, the problem at hand can also be deemed as a room-to-face assignment problem, where multiple faces are assigned to a labeled room/department. As such, this can be considered a problem of graph coloring or vertex labeling. Each level has its room-to-face problem to solve for the levels determined at the stage of stacking. Each level can have different goals and requirements so that general problem objectives and constraints can be specialized for each level. At this stage, we focus on the allocation of space to the list of sub-units within each cluster/floor. For example, during the stage of stacking, we would consider the cluster of all diagnostic units as the main unit, but here we consider sub-units of the diagnostic department as rooms to be laid out, such as radiology, x-ray, laboratories, etcetera. In this sub-problem, enough mesh faces are to be allocated to the rooms of the floor plan such that their area requirements are fulfilled. We consider the following aspects in our zoning model:

- Closeness objective for interrelated areas
- Space area requirements
- Cohesion (as in connectedness and contiguity)
- Contiguous areas (adjacent rooms)
- [optional] fixed locations/adjacencies for some spaces

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- Non-overlapping spaces (To avoid different rooms assigned to the same mesh faces)
- Adjacency to NEWS[4] borders because of lighting requirements, and discrete entrance requirements.
- Flexibility requirements for the spaces that can need future expansion
- Privacy/Community requirements
- Boundary constraints

For various reasons we perform the zoning operation before corridor generation, namely that: We need to know in the routing problem the shape of the rooms to avoid cross-cutting the rooms with corridors and more importantly, to ensure that all the rooms are connected to the set of edges designated as corridors (the CAD interface can be seen in Figure 4.17 and Figure 4.19). Additionally, the so-called sink vertices (the main entrance) are defined based on the known location of the zones. Moreover, in 4.3.4.2 (Route Separation). In the zoning problem formulation, however, we have already considered the closeness ratings by minimizing the Manhattan distance between the zones. This is because the Manhattan distance between pairs of rooms is the lower limit of their eventual geodesic distance through the corridors.

-

ALGORITHM 4.3 Zoning and Room Generation, based on assigned floors

Input Notation	[Data-Structure] Data Type	Input Name: Notes
$M(V,E,F)$	Quad Mesh	**Space:** A map consisting of vertices, edges, and faces in the form of pixels/quads to be assigned to rooms
$[s_i]_{n\times 1}$	Array of Float	**Surface Areas:** To be converted to a list of integers and to be realized as constraints, where n is the number of rooms
$[T_{i,j}]_{n\times n}$	Matrix of Float	**Closeness Matrix:** indicating whether closeness (in the network space) is to be sought as an objective with respect to every two nodes
$[A_{i,j}]_{n\times n}$	Matrix of Boolean	**Adjacency Matrix:** indicating whether adjacency (as in sharing walls) is to be ensured as a constraint with respect to every two nodes
C	List/Set of (Integer, Integer, Integer)	**Locations:** integer tuple coordinates (i,x,y) of the index of room and the coordinates of the top left corners of spaces/faces which are to be constrained to a specific location

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[4] N: North, E: East, W: West, S: South

ALGORITHM 4.3 Zoning and Room Generation, based on assigned floors

B	List/Set of (Integer, Integer)	**Adjacency to Borders:** integer tuples in the form of $(i, which\_border)$ i-ndicating whether space is to be constrained to be adjacent to a border as to light or accessibility reasons.

Output Notation	[Data-Structure] Data Type	Output Name: Notes
$\left[x_i, y_i\right]_{n\times 2}$	Array of Integer	Top-Left Coordinates
$\left[w_i, l_i\right]_{n\times 2}$	Array of Integer	Width-Length from Top-Left Corners
$\left[R_{i,f}\right]_{n\times\lvert F\rvert}$	Matrix of Boolean	Face to Room Assignment Matrix: indicating Face Regions in its rows

Problem: given the input space as a map of vertices, edges, and faces, find an assignment of faces to rooms, such that the sum of Manhattan distances between close pairs is minimized, subject to several validity constraints, namely, cohesion and non-overlapping zones. The problem-solver method can take the problem in the [minimization] standard MILP form*:

$$\min_{x,y} \sum_{(i,j)\in E} d_{i,j} = \sum_{(i,j)\in E} \left|x_i - x_j\right| + \left|y_i - y_j\right| \forall (i,j)\in E\,,$$

where E is the edge list of the ARC/Adjacency graph, subject to:

$h_k\left(x,y,w,l\right)=0\,,k\in\{0,1,2\}$

% equality constraints for adjacent rooms, fixed locations, adjacency to NEWS borders

$g_n\left(x,y,w,l\right)\le 0\,,\ n\in\{0,1,2\}$

% ensuring cohesion, non-overlapping spaces, boundary

$0 < x[i] < f_1$

$0 < y[i] < f_2$

$w_{min}[i] < w[i] < w_{max}[i]$

$l_{min}[i] < l[i] < l_{max}[i]$

$W = f_1$

$L = f_2$

where f_1 is the number of faces in M along {x} direction and f_2 is in {y} direction.

Procedure Zoning & Room Generation:

```
1. For the $m_{th}$ floor mesh $M$
2. Define Mesh with several faces along {x} direction: $f_1$ ;and of faces along {y} direction: $f_2$
3. Enter $w_{min}$, $w_{max}$, $l_{min}$, $l_{max}$ of each space
4. Enter $T_{i,j}$ matrix between each space
5. Enter the number of spaces (rooms): num_rooms
6. Define decision variables: $[x_i, y_i]_{n\times 2}, [w_i, l_i]_{n\times 2}$
7. Generate constraints (details are in sub-sections: $h_k, k=0,1,2$ & $g_n, n=0,1,2$)
8. Generate objective function (details are in sub-section: closeness objective $d_{i,j}$)
9. Run the model
10. Get $x,y,w,l$ and $[R_{i,f}]_{n\times|F|}$ values and visualize the allocated rooms with nominal colors on the 3D model of the $m_{th}$ floor
11. $m \leftarrow m-1$ and go back to Step 2 and repeat until all floors are finished
```

>>>

ALGORITHM 4.3 Zoning and Room Generation, based on assigned floors

* *Please note that this formulation is showing our implementation in Google OR-Tools. As we will show below, this formulation is not exactly in the linear form that would be acceptable by a conventional LP solver. However, as explained in the implementation details, due to the possibility of inserting auxillary conditional statements, we can utilize the library for dealing with this non-linear objective function as if it is linear. Code 4.1 reveals this point. In the following we can show the closed form of the objective function solved in this way:*
Consider vector at the length of the number of edges in the adjacency graph $G=(V,E)$*, with two columns containing the coordinate differences of the edge-lines, we can define:*

$$\mathbf{E}:=\begin{bmatrix} \vdots & \vdots \\ (x_i-x_j) & (y_i-y_j) \\ \vdots & \vdots \end{bmatrix}_{|E|\times 2}$$

Now, the L_1 *norm of this vector will be:*

$$\|\mathbf{E}\|_1=1^T|\mathbf{E}|=\sum_{e[k,:]=V[j,:]-V[i,:]|(i,j)\in E}\left|\mathbf{E}[:,0]\right|+\left|\mathbf{E}[:,1]\right|,$$

where $\boldsymbol{V}:=\begin{bmatrix} \vdots & \vdots \\ x_i & y_i \\ \vdots & \vdots \end{bmatrix}_{|V|\times 2}$ *is a matrix containing the vertex coordinates of a graph embedding.*

However, e in this equation is not written in terms of the decision variables yet. To write it in terms of the decision variables, we need to use a matrix called the Incidence Matrix of the graph in question defined as below:

$$M_{|E|x|V|}=\left[M_{e,v}\right]_{|E|x|V|}\mid M_{e,v}=\begin{cases} M_{e,v}=-1, & if \quad v=s \quad in \quad e=(s,t) \\ M_{e,v}=+1, & if \quad v=t \quad in \quad e=(s,t) \\ M_{e,v}=0, & otherwise \end{cases}$$

Then we can write:

$$\mathbf{E}=\mathbf{MV}$$

So, the closed form of the objective function can be written as follows:

$$\min_{V} 1^T|\mathbf{MV}|$$

, where the decision variable is actually a matrix rather than a vector.
Which is not exactly in the canonical form of an LP problem, as a classical LP problem would be in the form of:

$$\min_{\boldsymbol{x}} \boldsymbol{c}^T\boldsymbol{x}$$

So, in conclusion, we get to solve a problem that is not exactly linear with the help of the conditional statements and the possibility of incremental development of a problem instance in OR-Tools.

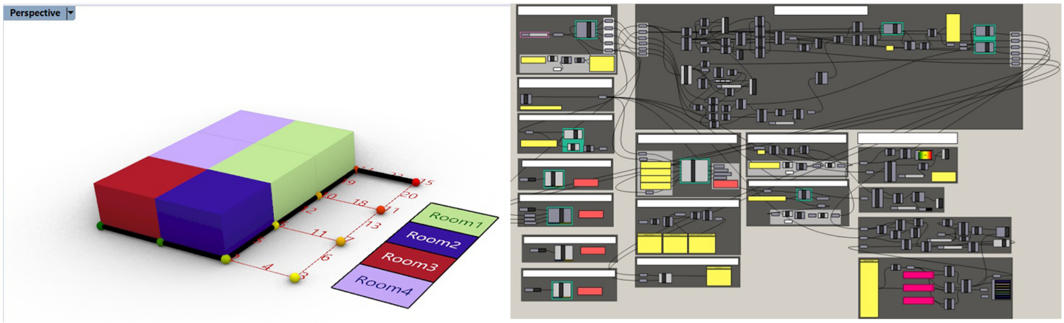

FIG. 4.17 Interface of the layout model developed in Rhino (illustrates CAD at the left) & Grasshopper3D (plug-in of Rhino & illustrates the computational model including python script components at the right)

4.3.3.1 Design Variables

For each room indexed with, four decision variables are defined as integer coordinates of each space and their sizes on the mesh. The origin point is the top left corner vertex of the mesh (Figure 4.18).

- x_i = x-integer coordinate of the top left corner of the space ***i*** on mesh
- y_i = y-integer coordinate of the top left corner of the space ***i*** on mesh
- w_i = the integer width of the space ***i*** on mesh
- l_i = the integer length of the space ***i*** on mesh

There are also two basic parameters as width and length of the building plot, which are represented by W and *L*, respectively. As shown in the figure below, a rectangular red-colored room R is placed at the (2,0) integer coordinates on mesh with a width=1 and length=2. In the end, this room is placed on the mesh faces indexed by 5 and 8. Even though it seems that we are dealing with the geometric coordinates of the spaces, it is a topological layout problem, since each coordinate pair is referenced by a vertex index in the mesh and width & length refer to the length of edges in the mesh.

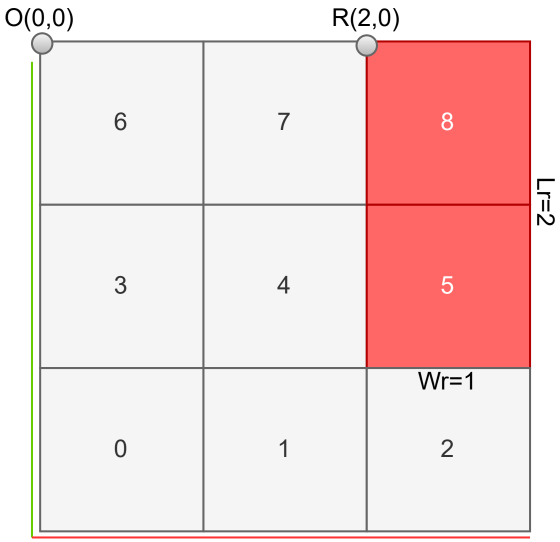

FIG. 4.18 Integer-coordinate of the layout model (Room R is placed on x=2, y=0 with length=2 and width=1 so that room R is assigned to mesh faces indexed by 5 and 8)

4.3.3.2 Closeness Objective

For this purpose, a binary closeness matrix is given between room **i** and **j**, denoted by $T_{i,j}$. This matrix consists of zeros and ones considering the closeness relationship between sub-units of each level. This objective is formulated as:

$$\text{if} \quad T_{i,j} = 1; \quad \min_{x,y} d_{i,j} = \left|x_i - x_j\right| + \left|y_i - y_j\right| \quad \forall i,j \in \left[0,n\right)$$

where “*num_rooms*” is the number of rooms on each level. This is one of the other differences between our approach with the recent works in the literature using MILP such as [300]: they only consider the distance in corridor generation and we use it also in-room space allocation. Thus, this is an additional objective in our zoning stage because rooms are defined with integer coordinates.

CODE 4.1 Closeness objective

```
#closeness objective
$\min_{x,y} \sum_{(i,j)\in E} d_{i,j} = \sum_{(i,j)\in E} |x_i - x_j| + |y_i - y_j|$
def ClosenessObj (x,y,num_rooms, T):
  k=0
  d=0
  for i in range(num_rooms):
      for j in range (i+1, num_rooms):
          if T[i][j] ==1:
              if x[i]-x[j]>0:
                  a_1=x[i]-x[j]
              else:
                  a_1=x[j]-x[i]
              if y[i]-y[j]>0:
                  a_2=y[i]-y[j]
              else:
                  a_2=y[j]-y[i]
              d=d+a_1+a_2
  model.Minimize(d)
```

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4.3.3.3 Space Area Requirements

There are two basic parameters as width and length of the building plot, which are represented by *W* and *L*, respectively. We control the width and the length of each room using the lower and upper limits, w_{min}, w_{max}, l_{min}, l_{max} where w_{min} and w_{max} are the minimal and the maximal width of space ***i*** while l_{min} and l_{max} are the minimal and maximal lengths of the $\boldsymbol{i}_{th}$ space, respectively. After having obtained the minimum area requirements of each room (verifiable employing a Discrete Event Simulation process such as the one introduced in [195], we define the minimum area requirements for the integer-programming model by defining w_{min}, w_{max}, l_{min}, l_{max} values of each spaces. Since we are dealing with a discrete mesh model, these values correspond to the square area requirements. For example, if space needs 120 m^2 area and one mesh face is 20 m^2; then this space requires a minimum (120/20) of six mesh faces on the grid domain and bounding box constraints of *w* and *l* can be defined accordingly.

$$w_{min_i} < w_i < w_{max_i} \quad for \quad \forall \quad room_i = 1,..,\mathrm{num\_rooms}$$
$$l_{min_i} < l_i < l_{max_i} \quad for \quad \forall \quad room_i = 1,..,\mathrm{num\_rooms}$$

Since there is more than one space, $\boldsymbol{w}_{min}, \boldsymbol{w}_{max}, \boldsymbol{l}_{min}, \boldsymbol{l}_{max}$ values can be defined in an array structure.

CODE 4.2 Space area requirements

```
#blackbox constraints, which also defines space area req.s
wmin= [5,3,3,2,2,2,2,2,2,3,3,3,2,3,1,1,1,1,1,1,3]
wmax= [5,3,3,3,3,3,3,3,3,3,3,6,2,3,1,1,1,1,1,1,3]
lmin= [1,1,1,1,1,1,4,3,6,1,3,8,2,1,1,1,1,1,1,1,2]
lmax= [2,2,2,2,2,2,4,4,6,2,3,8,2,2,1,1,1,1,1,1,2]
```

4.3.3.4 Cohesion between Rooms

Ensuring cohesion between rooms is defined as a constraint to attaching the rooms [327]. As this constraint can be too strict for the problems with too many rooms, we have added a tolerance value t to this constraint to ensure room placements as connected as possible. For this purpose, we introduce two binary decision variables (a_{ij}, b_{ij}) encoding four positioning constraints together corresponding to left (00_b), right (10_b), above (01_b), and below (11_b), which are defined as follows:

$$\begin{array}{llll}
\text{if} & a_{ij}=0 \,\&\, b_{ij}=0; & x_i+w_i+t \geq x_j - W(a_{ij}+b_{ij}) & \text{left}-\text{positioning} \\
\text{if} & a_{ij}=1 \,\&\, b_{ij}=0; & x_j+w_j+t \geq x_i - W(1-a_{ij}+b_{ij}) & \text{right}-\text{positioning} \\
\text{if} & a_{ij}=0 \,\&\, b_{ij}=1; & y_j+l_j+t \geq y_i - L(1+a_{ij}-b_{ij}) & \text{above}-\text{positioning} \\
\text{if} & a_{ij}=1 \,\&\, b_{ij}=1; & y_i+l_i+t \geq y_j - L(2-a_{ij}-b_{ij}) & \text{below}-\text{positioning}
\end{array}$$

these positioning constraints do not necessarily enforce adjacency but only relative positioning constraints. In other words, when some space is to be placed to the right of another one, it does not necessarily have to be immediate to the right of the other space but possibly with other spaces in between. Python script of the cohesion constraint is given below by taking the tolerance value equal to five (faces). The tolerance value controls how wide can a gap between two spaces be concerning the pixel size.

CODE 4.3 Ensuring cohesion constraint

```
#cohesion constraint with tolerance=5
$ g_0(x,y,w,l) \leq 0 $
def cohesion(x,y,w,l,num_rooms, W, L):
  tolerance=5 # define tolerance here
  for i in range(num_rooms):
    for j in range(i+1,num_rooms):
      if a[i,j]==0: # a and b are temporary parameters defined here
        if b[i,j]==0:
          model.Add(x[i]+w[i]+tolerance>=x[j]-W*(a[i,j]+b[i,j]))
        if b[i,j]==1:
          model.Add(y[j]+l[j]+tolerance>=y[i]-L*(1+a[i,j]-b[i,j]))
      if a[i,j]==1:
        if b[i,j]==0:
          model.Add(x[j]+w[j]+tolerance>=x[i]-W*(1-a[i,j]+b[i,j]))
        if b[i,j]==1:
          model.Add(y[i]+l[i]+tolerance>=y[j]-L*(2-a[i,j]-b[i,j]))
```

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4.3.3.5 Adjacent Rooms

Especially in hospitals, some of the partition walls need to be attached. For example, the intensive care unit must be adjoined to the operating theatre recovery room due to the use of common equipment. Therefore, the adjacent room constraint is defined. It is used for two specific areas, which must be specifically adjoined. The following python script is written for two adjacent spaces indexed with $i=1$ and $j=2$. As can be seen in the example in Figure 4.19, Rooms 2 & 3, which have indices 1 and 2 respectively, must be adjacent to each other.

CODE 4.4 Contiguous areas constraint

```
#contiguous areas, repeat it for each couple
$h_0(x,y,w,l)=0$
def AdjacentRooms(x,y,w,l,A,num_rooms):
  for i in range(num_rooms):
     for j in range(i+1,num_rooms):
        if A[i,j]==1: #if i &j must be adjacent:
           b_1 = model.NewBoolVar(‘’) #horizontal or vertical
           b_2 = model.NewBoolVar(‘’) #left/top or right/bottom
           b_3 = model.NewBoolVar(‘’) #full or partial adjacency
           if b_1: #horizontal adjoin
              if b_3:
                 model.Add(y[i]==y[j])
              else:
                 model.Add(y[i]==y[j]+(l[j]-l[i]))
              model.Add(x[i]==x[j]+w[j]).OnlyEnforceIf(b_2) #to the left
              model.Add(x[i]==x[j]-w[i]).OnlyEnforceIf(b_2.Not()) #to the right
           else: #vertical adjoin
              if b_3:
                 model.Add(x[i]==x[j])
              else:
                 model.Add(x[i]==x[j]+(w[j]-w[i]))
              model.Add(y[i]==y[j]-l[i]).OnlyEnforceIf(b_2) #to the top
              model.Add(y[i]==y[j]+l[j]).OnlyEnforceIf(b_2.Not()) #to the bottom
```

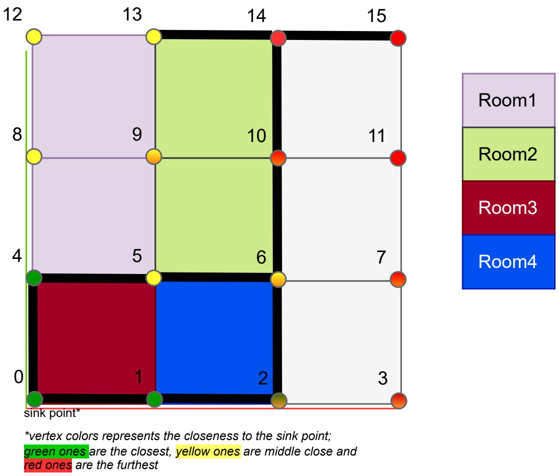

FIG. 4.19 Example layout representation as an output of our computational design tool (four rooms are placed to the faces of a boundary mesh with respect to their area requirements)

4.3.3.6 Fixed Locations

Some of the spaces require fixed or specific locations while also having a relationship with the other spaces. For example, vertical circulation areas or building cores are considered at fixed positions on the grid domain. Their certain coordinates are defined as constrained indices in the model. Python script examples for the space with index 14 are given below e.g. 14th space should be on (x=5, y=6) coordinates. Mathematically this means that some decision variables are predetermined, and so the problem gets somewhat smaller by changing them from variables to constants.

CODE 4.5 Fixed location constraint

```
#fixed positions
$h_1(x,y,w,l)=0$
 def fixed(x,y,C,num_rooms): #the fixed indices are read from the list C
     for k in range(num_rooms):
        if k in C:
           model.Add(x[k]=C[k][0])
           model.Add(y[k]=C[k][1])
##### examples:
#defining fixed locations of elevators
model.Add(x[14]==5)
model.Add(y[14]==6)
```

4.3.3.7 Non-Overlapping Spaces

Non-overlapping constraint prevents two rooms from occupying the same space [327]. We use the same pair of binary decision variables (a_{ij}, b_{ij}) to define this constraint. These requirements can be illustrated as follows. The example python script is given in Code 4.6.

$$\begin{array}{llll}
\mathit{if} & a_{ij}=0\,\&\,b_{ij}=0; & x_i+w_i \le x_j+W(a_{ij}+b_{ij}) & \mathit{left-positioning} \\
\mathit{if} & a_{ij}=1\,\&\,b_{ij}=0; & x_j+w_j \le x_i+W(1-a_{ij}+b_{ij}) & \mathit{right-positioning} \\
\mathit{if} & a_{ij}=0\,\&\,b_{ij}=1; & y_j+l_j \le y_i+L(1+a_{ij}-b_{ij}) & \mathit{above-positioning} \\
\mathit{if} & a_{ij}=1\,\&\,b_{ij}=1; & y_i+l_i \le y_j+L(2-a_{ij}-b_{ij}) & \mathit{below-positioning}
\end{array}$$

CODE 4.6 Non-overlapping spaces constraint

```
#non-overlapping constraint
$ g_1(x,y,w,l) \leq 0 $
def overlap(x,y,w,l,W,L,num_rooms):
  for i in range(num_rooms):
     for j in range(i+1,num_rooms):
        if a[i,j]==0: # a and b are temporary parameters
           if b[i,j]==0: # room i to the left of room j
              model.Add(x[i]+w[i]<=x[j]+W*(a[i,j]+b[i,j]))
           if b[i,j]==1: # room i above room j
              model.Add(y[j]+l[j]<=y[i]+L*(1+a[i,j]-b[i,j]))
        if a[i,j]==1:
           if b[i,j]==0: # room i to the right of room j
              model.Add(x[j]+w[j]<=x[i]+W*(1-a[i,j]+b[i,j]))
           if b[i,j]==1: # room i below room j
              model.Add(y[i]+l[i]<=y[j]+L*(2-a[i,j]-b[i,j]))
```

4.3.3.8 Adjacency to NEWS Borders

Due to natural lighting requirements, discrete entrance requirements, or the necessity of ensuring distinct entrances, we introduce fixed-border constraints to ensure adjacency to borders (boundaries) for some rooms. This constraint is divided into four types: north, south, east, and west. For example, a room is positioned to the “absolutely north” if it is to touch the top border. As an example, to a hospital, a mortuary needs a discrete entrance, and so it should be placed on one of the borders of the grid domain. Similarly, patient wards need natural lighting and so they should be positioned adjacent to the south façade because of hospital design standards and due to the positive effects of daylight on the patient recovery process.

CODE 4.7 Adjacency to NEWS border constraint

```
#adjacency to NEWS border 0: ‘North’, 1: ‘South’, 2: ‘East’, 3: ‘West’, the
following is enforcing adjacency of the, space 1 to south, space 2 to east
$h_2(x,y,w,l)=0$
def NEWS(x,y,w,l,B, num_rooms):
  for k in range(num_rooms):
     if k in B:
        if B[k]=0:
           model.Add(y[k]==0) # space k to the North façade
        if B[k]=1:
           model.Add(y[k]+l[k]==L) #space k to the South façade
        if B[k]=2:
           model.Add(x[k]+w[k]==W) #space k to the East façade
        if B[k]=3:
           model.Add(x[k]==0) #space k to the West façade
```

4.3.3.9 Flexibility Requirements

In hospitals, planning for future expansion is important. For example, space requirements for laboratories tend to double every 10 years according to the hospital design guidelines [177]. This type of space should be flexible. Our design strategy for flexible spaces is listed as follows:

- if vertical expansion: place it on top
- if horizontal expansion (geometric and modular): place it on the perimeter and later add up some extra building modules when expansion needed

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- place it close to temporary spaces where their functions can be later changed e.g. exhibition hall

The first point can be ensured during the stacking stage by placing the space that needs future expansion on the top level. The second point can be ensured with adjacency to NEWS borders constraint (h_2) by putting the space that can need future expansion at one of the borders. For the third point, we define an exhibition hall area in the hospital and place it adjoined to the space that needs flexibility using the adjoining areas (adjacent rooms h_0) constraint. If the space needs an expansion then we can convert the exhibition hall's function to this space's function.

4.3.3.10 Privacy/Community Requirements

Our design strategy for private or communal spaces:

- communal spaces will be on the lower floors (close to the main entrance)
- private spaces should be carried away from the core or the main entrance

This requirement ensures closeness objective (d_{ij}) as core and main entrances are considered functional units that are occupying areas on the grid domain.

4.3.3.11 Boundary Constraint

Boundary constraint forces a room to be inside a boundary:

$$
\begin{aligned}
&\mathrm{x_i + w_i \le W} \quad \text{for} \quad \forall \quad \mathrm{room_i = 1, \ldots, num\_rooms} \\
&\mathrm{y_i + l_i \le L} \quad \text{for} \quad \forall \quad \mathrm{room_i = 1, \ldots, num\_rooms}
\end{aligned}
$$

CODE 4.8 Boundary constraint

```
#boundary constraint
$ g_2(x, y, w, l) \le 0 $
def boundary(x, w, y, l, num_rooms,W, L):
  for i in range(num_rooms):
     model.Add(x[i]+w[i]<=W)
     model.Add(y[i]+l[i]<=L)
```

4.3.4 Generating Corridors

After the rooms are positioned, the main circulation routes within the rooms are created in this stage utilizing Integer Programming. The decision variables of the problem are Boolean variables that indicate the active or inactive status of the mesh edges. The logic of selecting the active edges as decision variables for a network design is inspired by the [300]. Our corridor model is created based on typical hospital layout requirements. The details of the Integer Programming model are given in Algorithm 4.4 and explained in the next sub-sections. Example corridor representation in CAD environment can be seen in Figure 4.21.

ALGORITHM 4.4 Routing and Corridor Generation based on Assigned Room

Input Notation	[Data-Structure] Data Type	Input Name: Notes
$M(V,E,F)$	Quad Mesh	**Space:** A map consisting of vertices, edges, and faces, of which edges are to be assigned to corridors
$[T_{i,j}]_{n\times n}$	Matrix of Float	**Closeness Matrix:** indicating closeness in network space, if $T_{i,j} > 0$ then a corridor needs to be generated between $i \& j$
$[R_{i,f}]_{n\times\|F\|}$	Matrix of Boolean	**Face Assignment Matrix:** indicating Face Regions in its rows
σ	Integer	**Sink Index:** a face index of the sink area, e.g. an elevator/stair core or the main entrance.
$\mathcal{A}$	Set of (Integer, Integer, Integer)	**Alternative Corridors (Optional Input):** a tuple of integers in the form of (o,d,k) where k is the number of shortest paths to be found as alternative paths, and $o \& d$ respectively denote origin and destination indices. Reasons for separating routes could be hygiene, privacy, and work efficiency for staff.
Output Notation	**[Data-Structure] Data Type**	**Output Name: Notes**
$\boldsymbol{p} = [p_e]_{\|E\|\times 1}$	Vector of Boolean	Edge to Corridor Assignment Vector: indicating which edges are to be designated as corridors in the whole floor plan.
$\Gamma(\bar{V},\bar{E})$	Graph	A graph connecting some of the mesh vertices $\bar{V} \subset V$ through some of the edges $\bar{E} \subset E$ marked as being parts of the corridors (True) in the above vector of Edge to Corridor assignment. This graph is used to compute the network distances below.
$[D_{i,j}]_{n\times n}$	Matrix of Integer	Graph Distance Matrix: containing the actual distances between rooms based on the found corridors

>>>

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ALGORITHM 4.4 Routing and Corridor Generation based on Assigned Room

Problem: given the input space as a map of vertices, edges, and faces, find an assignment of edges to corridors as paths, such that the sum of graph distances between close pairs and the angle between active graph edges is minimized (way-finding objective), subject to several validity constraints: namely ensuring all rooms to be accessible through a corridor, inner-edges (those passing through rooms) to be excluded from the corridor graph; the continuity of the paths to be ensured; and that every room is accessible from the sink through a path. The problem-solver method can take the problem in the [minimization] standard ILP form:

$\min_{p} \alpha(\Theta 1)^{T} p + (1-\alpha) d^{T} p$

subject to:

$h(p) = 0$ %equality constraint for alternative corridors

$g_l(p) \leq 0,\ l = 0,1,2,3,4$ %validity constraints

$p \in \{0,1\}^{|E|}$

where α is a weighting factor for enforcing the simple paths objective.

Procedure Routing & Corridor Generation:

```
1. For the $m_{th}$ floormesh $M$
2. Define Mesh with several faces along {x} direction: $f_1$ ;and faces along {y} direction: $f_2$
3. Get outputs of the Zoning model ($[R_{i,f}]_{n\times|F|}$) of the $m_{th}$ floor as an input of the Routing model
4. Enter REL Chart matrix T showing the predicted flow between spaces
5. Enter the number of spaces (rooms): num_rooms; the number of edges:$|E|$; the number of vertices: $|V|$
6. Define decision variables:
   $[p_e]_{|E|x1}$ s.t. $p_e = \begin{cases} 1, & if\ \ edge_e\ \ allocated\ \ to\ \ corridors,\ \ e \in [0,|E|) \\ 0, & otherwise \end{cases}$
8. Generate objective function (details are in sub-section: way-finding objective)
7. Generate constraints (details are in sub-sections related to separate routings and validity)
9. Run the model
10. Get $\mathrm{Edges}[e], \Gamma, [D_{i,j}]_{nxn}$ values and visualize the allocated edges as 3D corridors on the $m_{th}$ floor
11. $m \leftarrow m-1$ and go back to Step 2 and repeat until all floors are finished
```

4.3.4.1 Way-Finding

This objective is very important for minimizing distances and path complexity in the outpatient area of hospitals for first-time visitors and patients who are unfamiliar with the hospital. We define this objective to minimize zig-zags and path lengths (distances from each active edge to the main entrance) which is one of the Wayfinding Cost Terms defined in [328]. The reason for minimizing path length (distance from the sink [main entrance]) is that pedestrians, in general, prefer to walk a short distance [329], [330], and [331]. On the other hand, this provides to decrease the number of nodes in the network. The nodes in our formulation correspond to decision points in the wayfinding literature [329]. Decision points are locations where pedestrians need to decide about which direction to go or where pedestrians need to confirm the identity of the current location. Directional or identification signs need to be placed at decision points to guide pedestrians to find their directions [329], [332], or identify their current locations. Paths with lots of

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decision points should be avoided [333] as making each navigation decision induces stress to the pedestrians for the fear of making a wrong decision that may lead to a wrong place [333], [334]. Minimizing zigzags is equivalent to decreasing network turns. Research in spatial orientation [335] suggests that paths with varying orientations tend to confuse pedestrians in wayfinding, causing disorientation, anxiety, and discomfort [336]. A wayfinding scheme composed of straight paths is more intuitive for navigation [337]. Another reason for minimizing path length (distance from the sink [vertical circulation core]) is to facilitate egress in case of emergencies such as fire. For formulating this objective, firstly we need to find the angle between all pairs of edges in the base mesh as shown in the python script in Code 9.

CODE 4.9 Forming a lookup table of angles between all pairs of adjacent edges

```
import rhinoscriptsyntax as rs
import math
import csv
def Theta(M, csvMeshEETopology):
  ang=[M.TopologyEdges.Count*[0] for e in range(M.TopologyEdges.Count)]
  adjacentedges=csv.reader(csvMeshEETopology) #reading adjacent edges from a csv
file
  for ij in range(M.TopologyEdges.Count):
     IJPair = M.TopologyEdges.GetTopologyVertices(ij)
     i = IJPair.I #vertex index i
     j = IJPair.J #vertex index j
     EV1=M.TopologyVertices[j]-M.TopologyVertices[i]
     for ab in range(len(adjacentedges[ij])):
        ABPair = M.TopologyEdges.GetTopologyVertices(adjacentedges[ij][ab])
        a = ABPair.I #vertex index a
        b = ABPair.J #vertex index b
        EV2=M.TopologyVertices[b]-M.TopologyVertices[a]
        ang[ij][ab]=int(abs(math.degrees(math.atan2(v1.Y, v1.X) - math.atan2(v2.Y,
v2.X))))
  return ang #a sparse matrix of angles between adjacent edges denoted as $Θ$
```

Then, we need to define the objective that minimizes the sum of the angle between each active edge and its active adjacent edges:

CODE 4.10 Zig-zag objective (wayfinding)

```
#zig-zag objective
$\min_{p}(\Theta 1)^{T} p$
def SimpleWaysObjective(edges, angle):
  total_sum=0
  for e in all_edges:
     total_sum=total_sum+sum(edges[e]*angle[e])
#angle is a list of angles of incidence between the e_th edge and its adjacent/
active edges
  model.Minimize(total_sum)
```

Another objective that contributes to the ease of wayfinding is minimizing the distance to sink (main-entrance vertex point) from each edge as shown below.

CODE 4.11 Calculating edge distances to the sink vertex

```
def distances(G, vlist, Sink):
  vlist=readfile(‘C:\\Users\\TOSHIBA\\Desktop\\files\\vertex.csv’)
  vertexindex=vlist
  G.add_edges_from(vertexindex)
  #distance from all vertices to sink vertex
  Sink=0
  Ds=nx.single_source_dijkstra_path_length(G,Sink)
  n = M.TopologyEdges.Count
  list edge_distance = [None] * n #populate list, length n with n entries “None”
  for ij in range(M.TopologyEdges.Count):
     IJPair = M.TopologyEdges.GetTopologyVertices(ij)
     i = IJPair.I
     j = IJPair.J
     #distance from each edge to sink vertex
     edge_distance[ij] = Ds[j]
  return edge_distance #a vector of edge distances towards the sink vertex denoted
as $d|E|x1$
```

CODE 4.12 Distance to sink objective (wayfinding)

```
#distance to sink objective
$\min_{p} d^{T} p$
def ShortWaysObjective(edges, edge_distance):
  model.Minimize(sum(edge_distance[e] * edges[e] for e in all_edges))
```

4.3.4.2 Route Separation

This requirement is defined as an equality constraint in the corridor design model because of such things as cleanliness, privacy, and working efficiency. Technically, we set to turn on the indexes of all edges to be included in an alternative shortest path in the assignment of edges to corridors. Regarding the cleanliness issue, we aim to separate the routing of the dirty waste and the medical staff such as the critical materials routing between CSSD (central sterile services department) and OT (operation theatre). Regarding the privacy issue, we aim to separate public corridors from private spaces such as the mortuary and elevators area. Regarding working efficiency, we aim to prevent unwanted interruptions of medical staff by relatives such as defining two different routes for doctors and relatives in the inpatient area. Our preliminary research resulted that patients' relatives are likely to stop and ask an employee for directions or the situation of the patients very frequently. Therefore, separating the routing between waiting areas and doctors' rooms and nursing units (wards) is important for keeping medical staff focused, productive, and free from interruptions. For formulating this constraint, we define alternative paths between two rooms that are used by different types of people or materials. In this way, different users will use different paths and their routes will not be conflicted. For this aim, we use the k-shortest path idea described in Figure 4.20.

```
– Considering n-edges that generate a path between room 1 and room 2:
– For all paths in k-shortest paths between room1 and room2:
– If a path in k-shortest paths does not include inner edges:
    – If vertices of each path are different than other path's vertices, except the first vertex and the last vertex (because they are origin and destination vertices):
– These all paths' edges are set as active (1) in $p$.
```

FIG. 4.20 k-shortest path idea pseudo code

As an example (see figure 4.21), between room-1 and room-4, which are located at vertex 5 and 12 respectively, we will create two different paths that are not conflicting with each other. Providing that two alternative routes (n=2) between room-1 and room-4 and the inner edge's index is 10. Then, path-1 edges' indices can be 7, 8, and 15; path-2 edges' indices can be 7, 8, 14, 17, and 21.

CODE 4.13 Defining shortest-1 and shortest-2 routes between start and finish nodes

```
start=48 #defining the index of start point
finish=110 #defining the index of finish point
def k_shortest_paths(G, source, target, k, weight=None):
  return list(islice(nx.shortest_simple_paths(G, source, target, weight=weight), k))
R=[]
R=k_shortest_paths(G,start,finish,30) #find shortest1 and shortest2
#convert k_shortest vertices to k_shortest edge indices
lt=[]
edg=[]
for t in range(0,len(R)):
  edg.append([])
  del lt[0:len(lt)]
  lt.extend(R[t])
  for i in range(len(vertexindex)):
     for k in range(len(lt)-1):
        if lt[k]==vertexindex[i][0] and lt[k+1]==vertexindex[i][1]:
           edg[t].append(i)
#find two shortest paths between start and finish which don’t include inner edges
for t in range(0,len(edg)):
  del list1[0:len(list1)]
  list1.extend(edg[t])
  for m in range(0,len(edg[t])):
     for v in range(0,len(inneredges)):
        if (edg[t][m] == inneredges[v]):
           del list1[0:len(list1)]
  if len(list1) > 0:
     indx=t #index of list1 in R[t][m]
     break
for t in range(indx+1,len(edg)):
  del list2[0:len(list2)]
  list2.extend(edg[t])
  for m in range(0,len(edg[t])):
     for v in range(0,len(inneredges)):
        if (edg[t][m] == inneredges[v]):
           del list2[0:len(list2)]
  if len(list2) > 0:
     indx=t #index of list2 in R[t][m]
     break
print(list1)
print(list2)
```

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After reading list1 and list2 as edge indices of shortest_1 and shortest_2, the constraint is defined in the model as follows:

CODE 4.14 Defining two different routes between pairs of rooms constraint

```
for i in range(len(shortest1)):
 model.Add(edges[shortest1[i]]==1) #edge indices of shortest path 1 are active
for j in range(len(shortest2)):
 model.Add(edges[shortest2[j]]==1) #edge indices of shortest path 2 are active
```

4.3.4.3 Validity Constraints

Corridors cannot pass through the inside of the room and each room must connect to at least one corridor as defined in Code 4.15 and Code 4.16.

CODE 4.15 Validity constraint #0, Inner Edges

```
#a room cannot have corridors in its interior
$ \boldsymbol{g}_0(\boldsymbol{p}) \leq 0 $
def g_0_Integrity(edges, all_rooms, inneredgesindex):
for n in all_rooms:
 for j in range(len(inneredgesindex[n])):
   model.Add(edges[inneredgesindex[n][j]]==0)
```

CODE 4.16 Validity constraint #1, Boundary Edges

```
#a room has to be connected to a corridor, i.e. at least one of the boundary edges
of each room must be active
$ \boldsymbol{g}_1(\boldsymbol{p}) \leq 0 $
def g_1_Accessibility(edges, all_rooms, boundaryedgesindex):
 for n in all_rooms:
   model.Add(sum(edges[boundaryedgesindex[n][t]] for t in
range(len(boundaryedgesindex[n])))>=1)
```

Another validity constraint is related to connectivity, which does not allow loop corridors. It was created by referring to TSP [338]–[340] as shown in Code 4.17.

CODE 4.17 Validity constraint #2, Corridor Connectivity

```
#connectivity constraint
$ g_2(p) \leq 0 $
def g_2_Connectivity(edges, adjacentedges):
 for e in all_edges:
    model.Add((edges[e]-sum(edges[adjacentedges[e][v]] for v in
range(len(adjacentedges[e]))))<=0)
```

Connection to sinks is another constraint that ensures the accessibility of the entire network from a sink point (a sink node could be the main entrance for the ground level or an elevator area for the other levels).

CODE 4.18 Validity constraint#3, Reachability of Sink

```
#reachability of sink (one of the sink-incident edges must be active)
$ g_3(p) \leq 0 $
def g_3_Connectivity(edges, sink, edgeToVertexIncidence):
 sinkEdges= edgeToVertexIncidence[sink]# sink-incident edges
 model.Add(sum([edges[sinkEdge] for sinkEdge in sinkEdges])>0)
```

In addition to the main circulation path, we defined some 'collector roads', which provide access to the main circulation path as well as short access between interrelated rooms using T_{ij}.

CODE 4.19 An optional constraint to enforce when it is desired to ensure short access between adjacent rooms

```
#collector roads
$ g_4(p) \leq 0 $
V=[95,88,62,91,110,39,41,112,114,73,66,80,116,90,117,58,37,36,55,49,60,48,59,61,50,
81] #rooms top left vertices
def g_4_Collectivity(edges, V, num_rooms, G, T, vertexindex, inneredges):
 R=[]
 for a in range(num_rooms):
    for b in range(a+1,num_rooms):
       if T[a][b]==1: #T is adjacency matrix
          R=k_shortest_paths(G,V[a],V[b],30)
          list1=[]
          #convert k_shortest vertices to k_shortest edge indices
          lt=[]
```

```
       edg=[]
       for t in range(0,len(R)):
         edg.append([])
         del lt[0:len(lt)]
         lt.extend(R[t])
         for i in range(len(vertexindex)):
           for k in range(len(lt)-1):
             if lt[k]==vertexindex[i][0] and lt[k+1]==vertexindex[i][1]:
               edg[t].append(i)
#find shortest path between start and finish which don't include inner edge
for t in range(0,len(edg)):
       del list1[0:len(list1)]
       list1.extend(edg[t])
       for m in range(0,len(edg[t])):
         for v in range(0,len(inneredges)):
           if (edg[t][m] == inneredges[v]):
             del list1[0:len(list1)]
       if len(list1) > 0:
         indx=t #index of list1 in R[t][m]
         break
for m in range(len(list1)):
 model.Add(edges[list1[m]]==1)
#the shortest edges between interrelated rooms will be active by this constraint
```

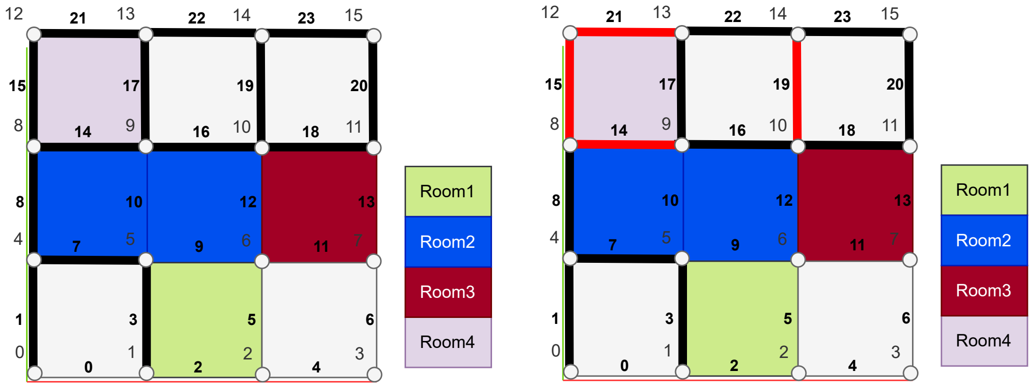

FIG. 4.21 Left: Example corridor representation as an output of our computational design tool; Right: Black lines refer to the main circulation path, red lines refer to collector roads

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4.3.5 Tool Implementation

The workflow presented in this paper has been implemented within a popular computational design platform (Rhino3D+Grasshopper3D), as a laboratory and testbed environment; and developing our tools using Python within Anaconda Spyder as an Integrated Development Environment (IDE). The codes are written in GHCPython and GHPython in Grasshopper 3D. Rhino is used for input processing and output visualization. All the algorithms presented in this paper are implemented in the GHPython nodes connected in the structured workflow diagram inside Grasshopper3D. A summary of this workflow is abstracted and illustrated in Figure 4.22. The partial components are illustrated in Figure 4.23 and Figure 4.24. We have used NumPy, Matplotlib, and NetworkX python libraries for the implementation of spectral clustering methods in the stacking stage. Used libraries (all free) in Python components at zoning and routing stages are listed below:

- Google or-tools integer programming tool-> CP-SAT solver [341]
- Pandas
- Sci-kit learn
- NetworkX
- Csv (for data-stream between different components)
- Random
- Numpy

One important note about the Google OR-Tools (Operations Research Tools) is that the models built with this library can also accept Linear Programming problems that are only partially linear (such as the absolute function). We do this effectively by adding conditional statements to the model-building algorithms (as shown in Code 4.1, Code 4.2, Code 4.3, Code 4.4, etc.) that would activate/deactivate partially some of the objectives or constraints that are all linear partially but not linear as a whole function. The possibility of adding these conditional statements means that this tool suite is more flexible than a tool suite that can only work with the canonical formulation of LP/MIP problems. The statements model.Add() in this tool suite is used for adding constraints and statements in the form of the model. Minimize() accept objective functions as input arguments. Additionally, statements in the form of model.NewBoolVar() and model.NewIntVar() are respectively used for adding Boolean and Integer decision variables. This tool consists of 6 components with component-0 for data preparation and a series of modules for visualizations. Between each component, all data streams are successfully realized by reading & writing csv files using both csv and pandas libraries.

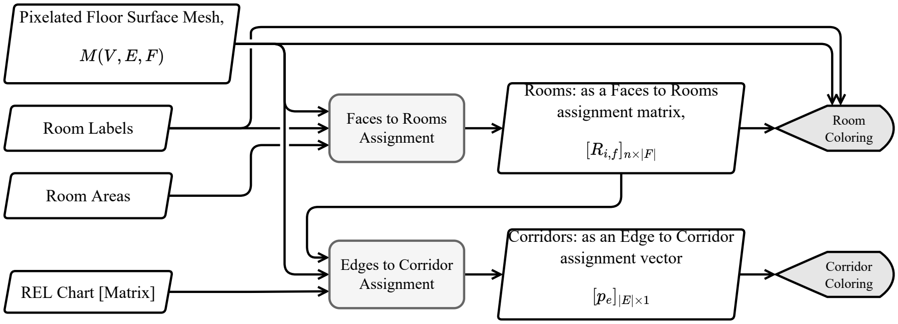
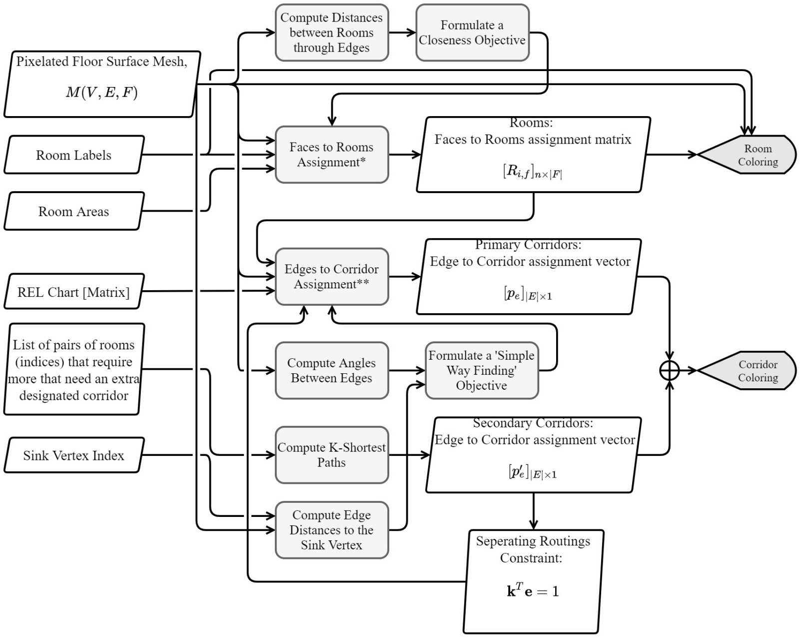


FIG. 4.22 General picture of the whole GH model including both zoning and corridor generation steps



* All zoning constraints are defined in "Faces to Rooms Assignment" module

** All validity constraints in corridor generation are defined in "Edges to Corridor Assignment" module

FIG. 4.23 Workflow of partial components of our computational design tool for new hospital layout designs

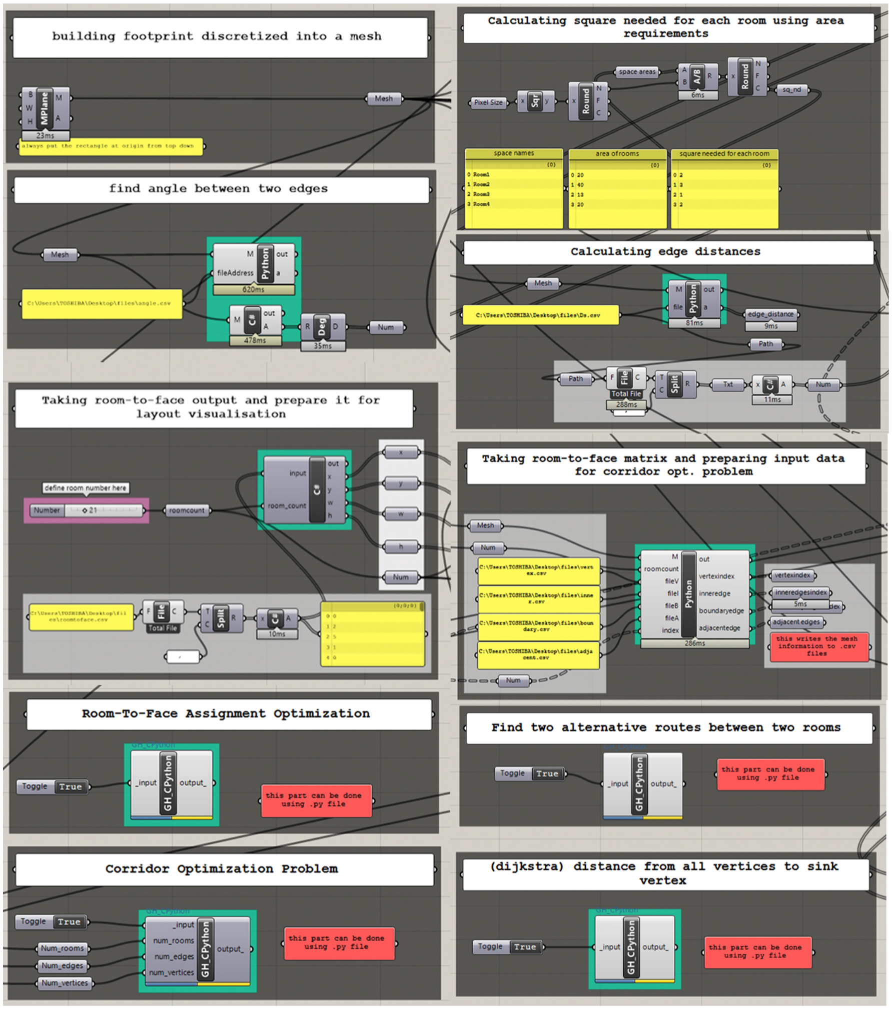


FIG. 4.24 Partial components of our computational design tool for new hospital layout designs in GH canvas

As a small case example to the tool implementation, for a building footprint discretized into a mesh with sizes of W=3 and H=3, the task is to locate 4 rooms with a $T_{ij}=[[0,1,1,1], [1,0,0,1],[1,0,0,0],[1,1,0,0]]$, $w_{min}=\{2,1,2,2\}$, $w_{max}=\{2,1,2,2\}$, $h_{min}=\{1,1,1,1\}$, $h_{max}=\{1,1,1,1\}$. Regarding the defined constraints, Room 1 and Room 2 are adjoined (using the constraint explained in 4.3.3.5) and the fixed location constraints are $x_0=0$; $y_0=0$; $x_2=1$. Fixed border constraint is defined as $x_1+w_1<=W$ where $x_i=[0,3]$, $y_i=[0,3]$ for all i=0,..,NA where NA is the number of rooms. As can be seen in the optimized result in Figure 4.25, rooms 1and 2 are adjoined, and room 1 is located to the {0,0} coordinates all of the size constraints are handled and the result is optimal. The computational result is given in Table 4.6 and the sensitivity analysis result is given in Table 4.7.

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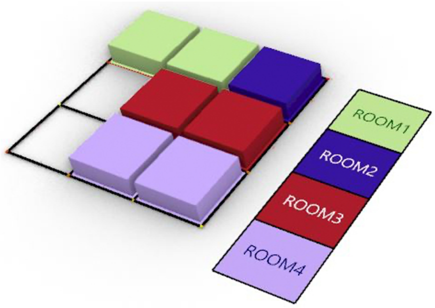

FIG. 4.25 A small example of optimized result of the zoning problem

TABLE 4.6 Computational result of zoning problem for a small case

	Result:
	index 0
x	0
y	0
w	2
h	1
	index 1
x	2
y	0
w	1
h	1
	index 2
x	1
y	1
w	2
h	1
	index 3
x	1
y	2
w	2
h	1
a_{ij}	{(0, 0): 0, (0, 1): 0, (0, 2): 1, (0, 3): 1, (1, 0): 0, (1, 1): 0, (1, 2): 1, (1, 3): 1, (2, 0): 0, (2, 1): 0, (2, 2): 0, (2, 3): 1, (3, 0): 0, (3, 1): 0, (3, 2): 0, (3, 3): 0}
b_{ij}	{(0, 0): 0, (0, 1): 0, (0, 2): 1, (0, 3): 1, (1, 0): 0, (1, 1): 0, (1, 2): 1, (1, 3): 1, (2, 0): 0, (2, 1): 0, (2, 2): 0, (2, 3): 1, (3, 0): 0, (3, 1): 0, (3, 2): 0, (3, 3): 0}
	status: OPTIMAL
	conflicts: 0
	branches: 0
	wall time: 0.001015

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TABLE 4.7 Sensitivity analysis

Global optimal solution found.
Objective value: 10.00000
Objective bound:10.00000
Infeasibilities: 0.000000
Extended solver steps: 0
Total solver iterations: 4
Elapsed runtime seconds: 0.03
Model Class:PINLP
Total variables:13
Nonlinear variables:5
Integer variables:13
Total constraints:21
Nonlinear constraints:1
Total nonzeros:48
Nonlinear nonzeros:5

Variable	Value	Reduced Cost
X0	0.000000	0.000000
X1	2.000000	0.000000
Y0	0.000000	0.000000
Y1	0.000000	0.000000
X2	1.000000	0.000000
Y2	1.000000	0.000000
X3	1.000000	0.000000
Y3	2.000000	0.000000
W0	2.000000	2.000000
H0	1.000000	2.000000
H1	1.000000	1.000000
H2	1.000000	2.000000
W1	1.000000	0.000000
W2	2.000000	0.000000
W3	2.000000	0.000000
H3	1.000000	0.000000

>>>

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TABLE 4.7 Sensitivity analysis

Row	Slack or Surplus	Dual Price
1	10.00000	-1.000000
2	5.000000	0.000000
3	5.000000	0.000000
4	4.000000	0.000000
5	5.000000	0.000000
6	4.000000	0.000000
7	5.000000	0.000000
8	0.000000	1.000000
9	0.000000	-1.000000
10	1.000000	0.000000
11	0.000000	0.000000
12	0.000000	0.000000
13	0.000000	0.000000
14	2.000000	0.000000
15	2.000000	0.000000
16	1.000000	0.000000
17	0.000000	0.000000
18	0.000000	-1.000000
19	0.000000	2.000000
20	0.000000	2.000000
21	1.000000	0.000000
22	0.000000	1.000000
23	1.000000	0.000000
24	0.000000	2.000000

As presented in Table 4.7, fixed location constraints for x_0, $y_{0,}$ and x_2 (Row 8,9,18), have an impact on the solution value when the right-hand side value of the constraints changed e.g. when increasing the RHS of the first fixed location constraint ($x_0=0$) to one, then the objective value (distance minimization) will be decreased by dual price=1. Likewise, the dual price of the non-intersecting constraints between Rooms 1&2 (Row 19), between Room 1&3 (Row 20), Room 2&3 (Row 22), and between Rooms 3&4 (Row 24) have non-zero values so that they affect the objective value. Other than these constraints like connectivity constraints, boundary constraints, and non-intersecting constraints between Room 1&4 and Room 2&4 have a zero dual price thus, changing the right-hand side a small amount will not affect the solution value. When decision variables result analyzing, it is observed that w_0, h_0, $h_{1,}$ and h_2 values have non-zero reduced costs (2,2,1,2 respectively). Therefore, we can say that the sizes of Room 1 have a great impact on the objective value as well as the height of Room 2 & Room 3.

4.3.6 Case Study: Hospital-B

Due to security reasons, we call the case study hospital as Hospital-B. Existing Hospital-B has 55 inpatient beds where 10 of which are in single-patient rooms. The side of the existing Hospital-B is not earthquake-resistant. Therefore, the existing hospital will be demolished and the new one will be built in a new place in the same district in Turkey. The new hospital is planned to have 75-100 inpatient beds and it will be classified as the 3rd level hospital in Turkey. Levels of hospitals are changing in Turkey according to the property of rooms. The higher the number of rooms with single beds, the higher the level of the hospital. Polyclinics in the new hospital are listed as Emergency, Ear-Nose-Throat, General Surgery, Orthopaedics, Pulmonary, Internal Medicine, Dermatology, Psychology, Cardiology, Eye, Child, Obstetrics, Infection, Tooth, Physiotherapy, Urology, Neurology. Services in the new hospital are medical units and surgical units. Diagnostic units in the new hospital are Radiology, Laboratory, Tomography, and Blood Center. The new hospital will have one ICU with 10 beds and 4 operation rooms while the existing one has 4 ICU beds and 4 operation room beds. In the hospital, frequent operations in the OT are eye operations 2 days a week, ear-nose-throat operations, and tooth operations 4 dentists (2 rooms: 1 is in one room and 3 are in one room). Other than these, the site area is a touristic place and very close to other touristic places. During summertime, Hospital B takes many patient transfers from a University Hospital located in the city center because of its limited capacity and frequent traffic accidents around the place. Future expansion of the hospital is very important because the city is in development. The new hospital's place is very close to the historical sides. Before planning the layout of the new hospital, the program of requirements of Hospital B is defined based on the methodology presented in [195]. Mainly, Turkey's hospital design standards are considered in this paper during this part. The minimum area requirements of each sub-unit are given in Table 4.8. In this table, the number of faces (in the form of the square) needed for each sub-unit is also calculated. Since each edge of the boundary mesh is 6 m, we divided the area requirement into 36 and get the minimum number of square faces for each unit in Hospital-B. We have divided the desired surface area of each unit by the area of a [pixel-like] mesh face and rounded up these values to end with integer surface values as shown in Table 4.8.

TABLE 4.8 PoR of Hospital-B [195]

Main-Units	Sub-Units	Area (M^2)	Number Of Faces
Outpatient	Ear-Nose-Throat	56	2
	General Surgery	56	2
	Orthopedics	56	2
	Eye	28	1
	Obstetrics	56	2
	Tooth	56	2
	Urology	56	2
	Pulmonary	56	2
	Internal Medicine	56	2
	Dermatology	28	1
	Psychology	28	1
	Cardiology	56	2
	Child	56	2
	Infection	56	2
	Physiotherapy	56	2
	Neurology	56	2
Inpatient	Medical Inpatient	555	16
	Surgical Inpatient	555	16
Icu	Wards, Waiting Areas	270	8
Ot	Operation Rooms, Post Anaesthesia Recovery, Scrub-Up Etc.	500	14
Emergency	Beds, Diagnostic, Waiting, etc.	900	25
Diagnostic	Radiology	56	2
	X-Ray & (Tomography)	56	2
	Ultrasound	56	2
	Laboratory	56	2
	Blood Centre	56	2
Administration	Business, Accounting Vs.	180	5
	Hospital Management Offices	110	4
Entrance	Welcome Desk	50	2
	Information Desk	50	2
	Cafeteria	75	3
Support	Worship Places	50	2
	Pharmacy	75	3
	Housekeeping	150	5
	Storages	150	5
	Kitchen Dining	150	5
	Parking Area	1312	37
	Bunker	120	4
	Mortuary	75	3
Total		6419	198

In addition to the units given in this table, the hospital needs more areas for exhibition halls for enabling the flexibility of the hospital. One service core is defined in the center of the building. This core constitutes service areas such as toilets, warehouses, stairs, and fire stairs. The area of a core is 68 m². Values of $w_{min}, w_{max}, l_{min}, l_{max}$ are defined according to this PoR table for each level of the hospital. We consider hospital standards pertained to its spatial planning as follows [222]:

- Outpatient rooms must be min 16 m^2.
- Outpatient waiting areas must be
    - min 12 m^2 for 1 doctor
    - min 24 m^2 for 2 doctors
    - additional 5 m^2 for each additional number of doctors.
- There must be min 6 elevators in 60-200 bed hospitals.
- There must be min 9 elevators in 201-350 bed hospitals.
- One-bed patient rooms must be min 9 m^2.
- Patient wards must be min 7 m^2 per bed.
- One-bed delivery patient rooms must be min 12 m^2.
- Delivery patient wards must be min 10 m^2 per bed.
- ICU units must be min 12 m^2 per bed.
- Neonatal ICU units must be min 6 m^2 per bed.
- Administrative offices must be 8-12 m^2 for each personnel.
- Bunker area = (number of beds) + (number of beds*20%)
- Parking area for healthcare buildings: 125 m^2 closed area = min 1 parking area
- Windows area must be between 1/5-1/7 of the floor area of each inpatient room.
- Stair width 2 m., Step height 17 cm., Step depth 28 cm., Landing width 2 m.

We defined the 6-elevator system in the hospital considering the 3rd bullet of hospital design standards given above; one is a service elevator, one is a dirty elevator, one is for transporting to operating rooms and two are for person elevators. Discrete waiting areas are defined for each outpatient department on the ground level considering the 1st and 2nd bullets of hospital design standards presented above. Calculations are done by assuming 2 doctors in each outpatient department. According to the 13th bullet, the hospital needs 115 parking areas we defined 31 parking areas in the basement and the rest are available in the outside area. Regarding the facade, windows are created based on the 14th bullet. The stairs areas are calculated according to the 15th bullet of the standards.

According to the method introduced in Chapter 4, we defined the stacking of the hospital. Ultrasound, laboratory, blood center, x-ray, radiology, exhibition hall, kitchen & dining, housekeeping, storages, prayer room, pharmacy, parking area, bunker, and mortuary are located on the basement level; all polyclinics with the accompanying waiting areas, emergency, main entrance, and cafeteria are located on the ground level; operation theatre, intensive care units, CSSD, engineering support, delivery units and nursery located on the first floor, administration, medical wards, surgical wards, doctors' rooms, waiting area are located on the second floor in this case study.

On each level, we selected different objectives and constraints concerning the requirements of the sub-units and we used different T_{ij} matrices between sub-units for each level (given in Figure 4.33). For example, in the basement, we considered distance-to-sink (sink: elevator point) minimization of the way-finding objective, and route separation constraint (for separating routing between the mortuary and elevator area for privacy issues). On the ground floor, we considered the angle minimization of the way-finding objective in addition to the distance-to-sink objective because of the unfamiliar visitors who come to the hospital and don't know about their way in the hospital. On the first floor, we considered distance-to-sink (sink: entrance point) minimization and route separation constraints (for separating routing between the central sterile department's dirty materials stocking part and dirty elevator for cleanliness issues). On the second floor, we considered distance-to-sink (sink: entrance point) minimization and route separation constraints (for separating routing between wards and doctors' rooms for work balance issues).

As can be seen in the basement plan, the parking area has a discrete entrance and thus it is located at one of the borders as expected. The blood center, laboratories, and x-ray and radiology departments are adjoined and the exhibition area is located next to the laboratories for future expansion reasons. There are two routes, that pass through the housekeeping between the mortuary and elevator area as expected. The pharmacy is located next to the elevator area for the ease of distribution of medicines. In the ground floor plan, the emergency has a discrete entrance and is located on one façade of the hospital building. Thus, the main entrance and emergency entrance are discretized as expected. The café is also located next to the main entrance. Related outpatient departments are close to others such as general surgery, pediatrics, and obstetrics. In the first-floor plan, ICU is located next to the recovery room of OT (blue pixels), in addition, the delivery unit and nursery share a wall as expected. There are two different routes between the elevator area and CSSD units. In the second-floor plan, all wards have a possibility of having windows as they are located to the borders with an “adjacency to NEWS” constraint. There are two different routes between the doctors' room and medical wards for not passing through the visitors' waiting area as expected from the "route separation" constraint. All of the codes for each floor plan are run on an Intel Core-i7 computer, with 2 GB of RAM. Case-study application results are given in Figure 4.26, Figure 4.27, Figure 4.28, Figure 4.29, Figure 4.30 and Figure 4.31.

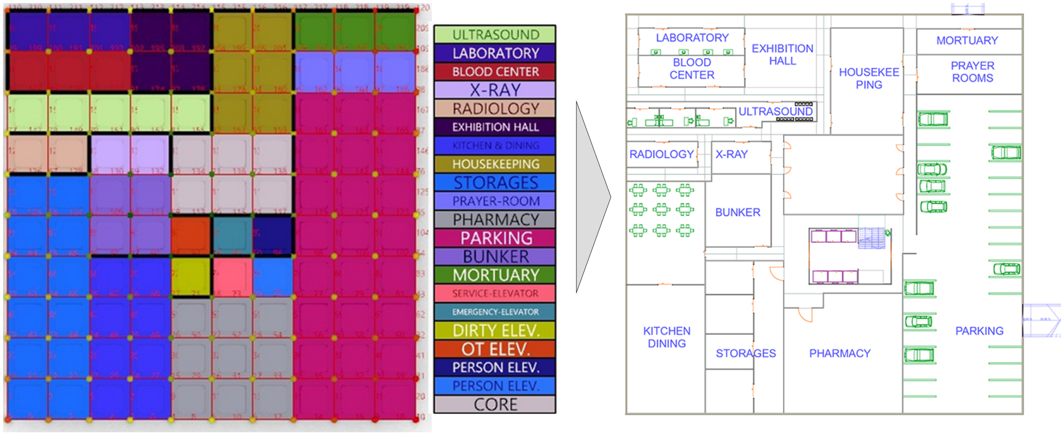

FIG. 4.26 Basement plans (left: output of the tool, right: technical plans)

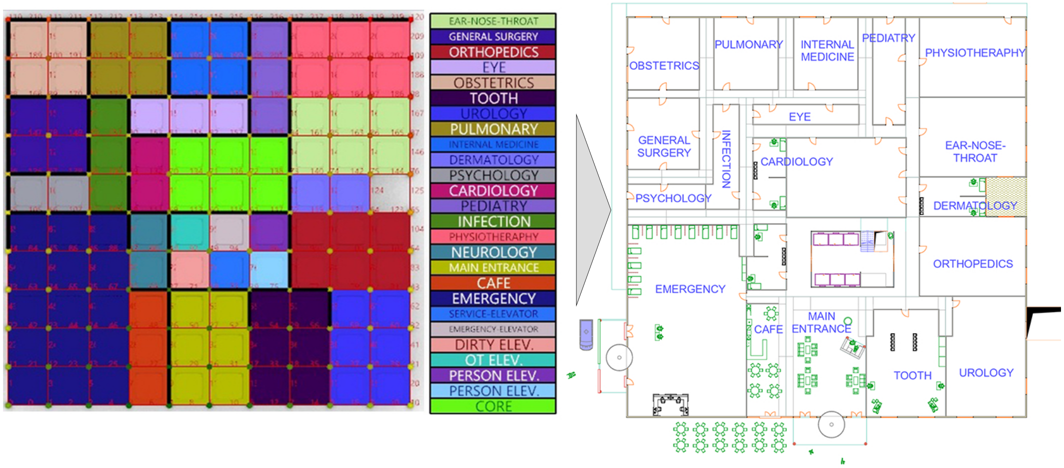

FIG. 4.27 Ground plans (left: output of the tool, right: technical plans)

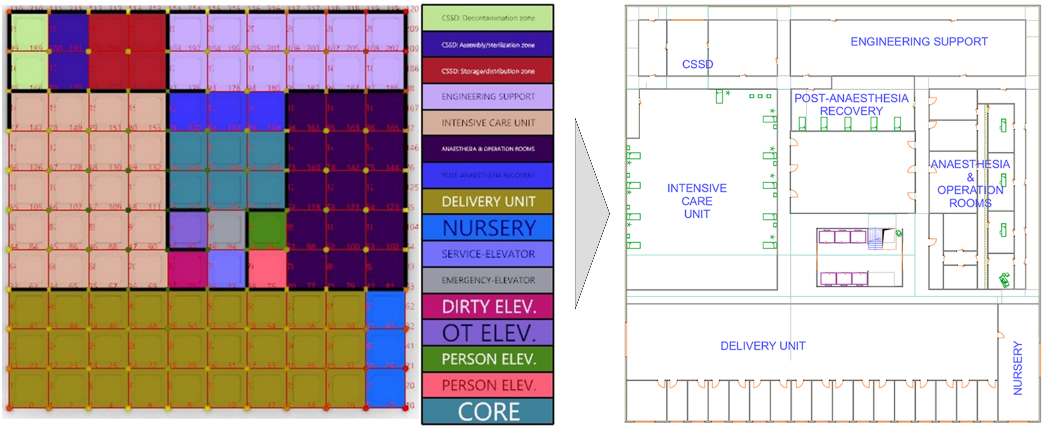

FIG. 4.28 First-floor plans (left: output of the tool, right: technical plans)

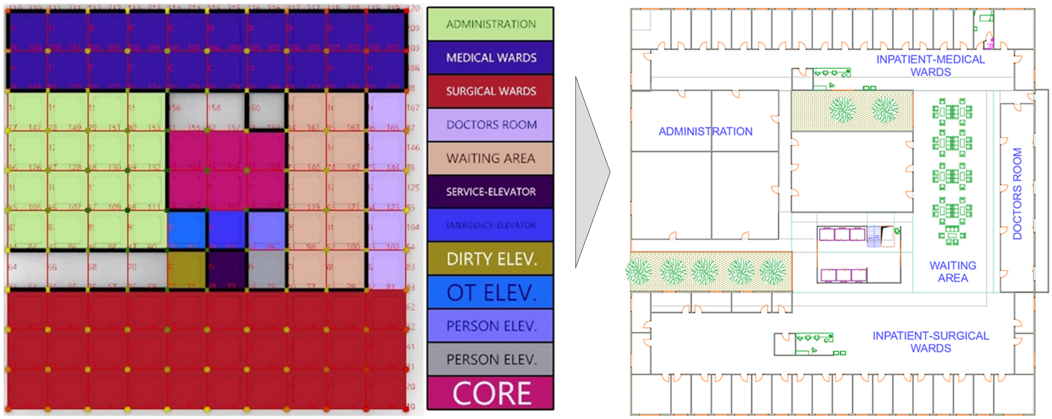

FIG. 4.29 Second-floor plans (left: output of the tool, right: technical plans)

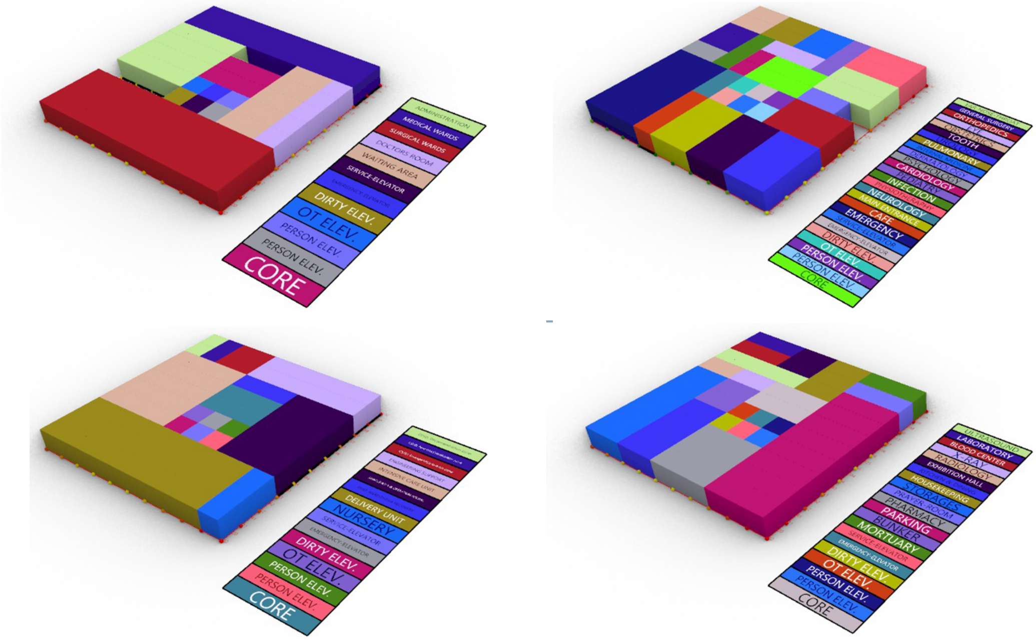

FIG. 4.30 Perspective plans of the hospital obtained by our computational design tool

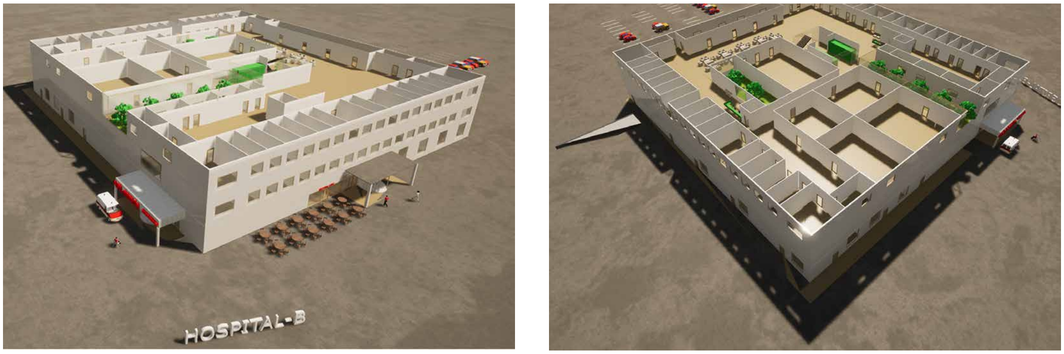

FIG. 4.31 Renders of the case study hospital

4.3.7 Modular Construction

The potential use of modular construction techniques (Figure 4.32) is another advantage of the model developed in this paper. This part of the paper aims to show the outlook of our method for being applied to space planning for the modular construction of hospitals. Our results show clearly that we can generate such modular configurations successfully. Many hospital and healthcare facility contractors are turning to modular, primarily for building components such as bathroom pods and headwalls, however, entire hospitals can be constructed utilizing modular construction techniques [342]. Modular construction offers quiet, safe, and clean applications for medical, surgical, clinical, and dental use and a fast and economical approach. The hospital layout design method based on the discrete mesh presented in this paper can provide a suitable infrastructure for modular construction in the next design stages of hospital buildings.

FIG. 4.32 Modular construction in hospitals example [342]

4.3.8 Conclusion and Discussion

We presented a formulation of the hospital layout problem as a Mixed-Integer Programming (optimization) problem, following a hierarchical framework that divides the main design stages into stacking, zoning, and routing (corridor generation). The formulation has been fed into an industry-standard MIP solver from Google OR tools (Operations Research Tools), implemented in Python, and adapted to work within the Mc Neel's Rhino3D CAD environment. The toolkit has been tested in the context

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of a real-world hospital design case study considering the actual strict design codes and standards for good practice. This paper reports a part of a larger hospital design optimization framework, which has been partially reported in two other papers (removed references for the double-blind review). The results show the viability of this approach in dealing with an overwhelming amount of constraints imposed by strict design codes combined with realistic optimization objectives. Compared to several other approaches, the main advantage of this approach is the holistic consideration of the zoning and routing problems within the same framework. From a methodological point of view, this paper shows a direct application of Graph Theory combined with Operations Research in solving some of the most daunting complex design problems pertaining to layout configuration. Arguably, the OR problem classes are the most well-known optimization problems and their long history in engineering applications entails that their solvers are quite standard, robust (guaranteed to converge in a reasonable time), and accessible. For these reasons, bringing a problem to these standard forms makes it possible to benefit from these advantages. The challenging part of such an undertaking is of course bringing the problem into a standard form. What this paper offers is thus a practical way of bringing such complex problems into canonical problem formulation thus opening a gateway towards OR methodologies for solving architectural design problems in practice. The methodology as presented in this paper is specially designed to tackle the hospital design problem but it can potentially be generalized into other types of complex building layout problems, albeit contingent on dealing with challenges and limitations as follows.

4.3.9 Limitations

In general, the problem of layout is a 3D problem that is simplified into a series of flat 2D layout problems in this paper due to the focus on hospital layout problems and the necessity of stacking. The combination of zoning and routing problems as explained in the last paragraph of related works makes the layout problem a very daunting task. Instead of avoiding such complexity and focusing only on one, we have chosen to deal with both problems in one framework, albeit by assuming to avoid the common chicken and egg problem: we deal with zoning first and later perform a routing task. In doing so, however, the consideration of the distance between rooms is based on Manhattan distance along the edges of a quadrilateral mesh, which is a supremum for network distances, i.e. a proxy indicator for the real network distance. While it is possible to generalize this part of the methodology to incorporate network distances by using a look-up table, in this paper, we have used Manhattan distance for simplicity. In this regard, it must be noted that the Manhattan

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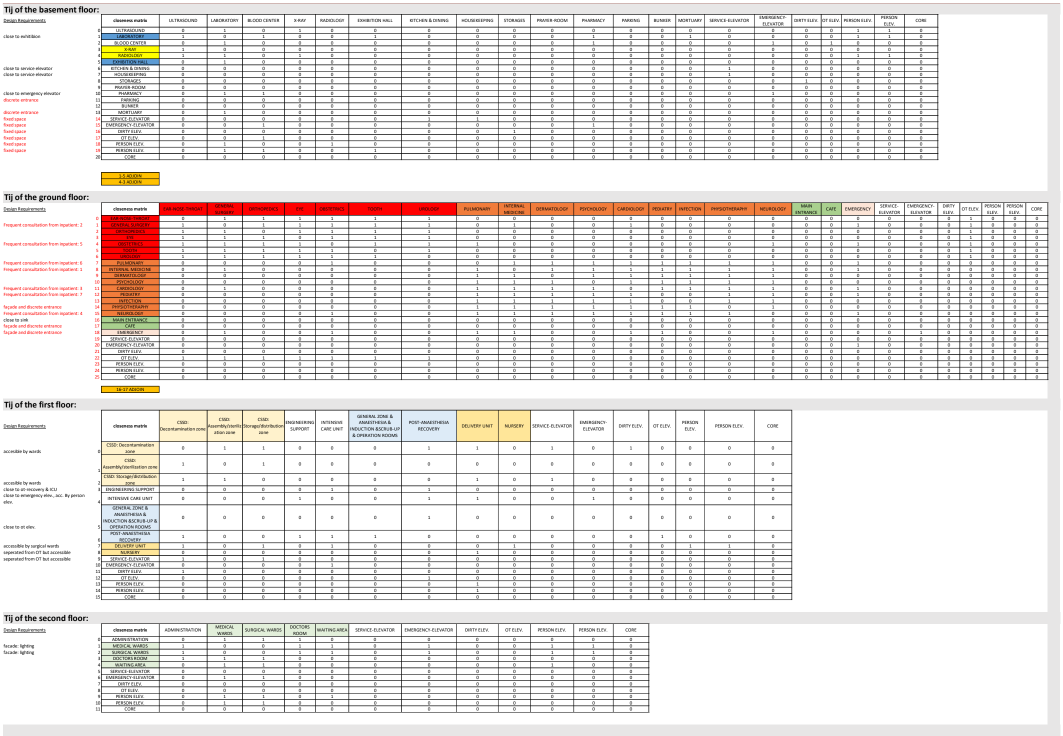
distance is in fact not a linear function, but because of the flexibility of the OR tools implementation, it is possible to enforce it as an objective. Similarly, the OR tools' solver can accept multiple additional constraints thanks to the possibility of adding auxiliary Boolean variables.

In this approach, the condition of the rectilinear form of rooms may seem to be overly strict. However, this is a matter of scale. A hospital unit consists of several rooms and this hospital unit can have an irregular shape in the form of several rectangular rooms. Architects generally consider near-convex room shapes to be preferable to strongly concave ones (q.v. [343] and [344]). Our case study shows a building with a perfectly rectilinear outline; however, in general, this is obviously not always the case. While it is possible to generalize the presented methodology to deal with non-rectilinear boundaries, we have not tested such cases. The presence of large obstacles or unavailable areas in the middle of a floor plan (e.g. because of an atrium) is also not considered in this example.

The scalability of the proposed algorithms for large problem instances is dubious as they depend on LP solvers based on the solver's implementation (Simplex, Branch & Bound, etc.), which are not all linear in terms of computational time and known to have scale-up issues with large numbers of decision variables [345].

4.3.10 Future Work

Generalizations and tests concerning the boundary and interior of the floor plans are the top priorities for future work. The next order of priority for tests and generalizations will be to replace Manhattan distance with network distance in the zoning stage. Another generalization may seem to be possible if we consider quadrilateral meshes in general rather than meshes only consisting of pixel-like quads; however, we maintain that the pixel-like quads have higher potential because if the solver is fast we can work with virtually any shape that can be pixelated.



Tij of the basement floor:

Design Requirements		closeness matrix	ULTRASOUND	LABORATORY	BLOOD CENTER	X-RAY	RADIOLOGY	EXHIBITION HALL	KITCHEN & DINING	HOUSEKEEPING	STORAGES	PRAYER-ROOM	PHARMACY	PARKING	BUNKER	MORTUARY	SERVICE-ELEVATOR	EMERGENCY-ELEVATOR	DIRTY ELEV.	OT ELEV.	PERSON ELEV.	PERSON ELEV.	CORE
	0	ULTRASOUND	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
close to exhitibion	1	LABORATORY	1	0	1	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	1	1	0
	2	BLOOD CENTER	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0
	3	X-RAY	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	RADIOLOGY	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
	5	EXHIBITION HALL	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
close to service elevator	6	KITCHEN & DINING	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
close to service elevator	7	HOUSEKEEPING	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	8	STORAGES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	9	PRAYER-ROOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
close to emergency elevator	10	PHARMACY	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
discrete entrance	11	PARKING	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	12	BUNKER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
discrete entrance	13	MORTUARY	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fixed space	14	SERVICE-ELEVATOR	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
fixed space	15	EMERGENCY-ELEVATOR	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
fixed space	16	DIRTY ELEV.	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
fixed space	17	OT ELEV.	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fixed space	18	PERSON ELEV.	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fixed space	19	PERSON ELEV.	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	20	CORE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1-5 ADJOIN
4-3 ADJOIN

Tij of the ground floor:

Design Requirements		closeness matrix	EAR-NOSE-THROAT	GENERAL SURGERY	ORTHOPEDICS	EYE	OBSTETRICS	TOOTH	UROLOGY	PULMONARY	INTERNAL MEDICINE	DERMATOLOGY	PSYCHOLOGY	CARDIOLOGY	PEDIATRY	INFECTION	PHYSIOTHERAPHY	NEUROLOGY	MAIN ENTRANCE	CAFE	EMERGENCY	SERVICE-ELEVATOR	EMERGENCY-ELEVATOR	DIRTY ELEV.	OT ELEV.	PERSON ELEV.	PERSON ELEV.	CORE
	0	EAR-NOSE-THROAT	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Frequent consultation from inpatient: 2	1	GENERAL SURGERY	1	0	1	1	1	1	1	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0
	2	ORTHOPEDICS	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	3	EYE	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Frequent consultation from inpatient: 5	4	OBSTETRICS	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0
	5	TOOTH	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	6	UROLOGY	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Frequent consultation from inpatient: 6	7	PULMONARY	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0
Frequent consultation from inpatient: 1	8	INTERNAL MEDICINE	0	1	0	0	0	0	0	1	0	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0
	9	DERMATOLOGY	0	0	0	0	0	0	0	1	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	10	PSYCHOLOGY	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Frequent consultation from inpatient: 3	11	CARDIOLOGY	0	1	0	0	0	0	0	1	1	1	1	0	1	1	1	1	0	0	1	0	0	0	0	0	0	0
Frequent consultation from inpatient: 7	12	PEDIATRY	0	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0
	13	INFECTION	0	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
façade and discrete entrance	14	PHYSIOTHERAPHY	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
Frequent consultation from inpatient: 4	15	NEUROLOGY	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0
close to sink	16	MAIN ENTRANCE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
façade and discrete entrance	17	CAFE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
façade and discrete entrance	18	EMERGENCY	0	1	0	0	1	0	0	1	1	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0
	19	SERVICE-ELEVATOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	20	EMERGENCY-ELEVATOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	21	DIRTY ELEV.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	22	OT ELEV.	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	23	PERSON ELEV.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	24	PERSON ELEV.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	25	CORE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

16-17 ADJOIN

Tij of the first floor:

Design Requirements		closeness matrix	CSSD: Decontamination zone	CSSD: Assembly/sterilization zone	CSSD: Storage/distribution zone	ENGINEERING SUPPORT	INTENSIVE CARE UNIT	GENERAL ZONE & ANAESTHESIA & INDUCTION &SCRUB-UP & OPERATION ROOMS	POST-ANAESTHESIA RECOVERY	DELIVERY UNIT	NURSERY	SERVICE-ELEVATOR	EMERGENCY-ELEVATOR	DIRTY ELEV.	OT ELEV.	PERSON ELEV.	PERSON ELEV.	CORE
accesible by wards	0	CSSD: Decontamination zone	0	1	1	0	0	0	1	1	0	1	0	1	0	0	0	0
	1	CSSD: Assembly/sterilization zone	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
accesible by wards	2	CSSD: Storage/distribution zone	1	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0
close to ot-recovery & ICU	3	ENGINEERING SUPPORT	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
close to emergency elev., acc. By person elev.	4	INTENSIVE CARE UNIT	0	0	0	1	0	0	1	1	0	0	1	0	0	0	0	0
close to ot elev.	5	GENERAL ZONE & ANAESTHESIA & INDUCTION &SCRUB-UP & OPERATION ROOMS	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	6	POST-ANAESTHESIA RECOVERY	1	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0
accessible by surgical wards	7	DELIVERY UNIT	1	0	1	0	1	0	0	0	1	0	0	0	0	1	1	0
seperated from OT but accessible	8	NURSERY	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
seperated from OT but accessible	9	SERVICE-ELEVATOR	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	10	EMERGENCY-ELEVATOR	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	11	DIRTY ELEV.	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	12	OT ELEV.	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	13	PERSON ELEV.	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	14	PERSON ELEV.	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	15	CORE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Tij of the second floor:

Design Requirements		closeness matrix	ADMINISTRATION	MEDICAL WARDS	SURGICAL WARDS	DOCTORS ROOM	WAITING AREA	SERVICE-ELEVATOR	EMERGENCY-ELEVATOR	DIRTY ELEV.	OT ELEV.	PERSON ELEV.	PERSON ELEV.	CORE
	0	ADMINISTRATION	0	1	1	1	0	0	0	0	0	0	0	0
facade: lighting	1	MEDICAL WARDS	1	0	0	1	1	0	1	0	0	1	1	0
facade: lighting	2	SURGICAL WARDS	1	0	0	1	1	0	1	0	0	1	1	0
	3	DOCTORS ROOM	1	1	1	0	0	0	0	0	0	0	0	0
	4	WAITING AREA	0	1	1	0	0	0	0	0	0	1	0	0
	5	SERVICE-ELEVATOR	0	0	0	0	0	0	0	0	0	0	0	0
	6	EMERGENCY-ELEVATOR	0	1	1	0	0	0	0	0	0	0	0	0
	7	DIRTY ELEV.	0	0	0	0	0	0	0	0	0	0	0	0
	8	OT ELEV.	0	0	0	0	0	0	0	0	0	0	0	0
	9	PERSON ELEV.	0	1	1	0	1	0	0	0	0	0	0	0
	10	PERSON ELEV.	0	1	1	0	0	0	0	0	0	0	0	0
	11	CORE	0	0	0	0	0	0	0	0	0	0	0	0

FIG. 4.33 T_{ij} matrices of each floor

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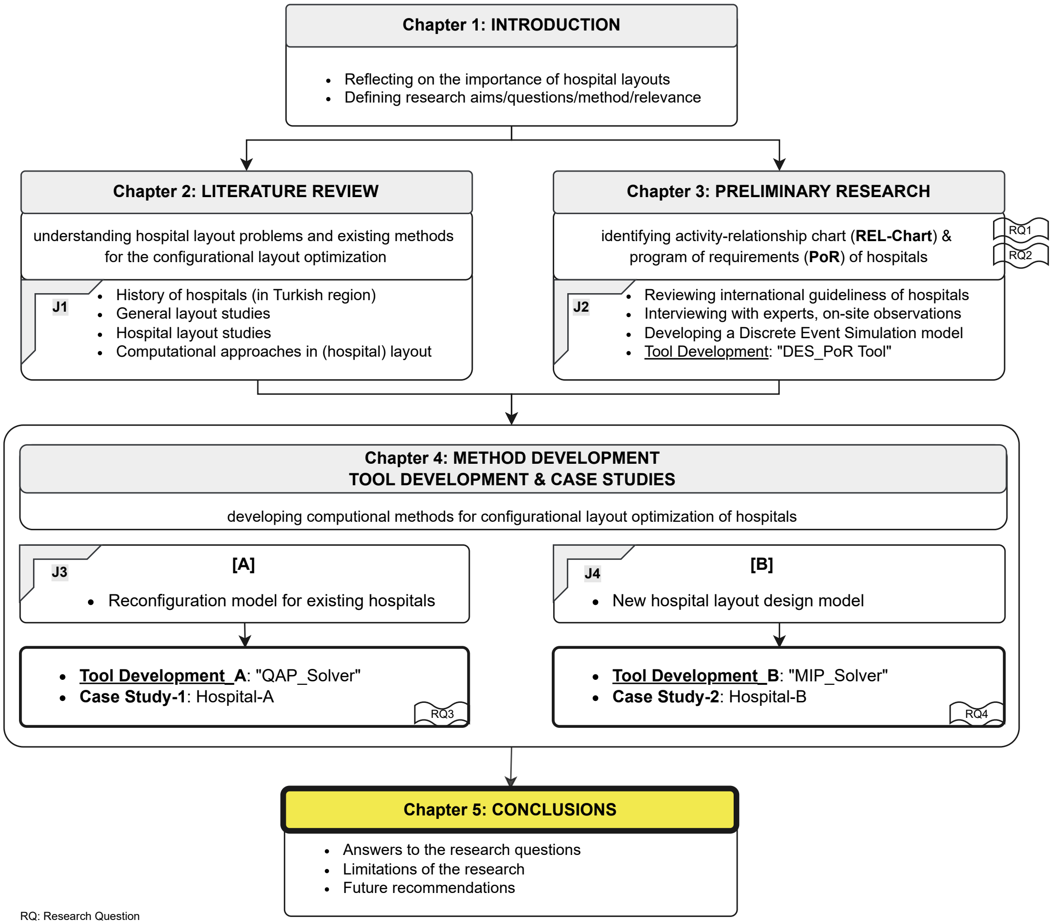

RQ: Research Question
J: Journal

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5 Conclusions

In this Ph.D. dissertation, a computational design methodology was developed for the configurational layout optimization of hospitals. In particular, two computational models consisting of “reconfiguration of the existing hospital layouts” and “designing new hospital layouts” were developed, which were also programmed in the form of design tools. The tool suite was created in a popular computational design platform (Rhino3D+Grasshopper3D) as a laboratory and testbed environment using C#.NET and Python languages. The models considered a various number of aspects in hospitals related to solving configurational problems such as inefficient circulation of medical staff, difficulty in wayfinding for visitors, lengthy procedures, long walking times, and so on. Both models were developed as generic models, that can be applied to any mid-size general-type hospital based on Turkey’s design codes. However, for the validation of the methods, each model was tested with real-world case study hospitals in Turkey. The case study hospitals were selected according to the suggestion of the vice president of Public Hospitals Services in Izmir. For the development of the models, methods, and tools, it was utilized from an interdisciplinary approach that combines various fields in this research, namely Architecture, Mathematics, Industrial Engineering (in particular the sub-field of Operations Research), Computational Optimization, and Social Sciences. In the design practice, this research provides planners, designers, architects, engineers and related municipalities with systematic problem formulations and methods for solving the configurational problems of hospital buildings. Especially, the developed tools are meant to act as design aids in the conceptual design phase of hospital layouts.

In this chapter, comprehensive answers to research questions will be presented, and highlighted the major findings and contributions of the research. Furthermore, the limitations of the research and future recommendations will be discussed.

5.1 Responses to Research Questions

This section discusses the major findings and contributions of the research, arranged according to the research questions formulated in chapter 1.3.

The main question is:

- **How to logically deduce a configurational layout of hospitals from functional requirements?**

In addressing this research question, the main aim of this thesis is to devise a computational design methodology for optimizing the space planning of hospitals with respect to physical matters & human factors. For this aim, this dissertation started with an extensive worldwide literature review, gathering expertise and knowledge in the related fields, and on-site observations of various hospitals; enduring with preliminary research, which aims to identify spatial closeness, connectivity, and adjacency requirements as well as the program of requirements of hospitals to get adequate hospital design inputs. The research continued with developing methods for configurational layout optimization for hospital design considering the defined configurational problems and followed by two case studies as improvement and construction cases. The first one is experimental, which is testing the method on existing hospitals to improve the spatial layout. The second one is hypothetical, which is testing the method for constructing the new hospital layout and designing the corridors. Due to the nature of the problems, in the first track, Quadratic Assignment Problem (QAP) formulation with geodesic distances and a modified version of the heuristic optimization algorithm were proposed. In the second track, Mixed Integer Programming (MIP) formulations integrated with graph-theoretical approaches and computational intelligence techniques were suggested. So-called QAP and MIP techniques are usually utilized in facility layout planning in the field of Operations Research (OR) and Industrial Engineering. Accordingly, facility layout problems and architectural layout problems differ from each other because of their focal objectives; but somehow, they are similar in that both are aiming at finding a spatial configuration. This causes to have similar problem formulations in designing the layout of a building. The FLPs are mostly focused on factory design for optimizing the production processes and the considered aspects are minimizing the production time, utilization of manpower, ergonomics of the employees, or minimizing the delays or bottlenecks in assembly lines. On the other hand, ALPs are focused on the efficient and effective functioning of buildings for optimizing human movement patterns, effective/safe accessibility, and so on. Operations Research (OR) formulations and methods are crucial for solving facility layout problems in Industrial Engineering. However, they are not very well-known in Architecture for their potential in solving layout problems. In this thesis, the architectural space planning problem is formulated in the form of FLP while using architectural objectives and constraints and solved with the modified versions of the OR techniques in a self-developed digital design toolkit in CAD software. From the stance of Architecture, new layout design tools and methods are developed for optimizing buildings, in particular for facilitating the performance-aware design of hospitals. From the point of Engineering, a new application field is opened for Industrial Engineering disciplines in addition to existing ones (such as logistics, finance, and production). The modified versions of some well-known OR algorithms appropriated for architectural design usage are also a contribution to the field of Computational Optimization. In conclusion, the research provided a methodological framework for bringing Operations Research (OR) into Architectural Space Planning and combined various disciplines as a major added value of this research.

This section is followed by the answer to the sub-questions:

1 How to define spatial adjacency, connectivity, and closeness requirements in hospitals?

For addressing this question, a theoretical study has been carried out by reviewing the international hospital design guidelines that present general design considerations, and common elements of hospitals and shows some typical arrangements of each facility in hospitals. During this review, the guidelines were chosen based on the focused size of the hospital for this research, namely general-type mid-size hospitals. In addition to the theoretical study, site visits and semi-structured interviews in the field of healthcare were carried out with medical practitioners and hospital architects to get adequate information about hospital requirements and the ideal planning of the functional units as well as validate the gathered results of the guidelines review. Ultimately, an activity-relationship chart, called REL-Chart, which is a very beneficial tool commonly used in Industrial Engineering, an improved version of a bubble diagram in Architecture, was developed to identify spatial, adjacency, connectivity, and closeness requirements in hospitals. According to the reviewed literature, previous layout planning research has been carried out in the hospital layout planning processes with a given REL-Chart. However, this research proposed a typical mid-size hospital REL-Chart with a systematic approach.

2 How to define a program of requirements in relation to design codes and standards concerning human comfort in following medical procedures?

For answering this question, a DES_PoR tool was developed to formulate and validate the program of requirements of a hospital referring to the patient-flow model by a discrete-event simulation method and hospital design codes/standards. In the DES_PoR tool, a discrete event simulation method was programmed in Parametric CAD software for modeling the patient movements in a hospital and calculating the waiting times and patient throughput based on some inputs related to operational planning of the hospitals such as the number of doctors, patient inter-arrival times, the number of beds, the number of outpatient units, etc. Since these inputs are directly attributed to the program of requirements, the hospital design codes/standards are also integrated into the developed tool. In this way, the defined square meters of each functional unit based on the standards can be validated in terms of some human comfort parameters as such the waiting areas can be wide enough for patients in the queue. On the other hand, a real-time Discrete-Event Simulation at the same time, the tool can give feedback on the performance indicators (patient waiting times, patient throughput), which is translatable into the likely functional/logical performance of the hospital plan layout patterns. For example, the number of doctors, respectively the needed area for polyclinics rooms can be defined to minimize the patient waiting times.

3 How to improve the layout configuration of an existing hospital?

For answering this question, a Quadratic Assignment Problem (QAP) formulation was proposed and re-formulated based on a graph theoretical concept specific to hospitals. QAP-type formulations are mainly intended to assign hospital units to existing locations, therefore this type of formulation is considered in the context of a re-design/renovation task. For solving the QAP, a heuristic optimization algorithm, called Iterated Local Search (ILS), was proposed since QAP is a complex problem having a goal in the quadratic form, namely a function of flows of people × distances. In the model, the design domain was voxelated to modularize the units of space so that the problem of layout can be formulated as an assignment problem. Another reason for voxelization is using the explicit topological relations between adjacent voxels for constructing a network model of space and computing the geodesic distances in the form of the logistic cost function. In addition, the method was programmed in the form of a design tool to enable the users to get improved hospital layout results.

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To sum up, the uniqueness of the methodology is

- the combination of QAP with graph theoretical aspects (considering walkable circulation routes in calculating distances with a spatial geodesic method in 3D),
- modularization/discretization of space layout problems both in terms of modularization of the departments and the walkable space in between the departments in 3D for solving a QAP,
- application to a real-world hospital case considering the whole units,
- implementation of the method in the form of a computational design tool called QAP_Solver, developed by the author of this dissertation.
- How to obtain a configurational layout for a new hospital?

For addressing this question, a hierarchical approach was proposed for configurational layout planning of hospitals that includes subsequent steps of determining the level of the facilities (**stacking**), spatial arrangements (**zoning**), and corridor design (**routing**). In the stacking part, a spectral clustering method in graph theory was proposed based on the proximity requirements, then each facility unit was assigned to the identified levels according to their cluster numbers. In the zoning and routing part, a Mixed Integer Programming (MIP) based optimization was introduced by using a standard engineering optimization engine library. All developed methods here were programmed in a popular computational design platform (Rhino3D+Grasshopper3D), as a laboratory and testbed environment, and a MIP_Solver tool was developed for facilitating the implementation of the methods in design practice. The codes are written using Python within Anaconda Spyder as an Integrated Development Environment (IDE), GHCPython, and GHPython in Grasshopper 3D.

In the developed model and the tool, the design domain is considered as a piecewise linear 2D polygon and discretized into a polygonal mesh. Based on this, an individual hypothetical mesh is defined for each level. The goal of the zoning model is to assign a subset of mesh faces to each functional unit such that the closeness of the interrelated spaces is minimized subject to a set of constraints: space area requirements, cohesion (as in connectedness and contiguity), contiguous areas (adjacent rooms), [optional] fixed locations/adjacencies for some spaces, non-overlapping spaces (to avoid different rooms assigned to same mesh faces), adjacency to facade because of lighting requirements, discrete entrance requirements, flexibility requirements for the spaces that can need future expansion, privacy/community requirements, boundary constraints. Hereafter, the goal of the routing model is to select a subset of mesh edges to design the network, called corridors. The optimized network was selected based on a subset of quality measures: way-finding for the ease of patient movement, route separation due to the working efficiency of medical staff, cleanliness and privacy requirements, and some validity constraints. The reason for considering both zoning and routing in our layout planning methodology is the difference between adjacency, closeness, and connectivity concepts. Locating two rooms close to each other doesn't mean that there is an efficient connection between these two spaces. The actual distance between these two rooms can be longer due to the problems caused by corridors (or connections). On the other hand, some connections are sometimes required to prohibit safety and security concerns. Therefore, the main contribution of this paper is to combine and transform two major space-planning problems, i.e. room layout (zoning/packing) and corridor generation (routing) to the standard forms of MIP problems so that they can be solved using standard engineering optimization engines.

5.2 Limitations

Although the research presented a comprehensive answer to each research question and the list of contributions of the proposed method, this research acknowledges some critical aspects that can benefit from further considerations. We have mentioned the limitations of our proposed methods in detail at the end of each corresponding chapter (Sections 3.3.6, 4.2.7, 4.3.9). Here we highlight the general ones.

In most of the layout planning research, an activity relations chart is given. In this research, we queried to find the ideal REL-chart following a series of qualitative/quantitative works. However, the presented REL-Chart may need to be updated if additional requirements have appeared in a hospital design. DES_PoR tool became a kind of decision-making tool for the conceptual design phase that can give an idea about the effects of PoR decisions on human factors. However, this tool is simulating the outpatient area. Updating the tool for other clinical units requires computational knowledge and needs sufficient data about the processes of these other units. In the developed methods and tools in both track A (QAP) and track B (MIP) parts, the research coped with considerable data for investigating configurational layout optimization for hospital design i.e. mid-size general-purpose hospitals. But, a computational challenge is valid here to deal with the layout problems in a hospital case. Investigating hospital layout designs on bigger scales may require other computational intelligence methods and algorithms.

5.3 Future Recommendations

Regarding the presented methods in chapter 4, limitations were detailly discussed in corresponding sub-sections, and future works were briefly recommended such as improving the problem formulations, using more-advanced algorithms, objective function changes, and so on. In general, hospital design requires teamwork consisting of people from various fields as an expert design team. For example, one sub-team can focus on energy efficiency and one sub-team can focus on HVAC, etc. So, this research can be extended by focusing on various fields related to hospital design that is seen as out-of-scope in this research with a bigger team from different professions. In addition, the presented workflow can be adapted to different countries and different functionally complex buildings by updating the standards in the models. Furthermore, it would be interesting to extend the developed tools for the purpose of indoor navigation of complex buildings due to the increasing use of smart phones.

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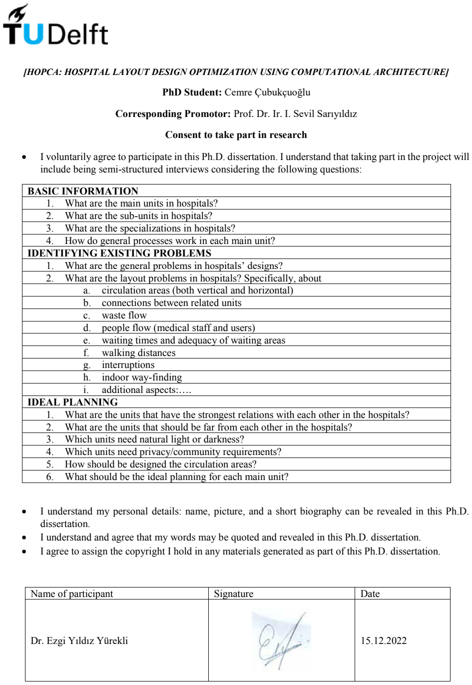
Consent forms



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Corresponding Promotor: Prof. Dr. Ir. I. Sevil Sarıyıldız

Consent to take part in research

- I voluntarily agree to participate in this Ph.D. dissertation. I understand that taking part in the project will include being semi-structured interviews considering the following questions:

BASIC INFORMATION
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3. What are the specializations in hospitals?
4. How do general processes work in each main unit?
IDENTIFYING EXISTING PROBLEMS
1. What are the general problems in hospitals' designs?
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IDEAL PLANNING
1. What are the units that have the strongest relations with each other in the hospitals?
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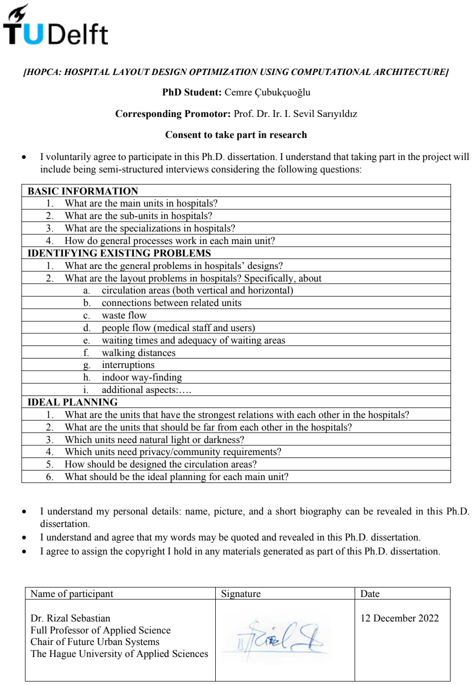

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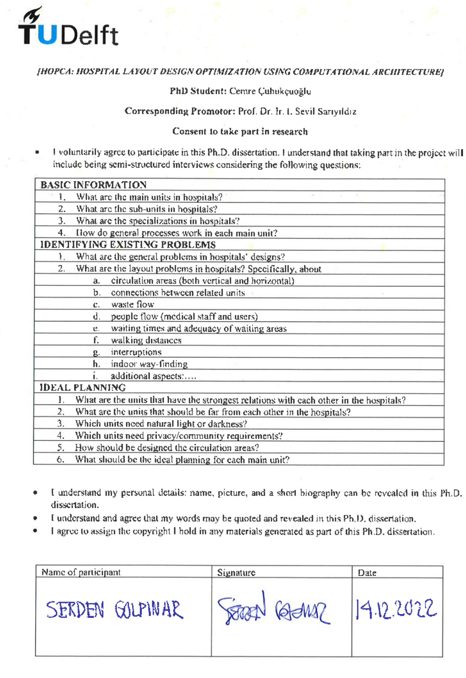

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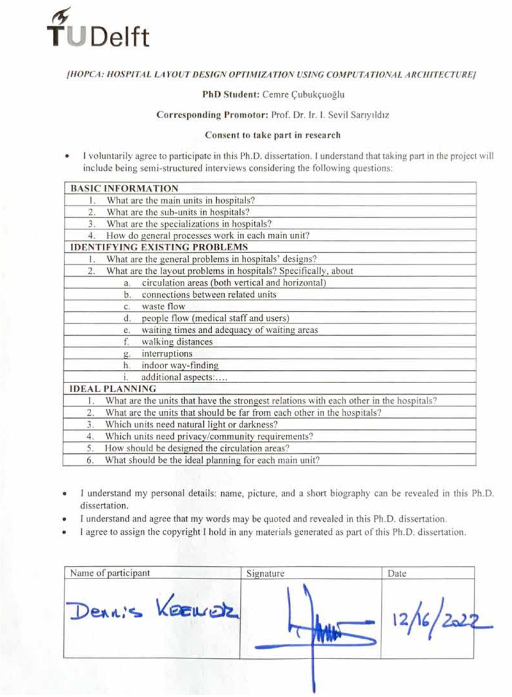

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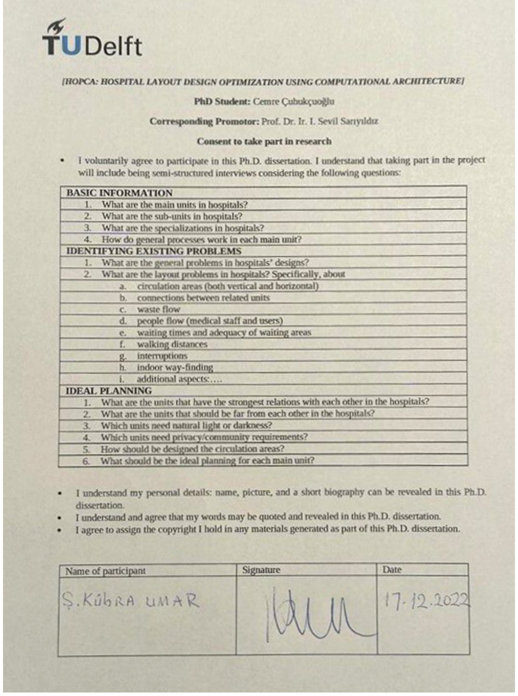
Dennis Koenerz		12/16/2022



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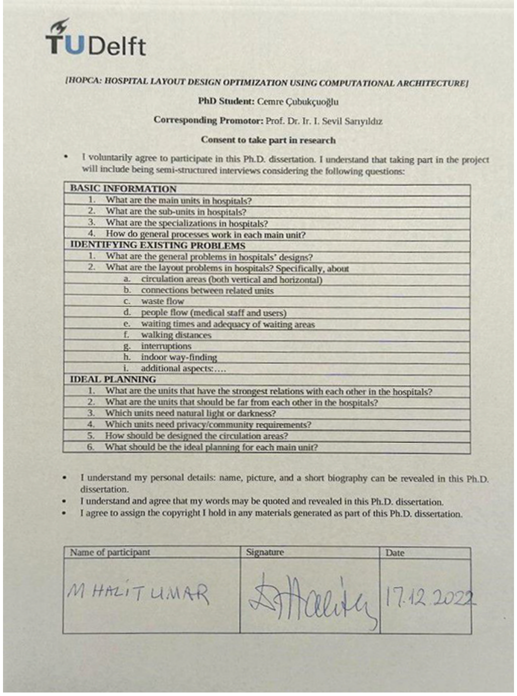

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M HALİT UMAR		17.12.2022

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Curriculum Vitae

Cemre Çubukçuoğlu

Date of Birth
18 February 1991
Place of Birth
Izmir, Turkey
E-mail
cemrecubukcuoglu@gmail.com
c.cubukcuoglu@tudelft.nl
cemre.cubukcuoglu@yasar.edu.tr

Work Experience

12/2013 – current **Research Assistant**
Yaşar University, Department of Interior Architecture and Environmental Design inar.yasar.edu.tr

- Course Assistantship (Master Design Studio, Computational Design, Digital Design Techniques, Spatial Geometry, Spatial Representations, Cad & Cam and Production Technologies)
- Research
- Administrative works

09/2012 – 06/2013 **Part-Time Assistant**
Yaşar University | Industrial Engineering

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Education And Training

03/2017 – current

PhD in Design Informatics /
Architectural Engineering + Technology
TU Delft, Graduate School of Architecture and the Built Environment, Holland | bk.tudelft.nl

09/2013 – 08/2015

Master of Science in Industrial Engineering
Yaşar University, Graduate School of Natural and Applied Sciences, Izmir – Turkey | lee.yasar.edu.tr

- **Thesis Title:** “Multi-Objective Computational Design in Architecture” (supervised by M. Fatih Tasgetiren)
- **Courses taken:** Probabilistic Analysis, Applied Stochastic Processes-I, Optimization Models and Algorithms, System Simulation, Computational Intelligence in Building Design, Architectural Design Studio I-II, Floating Cities, Heuristic Optimization, Advanced Computational Design, Scheduling Theory

09/2009 – 06/2013

Bachelor of Industrial Engineering (3.75 / 4.00)
Yaşar University, Department of Industrial Engineering, Izmir – Turkey | ie.yasar.edu.tr

06/2012 – 07/2012

Internship
Vestel White Goods, Washing Machine Factory, Production Department

08/2011 – 09/2011

Internship
Cevher Factory, Production Planning Department

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Projects

03/2021 – 06/2022

Research project name: TÜBİTAK 1002
(Grant No: 220K287)
Project Title: Elderly Friendly Interiors
Task: Creating the parametric model (Energy and Cost objectives, design variables of the elder room and Indoor Environmental Quality constraints), optimizing the model using evolutionary algorithms, and presenting the design alternatives.

09/2015 – 09/2016

Research project name: PULSE TU Delft
(in collaboration with Ector Hoogstad Architects)
Project Title: Design of Smart Sun Shading Elements for a Building on the TU-Delft Campus.
Task: Creating the parametric model (objectives, design variables and constraints), optimizing the model using evolutionary algorithms, and presenting the design alternatives to the architecture firm.

Workshops

Given

09/2022 Energy Analysis Workshop to ARCH 4410 Students of Yasar University

Organized

07/2019 Computational Design
(in collaboration with Esteco / Bouygues Construction)

11/2017 Stuffed Cast
(in collaboration with BetonArt & Tuşpa NK Architects)

05/2015 FlexiMold
(in collaboration with Faculty of Architecture,TU Delft)

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Awards

05/2018	TMCE 2018 Las Palmas, Spain / Best Paper Award https://haber.yasar.edu.tr/genel/uluslararasi-en-iyi-bildiri-odulu.html
06/2013	TUBITAK / Industry Focused Graduation Projects Competition Semi-Finalist
06/2013	Yaşar University Department of Industrial Engineering / Top 3rd Student
05/2012	Faculty of Engineering / Dean’s Success Award

Scientific Organizations

Technical Committee Member
2016 IEEE Congress on Computational Intelligence, Vancouver (Canada) www.wcci2016.org
Special Session No:36 Evolutionary Computation in Architectural Design (14 papers published)

Reviewer
2016 Yöneylem Araştırması ve Endüstri Mühendisliği 36. Ulusal Kongresi
https://yaem2016.yasar.edu.tr/YAEM_BildiriOzetleri.pdf

Associate Editor
2020 İÇLİS İç Mimarlik Lisansüstü Çalişmalar Sempozyumu-III https://iclis2020.yasar.edu.tr/

Academic Secretariat
2022 DOCOMOMO_Türkiye’de Modern İç Mekanlar Sempozyumu II https://docomomo.yasar.edu.tr

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Teaching Experience

Supervision

Yasar University, Izmir, Turkey:

- Energy and Daylight Performance Optimization for High-Rise Office Buildings
(Yaşar University MSc Student: Muhittin Yufka)

Coordinator

Yasar University, Izmir, Turkey:

2022–2023 Fall Semester, INAR 2211, Digital Design Techniques

Instructor

Yasar University, Izmir, Turkey:

2022–2023 Fall Semester, INAR 1111, Spatial Representations I

2021–2022 Spring Semester, INAR 3352, Computational Design for Interiors

Guest Lecturer

Courses and Studios at Yasar University, Izmir, Turkey:

2021–2022 Spring Semester, INAR 1112, Spatial Representations II

2017–2018 Spring Semester, INAR 252, Modelling and Rendering for Interior Architects

2015–2016 Spring Semester, ARCH 324, Computational Design

Courses at the TU Delft, The Netherlands:

12/10/2018 Lecture on "The effects of configuration/network structure on the functionality of a hospital", MSc Geomatics

16/04/2021 Lecture on "The application of Operations Research and Facilities Layout Planning in Hospital Design", Spatial Computing in Architectural Design Course

29/09/2022 Lecture and Online Tutoring on “Configurational Layout Optimization” at CORE MSc Building Technology Course, Faculty of Architecture

23/11/2022 Lecture on “Configurational Design in Architecture” at Spatial Computing Minor Course, Faculty of Architecture

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Tool Development

- *Optimus*
  https://www.food4rhino.com/en/app/optimus
  (in collaboration with Dr. Berk Ekici)
- *DES_PoR Tool*
  https://github.com/CemreTUDelft/DES_PoR_Tool
- *Hopca1*
  QAP_Solver
  https://www.youtube.com/watch?v=Lv52qy1OjSw
- *Hopca2*
  MIP_Solver
  https://www.youtube.com/watch?v=bMVyu6ff7pY

Professional Skills

- AutoCAD, Rhinoceros 3D, Grasshopper and several plug-ins (e.g. Honeybee+Ladybug, Pachyderm Acoustics, Climate Studio etc.), ArchiCAD, Revit, SketchUp, Twinmotion, Photoshop, Python, GH_Python, C#

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List of Publications

Primary Scientific Outputs of this Dissertation

- **Cubukcuoglu, C.**, Durmuslar, F. and Sariyildiz, S., 2022. Architectural Evolution of Hospital Buildings. Submitted. Journal of Architectural Histories.
- **Cubukcuoglu, C.**, Nourian, P., Sariyildiz, I. S., & Tasgetiren, M. F. (2022). Optimal Design of new Hospitals: A Computational Workflow for Stacking, Zoning, and Routing. Automation in Construction, 134, 104102. (WoS index: Science Citation Index (SCI), impact factor: 7.7, cite score: 12) https://doi.org/10.1016/j.autcon.2021.104102
- **Cubukcuoglu, C.**, Nourian, P., Tasgetiren, M. F., Sariyildiz, I. S., & Azadi, S. (2021). Hospital layout design renovation as a Quadratic Assignment Problem with geodesic distances. Journal of Building Engineering, 44, 102952. (WoS index: Science Citation Index (SCI), impact factor: 5.318, cite score: 5.5) https://doi.org/10.1016/j.jobe.2021.102952
- **Cubukcuoglu, C.**, Nourian, P., Sariyildiz, I.S., Tasgetiren, M.F., (2020) A Discrete Event Simulation Procedure for Validating Programs of Requirements: The Case of Hospital Space Planning, SoftwareX, 12, 1-8. (WoS index: Emerging Sources Citation Index (ESCI), Scopus) https://doi.org/10.1016/j.softx.2020.100539

Outputs from Collaborations during PhD (2017-2022)

- **Cubukcuoglu, C.**, Tasgetiren, M. F., Sariyildiz, I. S., Gao, L., Kucukvar, M. (2020). A Memetic Algorithm for the Bi-Objective Quadratic Assignment Problem, Elsevier’s Procedia Manufacturing, 39, 1215-1222. (WoS index: Conference Proceedings Citation Index-Science, Scopus) https://doi.org/10.1016/j.promfg.2020.01.348
- Chatzikonstantinou, I., Turrin, M., **Cubukcuoglu, C.**, Kirimtat, A., Sariyildiz, S. (2020). A Comprehensive Optimization Approach for Modular Facades: The Case of PULSE Sunshading, International Journal of Design Sciences & Technology, 23(2), 159-185. (Scopus)
- **Cubukcuoglu, C.**, Ekici, B., Tasgetiren, M. F., & Sariyildiz, S. (2019). OPTIMUS: Self-Adaptive Differential Evolution with Ensemble of Mutation Strategies for Grasshopper Algorithmic Modeling. Algorithms, 12(7), 141. (WoS index: Emerging Sources Citation Index (ESCI), Scopus) https://doi.org/10.3390/a12070141

- Ekici, B., **Cubukcuoglu, C.**, Turrin, M., & Sariyildiz, I. S. (2019). Performative computational architecture using swarm and evolutionary optimisation: A review. Building and Environment. (WoS index: Science Citation Index (SCI), impact factor: 4.539, 5-year impact factor: 5.221) https://doi.org/10.1016/j.buildenv.2018.10.023
- **Cubukcuoglu, C.**, Kirimtat, A., Ekici, B., Tasgetiren, F., & Suganthan, P. N. (2018). Evolutionary Computation for Theatre Hall Acoustics. In *Optimization in Industry* (pp. 55-83). Springer, Cham.
- Kirimtat, A., Ekici, B., **Cubukcuoglu, C.**, Sariyildiz, S., & Tasgetiren, F. (2018). Evolutionary Algorithms for Designing Self-sufficient Floating Neighbourhoods. In Optimization in Industry (pp. 121-147). Springer, Cham.
- Unlu N.P., Ekici B., Chatzikonstantinou I., **Cubukcuoglu C.**, Sariyildiz I.S., Tasgetiren M.F., Diagrid Façade Design for Public Pool Building Using Differential Evolution, Twelfth International Tools and Methods of Competitive Engineering Symposium, TMCE 2018, Las Palmas de Gran Canaria. Full paper accepted, **Best Paper Award**.
- Yufka M., Ekici B., **Cubukcuoglu C.**, Chatzikonstantinou I., Sariyildiz I.S., Multi Objective Skylight Optimization for a Healthcare Facility Foyer Space, Accepted to IEEE CEC 2017 in Spain, pp. 1008-1014.
- Karaman S., Ekici B., **Cubukcuoglu C.**, Kundakci Koyunbaba B., Kahraman I., Design of Rectangular Facade Modules through Computational Intelligence, Accepted to IEEE CEC 2017 in Spain, pp. 1021-1028.

Other Researches

- **Cubukcuoglu, C.**, Chatzikonstantinou, I., Tasgetiren, M. F., Sariyildiz, I. S., & Pan, Q. K. (2016). A Multi-Objective Harmony Search Algorithm for Sustainable Design of Floating Settlements. Algorithms, 9(3), 51. (WoS index: Emerging Sources Citation Index (ESCI), Scopus) https://doi.org/10.3390/a9030051
- Gorgun A.O., **Cubukcuoglu C.**, Ekici B., Kundakci Koyunbaba B., Kahraman I., Diagrid Façade Design Using Multi-Objective Evolutionary Algorithms, accepted full paper to International Symposium for Production Research 2017, 13 – 15 September 2017, Vienna.
- Ozbey F., **Cubukcuoglu C.**, Ekici B., Cilasun Kunduraci A., Chatzikonstantinou I., Bi-objective Visual Perception Optimization for a Healthcare Education Facility, accepted full paper to International Symposium for Production Research 2017, 13 – 15 September 2017, Vienna.
- Yildirim E., Ekici B., **Cubukcuoglu C.**,Chatzikonstantinou I., Sariyildiz I.S., Optimization of Free Form Long Span Roof Structure for Pool Facility Using Evolutionary Algorithms, accepted full paper to International Symposium for Production Research 2017, 13 – 15 September 2017, Vienna.

- Yavuzarslan G., Ekici B., **Cubukcuoglu C.**, Cilasun Kunduraci A., Envelope Design of Healthcare Public Space Using Multi-Objective Optimization, accepted full paper to International Symposium for Production Research 2017, 13 – 15 September 2017, Vienna.
- Paldrak M., **Cubukcuoglu C.**, Ekici B., Tasgetiren M.F., Cilasun Kunduraci A., Diagrid and Honeycomb Façade Design Optimization with Multi-Objective Evolutionary Algorithms, accepted full paper to International Symposium for Production Research 2017, 13 – 15 September 2017, Vienna.
- Kurtbas E., **Cubukcuoglu C.**, Ekici B., Cilasun Kunduraci A., Kahraman I., Addressing a Façade Design for Healthcare Facility Using Multi-Objective Optimization, accepted full paper to International Symposium for Production Research 2017, 13 – 15 September 2017, Vienna.
- Unlu N.P., Tasgetiren M.F., Ekici B., **Cubukcuoglu C.**, Chatzikonstantinou I., Structure Optimization of Shelter Design for Semi-Closed Public Space in Urban, accepted full paper to International Symposium for Production Research 2017, 13 – 15 September 2017, Vienna.
- **Cubukcuoglu C.**, Kirimtat A., Tasgetiren M.F., Suganthan PN., Pan QK., Multi-Objective Harmony Search Algorithm for Layout Design in Theatre Hall Acoustics, Accepted to IEEE WCCI 2016, Vancouver Canada, pp. 2280-2287.
- **Cubukcuoglu C.**, Chatzikonstantinou I., Ekici B., Sariyildiz S., Tasgetiren M.F., Multi-Objective Optimization Through Differential Evolution for Restaurant Design, Accepted to IEEE WCCI 2016, Vancouver Canada, pp. 2288-2295.
- **Ugurlu C.**, Chatzikonstantinou I., Sariyildiz S., Tasgetiren M.F., Identification of Sustainable Designs for Floating Settlements Using Computational Design Techniques, Accepted to IEEE CEC 2015 Sendai, Japan, pp. 2303-2310.
- **Ugurlu C.**, Chatzikonstantinou I., Sariyildiz S., Tasgetiren M.F., Evolutionary Computation for Architectural Design of Restaurant Layouts, Accepted to IEEE CEC 2015 Sendai, Japan, pp. 2279-2286.
- Basak Kundakci Koyunbaba, Sevil Sariyildiz, Ayca Kirimtat, **Cemre Ugurlu**, (2015) Removing Market Barriers for Energy-Efficient Building Renovation, Proc. Of ECSEE 2015, 9-12 July, 2015.
- **Cemre Cubukcuoglu**, Ioannis Chatzikonstantionu, Berk Ekici, M. Fatih Tasgetiren ve Sevil Sarıyıldız, Restoran Tasarımı Optimizasyonu için Çok Amaçlı Diferansiyel Evrim Algoritması, Yöneylem Araştırması Endüstri Mühendisliği (YAEM) 36. Ulusal Kongresi, Yaşar Üniversitesi, İzmir, Türkiye, 2016.
- **Cemre Ugurlu**, Ioannis Chatzikonstantinou, Sevil Sariyildiz, Fatih Tasgetiren, Restoran Yerleşiminin Mimari Tasarımı için Bir Farksal Evrim Algoritması, Yöneylem Araştırması ve Endüstri Mühendisliği (YAEM) 35. Ulusal Kongresi, ODTÜ, Ankara, Türkiye, 2015.
- Ioannis Chatzikonstantinou, Sevil Sarıyıldız, **Cemre Ugurlu**, Fatih Taşgetiren, Restoran Tasarımında Yerleşim Sorunu için Evrimsel Hesaplama Yöntemi, MSTAS 2014, 26 Haziran 2014.

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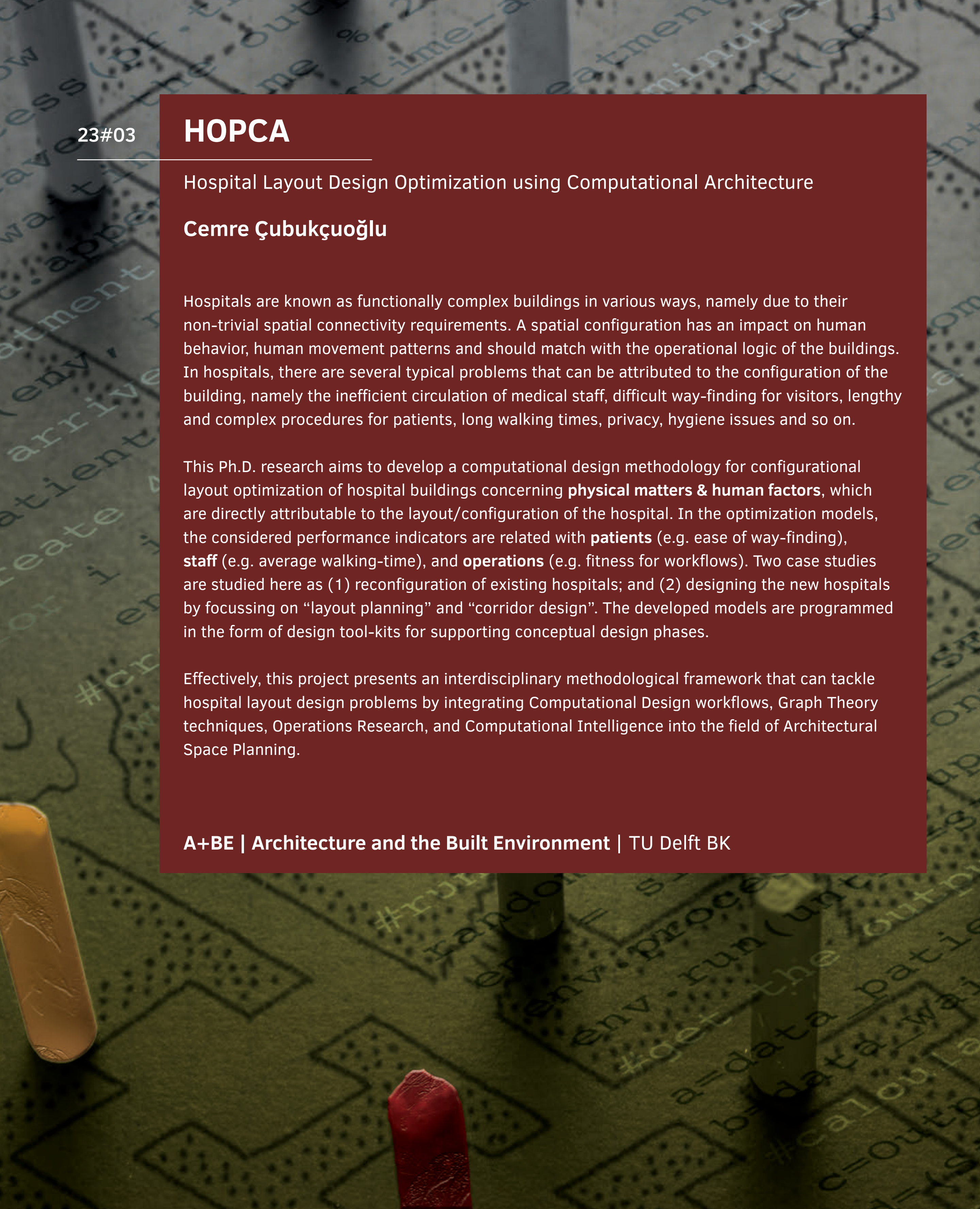

23#03

HOPCA

Hospital Layout Design Optimization using Computational Architecture

Cemre Çubukçuoğlu

Hospitals are known as functionally complex buildings in various ways, namely due to their non-trivial spatial connectivity requirements. A spatial configuration has an impact on human behavior, human movement patterns and should match with the operational logic of the buildings. In hospitals, there are several typical problems that can be attributed to the configuration of the building, namely the inefficient circulation of medical staff, difficult way-finding for visitors, lengthy and complex procedures for patients, long walking times, privacy, hygiene issues and so on.

This Ph.D. research aims to develop a computational design methodology for configurational layout optimization of hospital buildings concerning **physical matters & human factors**, which are directly attributable to the layout/configuration of the hospital. In the optimization models, the considered performance indicators are related with **patients** (e.g. ease of way-finding), **staff** (e.g. average walking-time), and **operations** (e.g. fitness for workflows). Two case studies are studied here as (1) reconfiguration of existing hospitals; and (2) designing the new hospitals by focussing on “layout planning” and “corridor design”. The developed models are programmed in the form of design tool-kits for supporting conceptual design phases.

Effectively, this project presents an interdisciplinary methodological framework that can tackle hospital layout design problems by integrating Computational Design workflows, Graph Theory techniques, Operations Research, and Computational Intelligence into the field of Architectural Space Planning.

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