Optimal Hospital Layout Design

Holst, Malene Kirstine

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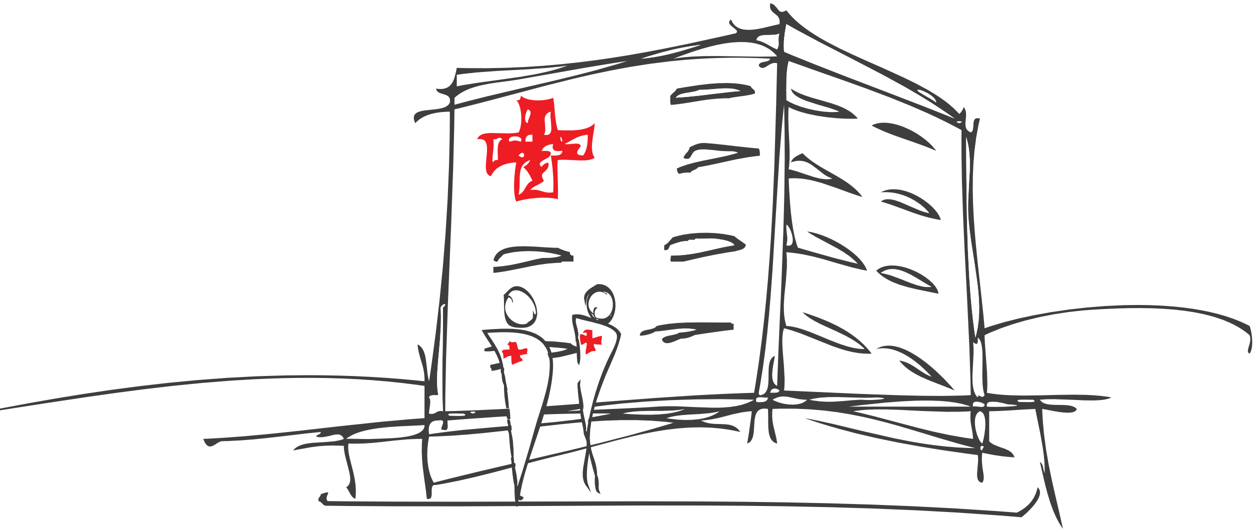

OPTIMAL HOSPITAL LAYOUT DESIGN

BY

MALENE KIRSTINE HOLST

DISSERTATION SUBMITTED 2015

AALBORG UNIVERSITY

DENMARK

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PhD supervisor: Prof. POUL HENNING KIRKEGAARD, PhD
Aarhus University

Assistant PhD supervisor: LARS D. CHRISTOFFERSEN, PhD
Technical University of Denmark, DTU Diplom
(Former research manager, ALECTIA A/S)

BIRGITTE FRIIS DELA STANG, PhD
ALECTIA A/S

PhD committee: Senior researcher, Head of department
JOOST VAN HOOF, PhD, Fontys University of Applied Sciences

Associate prof. KIM MOESGAARD IBURG, PhD,
Aarhus University

Senior researcher, EVA BIRGIT MØLLER, PhD,
Aalborg University

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CV

Malene Kirstine Holst graduated from Aalborg University in 2009 with a Master of Science degree in Engineering Architectural Design.

In her master's thesis, she studied performative architecture and tectonics, and defined the framework for 'Performative Tectonics'. She continued the work of her Master's thesis as a research assistant at Aalborg University, Department of Architecture, Design and Media Technology immediately after her studies. For two years, Holst researched and taught performative architecture, generative design and design modeling.

In 2011, Holst commenced the research on generative hospital design for this thesis. The organizational framework is Aalborg University, Department of Civil Engineering and the consulting engineering company ALECTIA A/S with more than 100 years of experience consulting in hospital design and construction.

ENGLISH SUMMARY

Hospital design is generally based on practice and standards implemented by experienced hospital planners, architects and authorities responsible for hospital construction, operation etc. Today's hospitals are subject to modernization by consolidations and increased requirements of efficiency, functionality and flexibility. With the computer development, opportunities emerge for implementing the use of numerical methods in hospital design for standardization, computation and visualization.

This PhD project proposes a numerical model for hospital design as the answer to the research questions driving the project. The research questions revolve around how hospitals can be conceptually designed as building entities that will respond to functionalities and around the question of the usability of systemized design models when applied to hospital functionality. The framework of the research questions is that the increased requirements of efficiency, functionality etc. of hospitals can be achieved by optimized design, and optimized design can be achieved by the involvement of systemized design models in the design process as a contribution to a more informed design process.

The basis of the model definition is the established mathematical models for layout design. The established models take their point of departure in computational problems of resources, rather than in optimized facilities, functionalities and performances. This project is based on an optimization the facilities, functionalities and performances, and so the project uses established mathematical models in the new context to solve the architectural design problem responding to functionalities and performances. This approach is emphasized by focusing on the practical applicability for architects, engineers and hospital planners for securing the usability of the design model.

While developing a design model for hospital design based on functionalities and performances, the model has to frame the engineering, architectural and political approaches to hospital design. By formal descriptions of the approaches, a design model can weigh and compare the impact of the different perspectives and, even in the early design phase, it can visualize and quantify consequences for design choices. The engineering objectives of cost and performance are easily transformed into quantitative input parameters, while the architectural objectives are more difficult to describe formally. By performing a qualitative study of hospital design and hospital functionality, a formal description of the architectural understanding is developed in a correlation matrix, as a significant contribution to the processing of the first research question. The correlation factor defines the framework for conceptual design, and this way the design considers functionalities and their

requirements and preferences. The correlation matrix facilitates implementation of evidence-based design as it is prepared for ongoing update. Actual data from hospital operation and governmental requirements and preferences define the matrix. The matrix secures the implementation of evidence in the design, and the design model facilitates it, so it is practically applicable for architects, engineers and hospital planners.

Through this PhD project a generative design model is developed. The design model generates and evaluates hospital designs as conceptual frameworks for further architectural explorations. The design concepts are generated based on the input from the correlation matrix with respect to the long-term performances and functionalities of the hospital. The design model visualizes and quantifies the costs and performances of the design concepts in the early design phases for qualified decision-making. This way, the design model provides transparency of the actual qualities and costs of a given design for informed decision-making and prioritization. This contributes to improved hospital design and more cost-effective hospitals, because choices are made on qualified and quantified information about the hospital qualities.

DANSK RESUME

Hospitalsdesign er generelt baseret på praksis og standarder, som implementeres af erfarne hospitalsplanlæggere, arkitekter og autoriteter med ansvar for hospitalsbyggeri, drift etc. Nutidens hospitaler er underlagt modernisering via konsolideringer og øgede krav til effektivitet, funktionalitet og fleksibilitet. Den computermæssige udvikling skaber muligheder for implementering af numeriske metoder i hospitalsdesign til standardisering, beregning og visualisering.

Dette ph.d.-projekt præsenterer en numerisk model for hospitalsdesign som svar på projektets problemstillinger. Problemstillingen fokuserer på, hvorledes hospitaler konceptuelt kan designes som bygningsenheder, der svarer til funktionaliteterne og spørgsmålet om anvendeligheden af systematiserede designmodeller, når de anvendes på hospitalers funktionalitet. Rammen for problemstillingen er, at de øgede krav til hospitalers effektivitet, funktionalitet etc. kan opnås via optimeret design – og optimeret design kan opnås ved at anvende systematiserede designmodeller i designprocessen med henblik på en mere oplyst designproces.

Modeldefinitionen er baseret på veletablerede matematiske modeller for layout design. De etablerede modeller er baseret på beregningsproblemer i forhold til ressourcer snarere end optimerede faciliteter, funktionalitet og ydelse. Dette projekt er baseret på en optimering af faciliteterne, funktionaliteten og ydelsen, således at projektet anvender etablerede matematiske modeller til at løse de arkitektoniske designproblemer med hensyn til funktionalitet og ydelse. Denne tilgang betones ved at fokusere på den praktiske anvendelighed for arkitekter, ingeniører og hospitalsplanlæggere med henblik på at sikre designmodellens anvendelighed.

I udviklingen af en designmodel til hospitalsdesign baseret på funktionalitet og ydelse skal modellen danne ramme om den ingeniørmæssige, arkitektoniske og politiske tilgang til hospitalsdesign. Gennnem formelle beskrivelser af disse tilgange kan en designmodel afveje og sammenligne effekten af forskellige perspektiver, selv i en tidlig designfase, hvor den kan visualisere og kvantificere konsekvenserne ved forskellige designvalg. Omkostninger og ydelser, som bygningstekniske mål, kan let omdannes til kvantitative input-parametre, mens de arkitektoniske mål er vanskeligere at beskrive formelt. Gennem et kvalitativt studie af hospitalsdesign og hospitalsfunktionalitet kan en formel beskrivelse af den arkitektoniske forståelse skabes i en korrelations-matrix, som et signifikant bidrag til behandlingen af problemstillingens første spørgsmål. Korrelationsfaktoren definerer rammen for det konceptuelle design, og på denne måde tager designet højde for funktionaliteten og dennes krav og præferencer. Korrelationsfaktoren faciliterer anvendelsen af evidensbaseret design, da den er forberedt for løbende opdateringer. Faktiske data fra hospitalsdrift og regeringsmæssige krav og

præferencer definerer matricen. Matricen sikrer, at evidens inkorporeres i designet, og at designmodellen faciliterer den, således at det er praktisk anvendeligt for arkitekter, ingeniører og hospitalsplanlæggere.

Dette ph.d.-projekt har udviklet og præsenterer en generativ designmodel. Designmodellen genererer og evaluerer hospitalsdesigns som konceptuelle rammer for yderligere arkitektonisk udforskning. Designkoncepterne genereres på basis af input fra en korrelationsmatrix med henblik på hospitalets ydelse og funktionalitet på lang sigt. Designmodellen visualiserer og kvantificerer designkoncepternes omkostninger og ydelse med henblik på kvalificeret beslutningstagen i de tidlige designfaser. På denne måde giver designmodellen transparens i forhold til de faktiske kvaliteter og omkostninger ved et givent design med henblik på beslutningstagen og prioritering på et oplyst grundlag. Dette bidrager til forbedret hospitalsdesign og mere omkostningseffektive hospitaler, fordi der træffes valg på baggrund af kvalificeret og kvantificeret information om hospitalets kvaliteter.

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Introduction

The costs of the health sector constantly increase and so it will be under a constant economic pressure. There is an ongoing development in treatments and technologies. New treatment methods and technologies allows treatment of known diseases. The development in demography and diseases create new lifestyle diseases, age-related diseases and increased comorbidity. The economic pressure increases because of the increased life-expectancy, and the development of especially the very demanding treatment for e.g. lifestyles diseases. In terms of hospitals this development is extensive and expensive, and prioritizing and planning are necessary. The health sector uses many resources on prioritizing and planning; planning of the use of facilities, staff and resources.

In 2007 the Danish Government launched a Quality Reform of the Danish health sector, ‘Kvalitetsfonden’. The Quality Reform consists of investments of more than € 5.3 billion in hospital constructions over the next 10-15 years (1) to make the facilities adequate for today’s needs. The investments are dedicated to a modernization of the physical framework of the health sector by constructing a number of new hospitals and modernizing a range of the existing hospitals, see Figure 1-1.

Figure 1-1 Map of ongoing Danish hospital construction. The constructions of the Quality Reform constructions are blue and the regional are yellow.

Danish taxes finance the health sector by block grants. The Danish health sector gives free and equal access to diagnostic and treatment services to all patients. The five Regions of Denmark manage the health sector. The Regions are under political management. They own the hospitals and manage the contracts with the independent general practitioners. The regions are responsible for capacity planning, general planning and prioritization (2).

Through the massive investments of The Quality Reform, the Danish Government encourages a process of consolidation and modernization of the physical framework of Danish hospitals. The consolidations of hospitals follow the consolidations of the municipal authorities into Regions. The number of hospitals is reduced from 35 to approximately 20 somatic hospitals. The reduction succeeds the development from 1980-2007, where the number of somatic hospitals decreased from 117 to 35 (3).

ALECTIA A/S is involved in a number of hospital constructions due to the Quality Reform, e.g. the two shown in Figure 1-2. ALECTIA A/S is a Danish engineering consultant with more than 100 years of experience in hospital constructions.

Aarhus University Hospital (2005-2019)	Køge University Hospital (2011-2020)
	
Project sum € 850 mil 250,000 m^2 (407,000 m^2 in total)	Project sum € 535 mil 130,000 m^2 (176,000 m^2 in total)

Figure 1-2 Aarhus Hospital is the first of the 16 projects of The Quality Reform. Køge Hospital is one of the last projects of The Quality Reform. ALECTIA A/S is involved in both projects.

The modernization through consolidation reflects a trend in hospitals (4-8). The trend anticipates that the professional quality and specialization will increase when concentrating treatment at fewer hospitals, because the critical mass increases. Moreover, the presupposition is that fewer consolidated hospitals provide a framework for utilizing resources more efficiently. An efficient use of resources is one of the main goals on The Quality Reform (1). The goals are:

- To achieve better and more cohesive patient treatment
- To improved patient safety
- To obtain greater efficiency and higher quality.

The hospital buildings ought to be more flexible and ready for the future. They need to be prepared for changes. Hospitals are constantly under reconstruction due to changes in technology, demography and approaches to treatment. The framework of the hospital constructions of The Quality Reform should secure improved utilization of technical equipment and facilities. The proposed method for this is by implementation of streamlined procedures, new technology and health innovation (1).

Hospital mergers and consolidations take place worldwide. The ambitions are financial and specialization benefits due to new and larger hospital constructions. Much research analyzes the cost benefit from mergers (9-16), while there will be less emphasis on the specialization benefits (17,18) .

The cost benefits of consolidations rely on different economic theories (3, 19-20). The theories of efficiency gains by expansion follow the theories of economies of scale and economies of scope. The efficiency of scope reflects the economic benefit for joint facilities by expansion of the product lines (3,12). In the studies by Gaynor et al. (20) the cost benefits are explored using the evidence of scope economies across specialties within the primary care and evidence of scope diseconomies across specialties in the secondary and the tertiary care.

The cost benefits in terms of scale economies reflect the decreased specialized costs due to increased utilization. Gaynor et al. present ample evidence for scale economies in the studies of primary care (20). The theories of scale economies assume that concentration into fewer units improves quality and the use of resources and thereby enhanced productivity in general (22).

For scale and scope economies, the cost functions consist of elements that are conflicting (16), and studies prove both economies and diseconomies across the level of care (20). Moreover, time influences the cost functions. The cost functions in the long term and short term are different (5,9,10) due to changes over time in inefficiency after the implementation of new routines, a conversion of effects etc. The cost functions on hospital economics are multi-product, because the hospitals produce several outputs, consist of several production lines with different performance objectives (10). The multiple production lines represent a major challenge in hospital cost functions.

Research into the impact of the physical framework on cost functions is rare. However, there is an anticipation that the construction of new hospitals and thereby new physical frameworks will increase effectivity. This perspective is a corner-stone in The Quality Reform (1). To achieve increased effectivity, the demands on the framework built must reflect the demands on the functionalities within.

The number of variables regarding the physical framework increases along with the increased mass of the large consolidated hospitals. The complexity in the hospital functionality likewise increases, and the production lines increase in either size or number or both. Consequently, the number of variables regarding the production of the hospital, the diagnosis, treatment and care of patients increases.

There are several trends in architectural design modeling that deal with the handling of numerous variables (23). These design approaches use computational power to manage, organize and use the variables that define central elements of the design (24). With this approach, it is easier to make changes in the input and alternative design outputs. This provides transparency of relationship between design requirements and design output (25). Consequently, the hospital design can benefit from computational handling of several variables, which describe the patient treatments, the current division of diagnostics, treatment and care and the building attributes. With this understanding, the problem statement and purpose of this PhD project is outlined in the following subsection.

1.1. Problem statement and purpose

The functionality of the hospital can increase when the design of the hospital improves. The design can benefit from using the potential in scientific computing. Scientific computing is concerned with constructing mathematical models and quantitative analysis techniques, in which computers and their calculative power are used to analyze and solve scientific and engineering problems. Observations of such successful implementations emphasize (24,26-33):

- improved clarity concerning the relationship between input variables and outcome.
- use of computational operations in terms of management, optimization and analysis the variables.
- use of digital models and computational handling entails the ability to make several iterations and alternative outputs fast and reliably.

Integration of scientific computing and its potential in architecture is based on the architectural development. Throughout architectural history, architecture has evolved according to available materials and technologies (34). One of today's technologies and materials is the computational potential. Applying computational potential in the design process allows for emerging design types with increased complexity (35,36). This problem statement is treated from an architectural perspective, where the computational potential is applied into the traditional architectural problem solving. The solutions emerge through iterations of sketching, evaluation and modification. According to this, the work deals with architectural problem solving by use of computation. The background of the research is in architectural design modelling and hospital design.

Increased transparency is an outcome of variables describing the central design elements (23,24,26,33,37). Transparency throughout the design process is a means to achieve the improved hospitals. The argument for transparency as a method relies on the complex nature of a hospital. The complexity requires simplifications in the initial design phases based on little information and overview of the consequences. The high complexity reduces the ability to foresee the consequences of design choices. There is a lack of transparency in relation to the consequences of choices made in especially the initial design phases, where relationships are unclear and/or undefined. With increased information on consequences, the choices can be made on an informed decision basis in order to optimize hospitals.

To obtain transparency of design consequences the central elements must be mapped and understood. The central elements of the participants are hospital design as an object and architectural modeling as a method. The following sections describe the participants.

1.2. Hospital design

Hospital design must be aligned with the fact that a hospital is a multi-product facility (38). The framework built must change and evolve along with technologies, demography and diseases. Moreover, the construction materials, construction technologies and design technologies influence the architectural development (35,36). An additional perspective is health economics, reflecting prevailing societal and economic trends. The latter is a primary driver in functionality planning.

The primary function of the multi-product facility is to enhance the health status of the patients (38). The hospital is a place for the diagnosis, treatment and care of the patients. The procedures and functionalities change as well as the relationship between them. Several variables and constraints can be used to define the relationships and requirements of the procedures and functionalities. The physical framework of the built environment encompasses additional variables concerning the inherent technologies, relations and spaces (39).

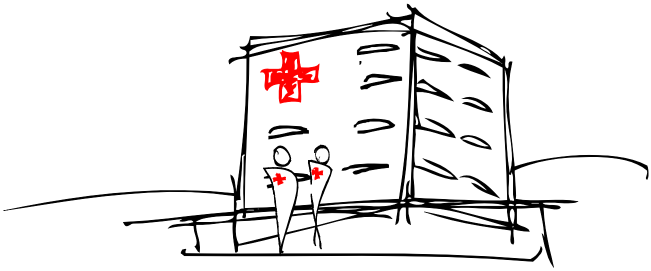


Figure 1-3 A hospital as a building – the facility framework

Several approaches to hospital design have influenced the built environment. It is easy to see the different approaches in Copenhagen's hospitals, where some are organized as towns with an emphasis on landscape and gardens and others are dominating constructions, raised high above the city and citizens. The present research project takes its point of departure in today's design approach in Denmark and Scandinavia. Today's approach consists of large and consolidated hospitals with the argument that they are more specialized and more cost-efficient due to the increased critical mass (3,6,40,41). The design approach should be evidence-based and patient-centred (1,42-44). Healing architecture is inherent in evidence-based design, where focus is on the healing environments of the building composition. The patient-centered design focuses on improved specialization, efficiency and patient safety e.g. due to coherent patient procedures.

1.2.1. Typologies of hospital design

In order to describe hospital design by variables, the design can be broken into typologies characterizing the differences. The background for the break-down will be explained in detail in Chapter 3.

It is possible to categorize hospitals recently built in Denmark and Scandinavia into different general typologies. By analyzing the overall building structures, it becomes evident how circumstances and contexts cause differences in the buildings in different situations. The typologies closely relate to contextual circumstances. A trend goes towards distributing the needed area of the large complex horizontally or vertically.

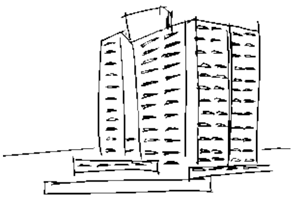
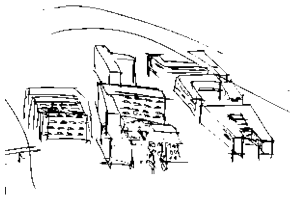
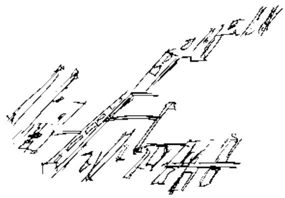
High-rise Vertical distribution	Urban Combined distribution	Campus Horizontal distribution
		
Herlev, Copenhagen Denmark	Skt. Olav, Trondheim Norway	OUH, Odense Denmark

Figure 1-4 Building Typologies

In Figure 1-4, a high-rise building illustrates the vertical distribution as opposed to the horizontal distribution illustrated by a campus typology. An urban hospital illustrates the mix between the two typologies, the combined distribution, with several building compositions of medium height. The basis for the building typologies originates from the physical context of the project of either city structure or greenfield. Along with the physical context, focus on scale and human relations is a driving perspective with interior-exterior integration and integration of green areas (45,46). The different building typologies are easily identifiable, as illustrated in Figure 1-4.

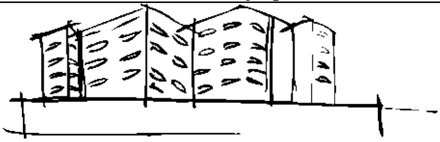
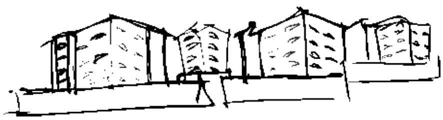
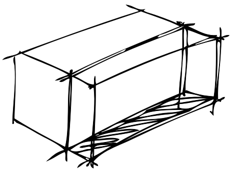
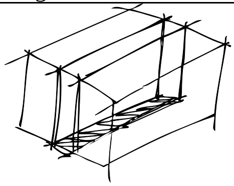
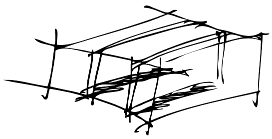
Functionally split	Traditional sectorized into specialties
	
Aalborg University Hospital, Aalborg Denmark	New University Hospital, Aarhus Denmark

Figure 1-5 Organizational Typologies

Parallel to the building typologies defining the outer framework of the hospital, two organizational typologies define the functional organization of the hospital. The organizational typologies are visually less easily identifiable. They consist of the traditional sectorized model or a functionally split model (45,46). The two approaches rely on different philosophies of efficiency, flexibility and patient focus. The traditional sectorized design approach takes its point of departure in the hospital specialties and patient treatment within the specialties. Because of this, all required facilities are organized within a department or specialty, ensuring that the hospital can be categorized as several hospitals within the hospital, as illustrated by Aarhus Hospital in Figure 1-5.

The functionally split model, on the other hand, joins the functionalities in larger entities and defines the departments of diagnosis, surgery etc. that are independent of the treatment or specialty. The organization is independent of individual patient treatments and functionalities respectively. The hospital can be categorized as a hospital factory.

Single Corridor, exterior	Single Corridor, interior	Double Corridor
		
Psychiatric Hospital Slagelse, Denmark	University Hospital Køge, Denmark	Hvidovre Hospital Copenhagen, Denmark

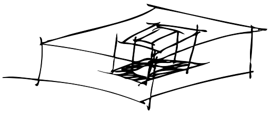
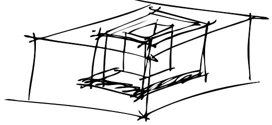
Corridor exterior, Courtyard	Corridor interior, Courtyard
	
Haraldsplass Hospital Bergen, Norway	Nya Karolinska Solna Stockholm, Sweden

Figure 1-6 Layout Typologies

For the physical organization within the built environment, different layout For the physical organization within the built environment, different layout typologies characterize the design approaches. The overall layout principles can be divided into five groups: 1) Single corridor exterior, 2) Single corridor interior, 3) Double corridor, 4) Corridor exterior courtyard, and 5) Corridor interior courtyard. The principles are illustrated in with three Danish hospitals with corridors, and a Norwegian and a Swedish hospital with courtyards.

The appearances and functionalities of the different layout typologies are based on daylight, views and integration of interior and exterior. Figure 1-6. illustrates the differences in the typologies with marked circulation areas and white functional areas. A decisive premise along with the appearance and functional qualities of the typologies is the gross/net factor (1,42-44).

1.2.2. Standardized framework for hospital design

The typologies of hospital design are one approach in describing a framework for the built environment. Another approach is through a standardized framework, where general principles valid the design. Along with The Quality Reformation, as described in the introduction, the Government founded an expert panel of consultants to counsel the Government in finance, quality and productivity within the hospital constructions.

The expert panel defined a standardized framework for hospitals, hospital design and the health sector, based on different evaluations within their respective professions (1,42-44). Their professions include physicians, architects and health economists. Having a deep understanding of the overall hospital structure, capacity utilization and economics, the expert panel defines principles for good hospital construction by:

- productivity and efficient resource utilization
- professional quality and patient safety
- the hospital as a workplace
- the patients' experience of quality and coherence

These general principles define the framework for hospital design along with a general commitment to best practice and evidence-based knowledge and standards. Moreover, the panel has worked out and decided on an adjusted financial framework. The framework describes conditions and dimensioning for the hospital constructions (1,44).

Table 1-1 Standardized conditions and dimensioning defined by the Government's expert panel.

Condition	Dimensioning	Comment
Occupancy	85%	With a large proportion of patients with acute problems
	>85 %	With a large proportion patients for elective treatment
Capacity utilization	7 h/day 245 days/year.	
Space standards	33-35 m^2	Standard for single occupancy rooms.
Gross/net factor	2.0	New somatic buildings
	1.8	New psychiatric buildings
Price level maximum	DKK 29,000/m^2	including DKK 5,800/m^2 for equipment, IT and furnishings.

Several requirements have derived from The Quality Reformation, and especially the principles for good hospital construction facilitate a standardized approach to hospital design. Table 1-1 illustrates, by listing occupancy and capacity utilization, how productivity and efficiency are focus areas. E.g. the projected occupancy of patients with acute problems of 85 % requires thorough planning of treatment procedures, bed-days and the physical framework. The people involved can plan the patient intake for patients for elective treatment, so the panel expects better bed utilization.

The requirements on capacity utilization and occupancy are combined with standardized conditions for definition of the physical framework. The framework is generic and defined by standardized variables or constraints. This outline of a standardized framework and the typological definitions of hospital design is the first element of the problem statement: the hospital design. The other element of the problem statement: Architectural design modeling follows this section.

1.3. Architectural design modeling

Architectural design modeling introduces the capacity to handle several variables with computation. A design model capable of handling complexities can facilitate the design process with information of design consequences on early design choices. As illustrated in Figure 1-7, the costs of changes increase when the design and construction develop. At the same time the ability to change decreases. Transparency of design consequences and outcome in the initial design phases can contribute with inexpensive changes in the design.

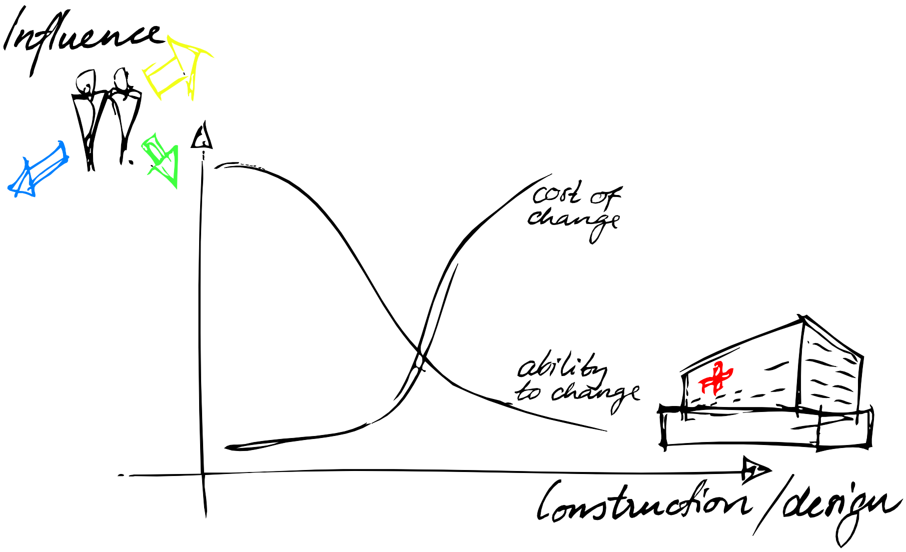


Figure 1-7 Influence decreases over time as design and construction develop. Meanwhile the cost of changes increases.

The transparency of consequences increases by the use of architectural design models making the total costs decrease (23-25,31,47-49). It is possible to program a standardized framework into the model as initial constraints. These initial constraints define the point of departure for the design. This way the design derives from a framework of standardized parameters and principles. This method has proven its worth when securing initial constraints and as a contributor to increased transparency of the consequences in the early design phases (25).

1.3.1. Design modeling paradigms

Several architectural, design-modeling paradigms have emerged through the use of computers and the computational potential. The paradigms emerge from form explorations of e.g. shapes of Non-Euclidean geometries, such as hyperbolic geometries, elliptic geometries etc. These explorations follow the architectural urge to experiment with shapes. An exploration of these shapes requires computational potential to handle the complex shapes and surfaces of complex geometries.

Genetic algorithm is a key concept within these architectural explorations. Algorithmic descriptions define a set of rules for the form exploration. The architectural concepts derived from genetic algorithms are within the framework of evolutionary architecture, where evolution and development expresses the architectural concepts (23).

The parametric design model embraces the form explorations and sets a framework for broader explorations. Parametric design emerges from the architectural design model, where a procedural, algorithmic description of the geometry defines and describes the parameters. Subsequently the parameters describe the intermediate construction of form, and form derives from the parameters as a reflection of the rules and the mathematical definitions. The resulting geometry becomes an exemplification of form defined by the parametric construction. It is easily possible to make several alterations to the design, because the different variations are inherent in the model (50).

The performative design model uses the parametric construction and the broad definition of performances drives the form finding. The design model uses the computational potential to handle the building performances as design principles. This way, quantitative and qualitative performance-based simulations can define the rules and parameters of the intermediate construction (24).

The design models have developed along with the development of the potential in scientific computing and the applicability of computation in design software. The development of soft computing techniques is evident for this applicability. Soft computing operates with approximations and imprecisions, which is very useful for design configurations with several variables (187). Soft computing is entirely different from hard computing, which requires a precisely stated analytical model in order to produce exact solutions. Computing time in hard computing is extensive, and the requirements for stating an analytical model are extensive because it has to be precise. Soft computing is useful in design because it uses the techniques of exploiting the tolerances of imprecision and uncertainties to design problems (51). It uses approximation and imprecision to achieve practicability and robustness as opposed to hard computing.

In hospital design, the complexity is high, and there are several imprecisions and uncertainties. Therefore, it is expected that the algorithms for soft computing can be used to create transparency in relation to the complexity and approximately optimize despite the imprecisions and uncertainties. Soft computing has proven its efficiency in especially complex systems (52).

1.3.2. Hospital design in practice

For the last decades, the industry of especially manufacturing companies has used automation of processes for layout design generation. The requirements for design in the production industry are parallel to those in hospital design. This analogy highights that more efficient and care-focused hospitals can be made by applying the known spatial configuration or route path planning (53,54) in the definition of the process and facility layout design (55-60).

Hospital design consists of the same issues to be found in industrial production. The issues to consider are: Low productivity in terms of supply shortage, queues and delays, bottlenecks, waste of resources, lengthy stays, inappropriateness of clinical settings and workload variability.

Digital tools have been developed to deal with these issues; however, researchers have mainly used the tools to analyze hospital systems with a focus on two areas: one is optimization and the analysis of patient flow; and the other is allocation of assets to improve the delivery of services (61-64). Research in digital tools for solving the design problem focuses on computer potential and solving the design problem computationally (65-68).

It is evident to apply the automated processes and genetic algorithms in the appropriate phase of the design process to solve the problem by defining a design model. Like before, experience from industrial production and general architectural engineering can inspire.

There are six main phases of 13 project phases in an architectural engineering project. The phases describe the process from analysis to operation cf. Table 1-2. The main phases work as collective designation for one or more project phases. The main phases illustrate a simplified form of the design process of a project.

Table 1-2 ALECTIA A/S General Information Delivery Manual, describing project phases in architectural engineering design. The model is inspired by project phase defined model by the Danish Association of Consulting Engineers (69).

Main Phases					
Analysis	Planning & Design	Tender & Contract	Execution	Tests & Acceptance	Operation
Project Phases					
1: Strategic Analysis	3: Project Possibilities	7: Tendering	9A: Design Follow up	11: Test and Training	13: Operation
2: Business/tec analysis	4: Project Definition	8: Contract	9B: Contractor design fol.	12: Acceptance hand-over	
	5: Project Planning		10: Execution		
	6A: Detailed Design				
	6B: Functional Design				

Phases 1 and 2 cover mainly stand-alone tasks that, as a precursor for the following phases, define the outline of the project. Phases 3 to 12 are the recommended sequence for the execution of most projects. Phase 13 can be a successor of phase 12, but it also covers stand-alone tasks.

Design modeling in architectural engineering involves the second main phase of planning and design based on Analysis. Phases 1 and 2 are stand-alone tasks that define an analytical model for the second main phase. The analytical model contains imprecisions and inaccuracies and indicates the applicability of soft computing techniques. By applying soft computing techniques, a project’s possibilities and definitions are identified initially by alternatives and exemplifications of inaccuracies. Soft computing contributes with a mapping of project possibilities and definitions while creating a basis for decision-making. The soft computing techniques are applicable in the Main Phase of Planning & Design. This way the initial design phases can be provided with an informed foundation for decision-making. This is very beneficial in large constructions where the dependencies are complex, which includes hospitals.

1.4. Research motivation and goal

The massive investments by The Quality Reform caused a lot of focus on hospital design and construction. A motivation for The Quality Reform is to improve patient treatment and reduce the costs by new hospital constructions. The claim of this research project is that computational design modeling can improve the design of hospitals because it creates transparency. This way consequences and relationships contribute to the decision-making processes and the design decisions are informed.

Society expects improved hospitals given the new constructions. This research claims that the potential in computational modeling can improve the functionality and thereby the architectural quality. With this approach, the goal is better functioning hospitals with higher patient satisfaction, improved conditions for the personnel and an optimized operation in general. Society will benefit from this on many levels. Directly, the running costs of the hospital will be reduced and consequently the expenses of society will go down when the hospital processes the patients more efficiently. Faster and better treatment of patients will affect the direct costs of the hospital due to a shorter hospitalization period and lower medication and personnel costs. Better treatment causes fewer re-hospitalizations, which will lower the indirect costs and the economic burden of the hospital will fall. However, some societal costs are merely transferred to other sectors as a contribution to the general economic pressure on hospitals.

Moreover, the combination of computational modeling and hospital design will contribute to the new knowledge accumulating along with the hospital constructions. Internationally, Denmark attracts attention because of the massive investments in hospital construction. It is a general expectation in society, and for the involved consultants, that the participants have expert knowledge of the state of the art in hospital construction that can be exported. Society and the involved consultants expect to benefit from this export in maintaining market shares and helping to secure Denmark’s status as a knowledge society and to gain new market shares.

The aim of this research is to contribute the knowledge accumulated from the ongoing construction projects. The combination of hospital design and computational modeling will contribute to the knowledge accumulation within the consulting companies on hospital design. It contributes with transparency in relation to improved and accelerated design processes. The contribution in literature relies on the background of this research in architectural design modeling and hospital design. Consequently, this research will contribute to the literature within hospital design, such as Lohfert (70), and literature in design modeling, methods such as (23,24,26,31,33). The decomposition of hospitals into operational variables is a knowledge contribution to research into architectural design models exploring shapes and emerging architectural paradigms. This contribution provides new knowledge of the relationship between architecture and a hospital, which can be generalized into other design subjects.

1.5. Research questions and hypotheses

The main goal for this research project is to contribute to increased hospital functionality using improved hospital design. The contribution is based on the potential of scientific computing, as described in the problem statement. Systematically, computation is applied into the design model, such as in the parametric design model, which operates systematically with computation representing a systemized design model. The purpose is to secure transparency throughout the design process as a method for improved design. Based on the research motivation and goal, the two following research questions will make up the problem statement:

- How can hospitals be designed conceptually as building entities that respond to functionalities?
- What is the usability of systemized design models when applied to hospital functionality?

1.5.1. How can hospitals be designed conceptually as building entities that respond to functionalities?

The hypothesis is that hospitals can be designed as building entities that respond to the inherent functionalities. The framework for the hypothesis is given by the variables, the population and the relationship:

- the variables are the components or building attributes of the building entity. The composition of the components defines the building entity.
- the population is the hospital functionality and the multiple production lines of the hospital facility. In this way, the population reflects the different treatments, technologies and evaluation parameters.
- the relationship between the variables and the population is the essence of the hypothesis and what is investigated in this part of the doctoral research, meaning the relationship between building attributes and hospital functionalities.

The hypothesis elaborates on statements such as ‘Form follows Function’ which have inspired architecture throughout history. This is a contemporary approach of ‘Form follows Hospital function’.

This approach contributes to the architectural research of computational modeling, where the question of solving the architectural design problem remains unanswered. Much research in architectural modeling regards geometric exploration and the computational potential. Answering this research question is a central contribution to practice. The purpose is to allow practitioners to use the computational modeling techniques to functional problem solving.

Practice must solve the architectural design problem of the complex hospital, where the building is required to be efficient and functional. Given this approach, there is an anticipation that structuring and designing the buildings as entities that respond to functionalities will increase architectural quality and quality of hospital operation throughout its life cycle. The design paradigms will change if it is possible to implement these technologies in practice, It will increase decision-making basis for lower costs of changes in the early phases. Consequently, consultants and developers will benefit.

1.5.2. What is the usability of systemized design models when applied to hospital functionality?

The hypothesis is that the use of systemized design models influence the hospital functionality. The framework for the hypothesis is given by the variables, the population and the relationship, as described by:

- the variables are the technologies of systemized design models, being visualization, optimization and evaluation.
- the population is the hospital functionality and the multiple performance objectives. In this way, the population reflects the performances of the different treatments, technologies and evaluation parameters.
- the relationship between the computational technologies of systemized design models and the hospital functionality is what this part of the research project investigates.

This research question is based on the development of computational modeling in architectural design. It is possible to perform and implement qualitative and quantitative evaluations during the design process. These potentials are related to increased computation power and the development of imprecise techniques, where approximations are allowed. Research in computation and computational problem solving has addressed these subjects. However, application to practice and visualization of real life optimization remains. The existing research deals with the possibilities and optimization of the techniques from a computational perspective.

The background for the hypothesis is that the use of systemized mathematical models can evaluate the hospital functionality even on an approximated and inaccurate information level. This information level is present in the early design phases when the impact of changes is the highest. The evaluations will contribute with the transparcy of the complex and interrelated functionalities.

Transparency throughout the design process can facilitate the right decision-making in the early phases with respect to functionality, cost, efficiency and flexibility. Therefore, the hypothesis is that the use of evaluation, optimization and visualization in the design influences the functionality of the hospital, which would be valuable for hospital planners, architects and decision-makers.

This part of the research project contributes with an approach for optimized hospital design, where six performance evaluators describe the overall hospital functionality. This approach brings transparency to the overall hospital performance with respect to the interdependencies between the individual hospital functionalities.

It is a contribution to practice that supports the design process with qualitative and quantitative analyses. This will be new knowledge in quantitative and qualitative evaluations of hospital functionality.

1.6. Research methodology

The present research is multidisciplinary. It is an attempt to solve the architectural design problem by using computational techniques. This way, it relies on several methodologies within architectural research. Architectural research requires knowledge of an array of phenomena from physical properties to visual perceptions (71). The system of inquiry in architectural research is within the natural sciences, the social sciences and the humanities. It is multidisciplinary in the methodological framework.

The system of inquiry of the research questions is within the natural sciences of positivism. The research questions are framed by the articulation of the objective system of inquiry. The objective system of inquiry represents the engineering framework of this architectural research. It utilizes methods and models that are based in what is measurable. The basis is a problem, as described by the research questions. The answer presents a hypothesis in the form of a theory or a contention describing the variables, the population and the relationship of the hypothesis. The theories are tested through inductions or deductions, observations or analysis of the world of physics (72).

However, the research design follows the subjective and the objective systems of inquiry in the model generation and verification. This follows the framework of architectural research that includes both the subjective and objective systems of inquiry (71). The objective and subjective systems of inquiry are combined into a continuum where the subjective and the objective are at either end (71). On this continuum any given tactics lends itself to a variety of uses according to the orientation of the researchers (71). A variety of both strategies and tactics can be orchestrated in ways consistent with the research design (71), as illustrated in Figure 1-8.

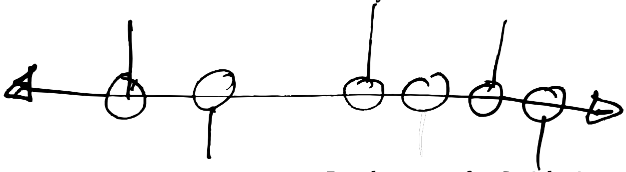


Figure 1-8 Conceptual framework for architectural research. The illustration is a reproduction based on Groat and Wang (71).

The objective and subjective systems on inquiry can by placed in the research clusters of positivism and naturalism. In positivism, the theories develop in a process of doing tests on the real world, i.e. inductions or deductions. Karl R. Popper describes the principle of induction as a synthetic statement, whose negation is not self-contradictory but logically possible (72). It is a prerequisite that the objects are physically present and available for the application of theories when analyzing or observing the behavior. The objects prove the physical data independently of time and space. It is a prerequisite that another competent person will conclude the same by following the given method. This statement characterizes the method as objective (72).

The subjective system of inquiry describes the naturalistic paradigm of qualitative, phenomenological and hermeneutic theories (71). The understanding of form and the ability to develop spaces typically relate to perception and the subjective. It involves a relation between time and space in contrast to the objective. Time and space are decisive parameters in the subjective systems of inquiry. Martin Heidegger describes the prerequisite by the way, in which man depends upon himself and his stand in relation to whatever is the objective (72).

This system of inquiry is the active process of perception. The subject opens its world and shows itself. The object's structure is determined by the options given culturally to the subject. The perception defeats the dualism of body and mind, because observable objects are understood in relation to the subject, as a body entering the world (73).

The integrated process of architectural problem solving with use of computation requires a system of inquiry with a reciprocal interaction between the objective and the subjective systems of inquiry (71). Hermeneutics is the system of inquiry that tries to explain the meaning of the single phenomenon from its context. It is a theory of interpretation. It is not reasonable trying to explain the phenomena from general formulas like science. Hans-Georg Gadamer describes how the interpretation broadens like a movement of the horizon. The horizon broadens by involving with the unknown (72). It starts with a thesis, which is tested by an antithesis, similar to the deductions of the objective established theory. However, hermeneutics advanced the thesis to a synthesis by not taking the immediate appearance as the whole truth. Insight broadens the horizon and the broadened horizon broadens the understanding. This perspective is a safeguard against missing the whole truth of the phenomenon (72). It is the interrelationship between the part and the whole, or the text and the context that defines the synthesis.

In the present research, the methodological framework involves the objective and subjective systems of inquiry. The research questions are articulated based on the objective system of inquiry, but the terms are within the subjective.

One of the contributions of this research is the quantification of architectural qualities as a derivative of solving the architectural design problem by computation. This requires the use of the different research designs. The approach uses and touches several research methods from the positive and naturalistic research clusters.

The investigation of the phenomena of the hypotheses and contribution with new knowledge rely on previous knowledge from the architectural field, the engineering field and the field of computer programming. The scientific objective strategies and tactics are based on the measurable and empirical evidence of hospital functionality and architectural design. The data on hospital functionality are operational data from two regional hospitals in Denmark: Herlev Hospital and Hillerød Hospital. The data represents a sample of the extensive mapping that Danish hospitals create.

Data on architectural design are the functional and physical requirements which the Governmental expert panel have defined and documented in the material of the Quality Reform (42,43). The data on architectural design also derives from several design competitions in connection with hospital constructions (45,46,74,75).

Modeling research reflects a simplified handling of the evidence. The simplifications are based on the description of hospital design in the introduction, where typologies define a framework. The simplifications make it possible to model using real-life data and to reproduce and evaluate relationships and sensitivities.

The following subsections outline the primary methodologies of this thesis. The two first subsections define the objective strategies and tactics of the mathematical and computational approach. Subsection 1.6.3 and 1.6.4 outline the subjective strategies and tactics regarding the architectural analysis. The three last subsections regard the definition of the design model primarily using subjective strategies and tactics. The subsections concern the hermeneutic method of interpretation.

1.6.1. Simulation and modeling research

Model and simulation are closely related. Simulation and modeling research emerges from various types of models and simulations. Models can exist in various forms from mathematical numerical expressions to physical models.

There are four types of simulation models: iconic, analog, operational and mathematical. The iconic and analog models relate to the physical context. The operational models relate to the interaction within the physical context, and mathematical models are systems of numerical coding capturing real-world relationships in quantifiable abstract values (71). The latter forms the framework of the present research project by capturing the real-world relationships of the hospital.

Co-variation of multiple factors is evident in simulation research, and the external manipulation of variables is an essential characteristic of simulation research (71). The external manipulation of variables and the numerical coding of real-world relationships is the essence of parametric modeling research.

1.6.2. Parametric modeling

Parametric modeling defines the construction of the design model. The parametric model consists of descriptions of formal behavior, defining the structures of the design, based on the various criteria and described by formal behavior. The construction reflects the research question of how to design and object, in this case: a hospital, where the design responds to the functionalities and the inherent behaviors.

Parametric modeling is the process in which several parameters define the starting points and the design emerges as alternates defined by a given set of parameters, relations and behaviors. Parametric modeling is finding a form from a set of parameters by extracting the problem: define it and define the boundaries, the starting points and the requirements. The will be solutions found to the problem, the design alternates, within the boundaries. Hence, the method emphasizes performance over appearance and processes over representation (29). A very relevant approach for hospital design, where solving the performance problem of the hospital is essential for solving the design problem.

1.6.3. Qualitative analysis

Qualitative analyses of existing hospitals are necessary in order to define the parameters of the model. Such analyses investigate the why and how of hospitals in order to produce information for particular cases within hospitals design. By doing so, it outlines general conclusions and parameters for modeling research. The qualitative analysis provides information for the identification of the different behaviors and concepts in the hospitals and hospital design as well as a qualification of thereof (71).

1.6.4. Case study

Case study is a method used along with the qualitative analyses. A case study investigates the state of the art of hospital design. Based on an empirical inquiry the case study is an investigation of a contemporary phenomenon within its real-life context. Case study is especially applicable when boundaries between phenomenon and context are not evident enough (71).

The present research project uses the case study research as a method of investigating the contemporary performance of hospital design. The following five primary characteristics define a case study and the output of case studies.

1. A focus on cases in their contexts
2. The capacity to explain causal links
3. The importance of theory development in the research design phase
4. A reliance on multiple sources of evidence, with data needing to converge in a triangulation
5. The power to generalize to theory

The five characteristics describe the framework of having an initial theory, that is tested by a case in a given context. By the study of cases in different contexts evidence is transformed into a general theory (71). In this way, the case supports and develops the initial theory into a general theory in a hermeneutic manner.

This doctoral research performed with a close relation to practice includes case study research at different levels. During the research project, case study research is used for data collection by participation in the design groups of selected hospitals.

1.6.5. Correlational research strategies

There is an extended similarity between correlational research and simulation research. Co-variation of multiple factors is evident in both cases. The independent variable reflecting external manipulation makes simulation research essentially different from correlational research (71). In correlational research the independent variable does not play a role in the correlational studies.

During the process of this doctoral research correlational research strategies are applied to understand and describe the hospital as relationships, correlations and variables. The relationship studies focus on the nature and predictive power of the relationships. Meanwhile, the casual–comparative studies hold an intermediate position between the predictive orientations of relationships and a focus on causality. The experimental research characterizes the latter. Correlational research typically seeks to clarify patterns of relationships between variables (71). The common data collection techniques and analysis techniques are present in other research design methodologies. In the present research study, data collection and analysis techniques are a combination of coding, observations and mapping.

1.6.6. Lateral thinking

Lateral thinking covers the research strategies applied to achieve an understanding of hospitals.

Lateral thinking allows problem solving through an indirect and creative approach by the use of reasoning. Reasoning does not need to be immediately obvious, and it can involve ideas that may not be obtainable by traditional step-by-step logic. Lateral thinking distances itself from the traditional vertical method for problem solving and perception in patterns, which is efficient but can limit creativity. Lateral thinking is concerned with the movement value of statements and ideas. It is lateral thinking in line with the designers' mentality of seeking alternatives to the given framework rather than finding a solution within the framework. By using traditional thinking and problem solving, the objective is to get a solution to a given problem. Meanwhile lateral thinking produces alternatives where the given problem appears. Lateral thinking often leads to the identification of problems that were not initially identified (71).

1.6.7. Space syntax

Together with parametric modeling, space syntax is a methodological cornerstone in the research project. Space syntax is the theory of arranging spaces in buildings based on the relations between people (39). Space syntax is a method for analyzing spatial configurations, especially where the spatial configuration seems to be significant for human affairs. Consequently space syntax is seen to be highly relevant in buildings hospitals, where the implications for human affairs is a focus area.

Professor Bill Hillier and colleagues originally conceived space syntax in the late 1970s and early 1980s as a tool to help architects simulate the likely effects of their designs. The general idea is that spaces can be broken down into components, analyzed as networks of choices, and then represented as maps and graphs describing the relative connectivity and integration of spaces (39). The decomposition and description of components attempt to facilitate a quantification of design as well as a description of way finding. Therefore space syntax has also been applied to predict the correlation between spatial layouts and social effects in architectural research i.e. clustering of people, path definition in open spaces etc. (39).

Space syntax is a method that represents space by its topological structure and translates its social meaning. The measures taken to identify a spatial structure are mostly borrowed from network theory. The spatial relations interpret the sense of adjacency and accessibility in the definition of relationships that link spaces together (39).

1.7. Summary

This chapter defines the problem statement for this PhD project and introduces the topics of the hospital design and architectural design modeling. The title is Optimal Hospital Layout Design, which emphasizes the problem statement that functionality can increase, when the design of the hospital improves. The statement uses the computational potential to enhance the design by optimizing the layout.

The problem statement explores hosptial design and architectural design modeling, which proved the vasis for the two research questions. The first research question investigates in how hospitals can be designed conceptuallly as building entities that respond to functionalities. The contribution of new knowledge with regard to this is in architectural modeling and hospital decomposition. The knowledge contributes to the defininition of a design model, where measurable and empirical evidence are input parameters. Meanwhile, it supplements by quantifying the architectural qualitative parameters. The hospital decomposition is an attempt at a simplified description of the hospital functionalities into variables for increased transparancy on the multiple production lines. This framework is applicable in archtiectural design modeling.

The second research question is based on computational modeling and the potential of optimizing, evaluating and visualizing quantities of qualities. The hypothesis is that the computational modeling influences the functionality of the hospital, because the planning and prioritization of the physical framework of the hospital is clarified with a quantification of the functionalities. This research question is based on research into computational modeling and uses the established methods. The contribution is an exemplification of integration of real-life data into the simplified models. The emphasis is on the architectural applicability and the ability to solve architectural design problems as the numerical methods are already developed.

The research project is motivated by the development in computational design modeling as an approach for improving hospital design for the benefit of patients, personnel and society in general.

1.8. Outline of the thesis and scope of the work

The thesis consists of three main parts.

Part one introduces the research field. It consists of Chapters 1 and 2 outlining the framework for the research project.

Part two consists of Chapters 3, 4 and 5 processing the research problem of how to design hospitals conceptually as building entities that respond to the functionalities of the hospital. Part two involves the transformation of the architectural understanding of hospitals as building entities into a formal description resulting in a numerical design model.

Part three focuses on the second research problem, i.e. the usability of systemized models on hospital functioning. Part three describes a numerical model definition in Chapters 6, 7, 8 and 9.

The thesis concludes with Chapter 10 with a discussion and summary of the work. This puts the research questions into perspective.

Several appendices follow the main text of the thesis. They include the correlation matrices that derive from this research and work as input for the developed design model. The appendices also consist of several examples of results by the design model.

The chapters of this thesis cover:

Chapter 2 sets the framework for the PhD project by outlining the research fields of hospital design and architectural design modeling. The chapter describes the hospital as a design object, hospital design as the subject, and architectural design modeling as the methodological framework for the problem solving.

Chapter 3 introduces the theory and defines the framework for architectural design modeling. It sets a decomposition of the hospital as functionalities framed by a building as the physical framework. The chapter outlines a formal description of the architectural typologies for architectural design modeling. The architectural typologies for hospital design consist of the three general typologies presented in the Introduction: The building typologies, the organizational typologies and the layout typologies. This chapter outlines the typologies.

Chapter 4 defines the data for the design model. The hospital is decomposed into functionalities described by a correlation matrix for implementation in a numerical design model. The correlation matrix mathematically describes the architectural requirements and preferences for correlations between functionalities in the hospital. The correlation matrix relates evidence regarding patient treatment, patient treatment processes and hospital functionality to architectural requirements and preferences.

Chapter 5 describes schematically the evaluators of hospital design. The evaluators are architectural, engineering and functional requirements and preferences regarding hospital design. The schematic and formal descriptions prepare the data for implementation in a design model. The evaluators combine a formal description of architectural, engineering and functional perspectives.

Chapter 6 presents the theory of numerical design models and describes the framework for the model making based on established models and research into layout design.

Chapter 7 is the numerical implementation of a hospital design model. It is the definition of the intermediate construction of the design model. Along with the definition of the design model, the chapter defines the cost functions. The cost functions evaluate the design configurations generated by the design model.

Chapter 8 implements the design model and evaluates the design configurations based on principal drivers. In this chapter, the design model is modified for appropriate design configurations and evaluations.

Chapter 9 evaluates the usability of the design model by the results of design configuration. The chapter exemplifies the resulting geometry generated by the design model and discusses the usability of the model in the hospital design context. This chapter draws parallels between the architectural design model and practice. Usability and application are of paramount importance when it comes to practice benefitting from the design model.

Chapter 2.
Framework for Architectural Hospital Design

Designing a hospital facility is based on the traditional architectural engineering design process. This chapter elaborates on the introduction to the fields of hospital design and architectural design modeling. Hospital design is part of architectural design. It is a specialization within the architectural engineering discipline in hospitals. Hospitals as objects are very complex, and there are several requirements and preferences in relation to the design. This chapter will define hospitals as design objects.

Architectural design modeling is a method within the architectural engineering discipline. The conceptual structuring of hospital design is within the second architectural engineering design phase Planning & Design, as defined in the introduction, as appears from Table 1-2.

The method of architectural design modeling and conceptual structuring and their development will be dealt with in this chapter. As stated in the Introduction, this and hospital design are the two main fields defining the framework of this research.

2.1. Hospital design

Hospital design is a specialization of architectural design. The design of hospitals is complex because of the multiple production lines and performance objectives. The decision-making in hospital design is likewise very complex. In Denmark, where the Regions own the hospitals and the Central Government funds the operation by block grants, the decision-making is very political. This perspective combined with the ongoing economic pressure because of prioritizations according to the development creates a need for prioritizing the different performance objectives in the decision-making.

This section will elaborate on the outline of hospital design in the Introduction based on the design phases of Table 1-2. The state of the art in hospital design defines a conceptual design model and outlines elements to be incorporated in the design. This section is a result of a combination of literature review and case study research. The literature review outlines the state of the art in research. The basis for the case studies is participation in user groups and design teams for actual hospital projects.

It is in the main phase of Planning & Design, Table 1-2, that the participant chooses the framework of the design. Planning and designing develop in collaboration with architects, engineers and hospital planners in a dialogue with user groups, developers and stakeholders. It is a time-consuming process, where numerous stakeholders, as illustrated in Figure 2-1, contribute to the process. The composition of the user groups is broad, and the contributions are based on reference hospitals, treatments and technologies. It becomes difficult to reproduce the design process and the prioritization is difficult because there is little transparency in relation to the consequences of the potentially conflicting contributions from e.g. technicians and relatives.

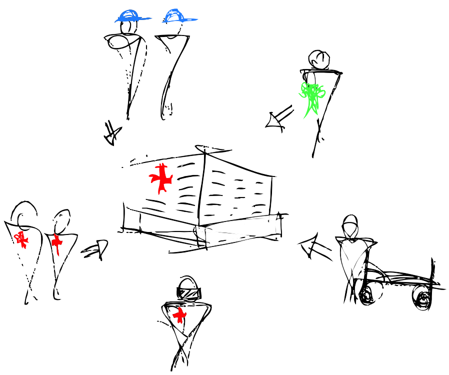


Figure 2-1 Hospital stakeholders are physicians, nurses, technicians, relatives and patients as well as developers and politicians. All possess individual approaches to the hospital and its design.

Conceptual design is in the initial Planning & Design phase. Conceptual design of the hospital facilities is a profession within the architectural engineering profession with a health-related specialty. It is parallel to other construction projects but the health-related specialty dominates the design process, and e.g. Lohfert (70) has developed a specific design model for hospital design.

2.1.1. Conceptual hospital design

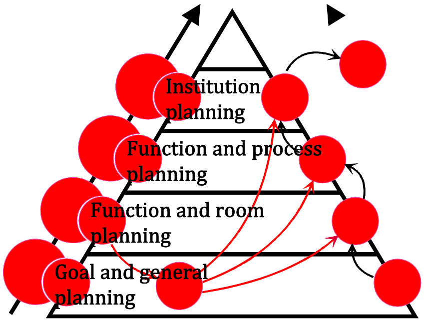


Figure 2-2 Illustration of the process of the method for hospital design (70). The design approach described from Goal and general planning of the hospital to Institution planning.

The design model in Figure 2-2 illustrates how the ‘Function and room planning’ influences the ‘Goal and general planning’. This is an expression of the integration of the health speciality in the design process. It is the ‘Function and room planning’ that defines the general plan for the hospital.

‘The Goal and general planning’ defines the basis for the design and development. The design process is a development and detailing of the design. ‘Function and process planning’ follows the defining ‘Function and room planning’, and the ‘Institution planning’ is the final planning of decoration and furnishing, where the institution is ready for operation.

The conceptual hospital design is parallel to conceptual architectural design consisting of area and function distribution. The distribution of the different areas and functions is aligned with design principles and volume studies.

2.1.2. Hospital design research

Benchmarks and practice dominate hospital design (76,77). However, research increasingly influences the profession, and the hospital owner requires an increased application of evidence-based design (1,45,74,75). Design-based research emphasizes the potential by improving and qualifying the architectural argumentation and discussion in overall terms (78,79).

Health care management and health economics have a strong relation to research. Much research analyses health care management and economics (3,6,10,18,80-83). Analyses of hospital operation also influence research, e.g. patient flow has gained much attention in management literature over the past few decades (84). However, the application of the patient flow analyses in the design process for influencing the built framework remains. The same applies to the application of the automated processes of transportation etc. The research fields are theoretical and regard analyses while the application in practice remains.

Healing architecture is the most dominating research field currently influencing the profession. It proposes better surroundings and healing atmospheres for patients (85,86) as effects of the built environment (87-92). The research presents analyses of patient health status showing reductions in depression, stress and pain caused by the impact of healing surroundings due to e.g. a view of green surroundings, natural lighting and exposure to sunlight (85). The practical translation of healing architecture is patient safety and hygiene (45,46,74,75), which is easier implementable and measurable than healing architecture.

The method of healing architecture establishes empirical knowledge of healing performances in architecture. Healing architecture consists of scientific knowledge from pioneering studies from the 1980s and forward. It has improved the health outcomes and safety of patients, along with documented shorter hospital stays, less medication, and less nursing care (85). Patient satisfaction levels are high when the following central elements are present:

- Access and view to gardens and nature
- Exposure to sunlight
- Natural lighting

Much hospital research emphasizes Ulrich’s (85) approach and healing architecture, which can be seen as a central element when aiming for increased efficiency and productivity in hospital operation. Payne et al. (93) outline the following aspects in continuation of the healing architectural perspectives introduced by Ulrich:

- Maximize natural lighting and use artificial light carefully
- Manage sound levels so that a quiet, peaceful center is created
- Use plants
- Use tonal colors to provide contrast for those with impaired vision
- Avoid strong colors, which can be over-stimulating for those with mental health problems

Further studies suggest improving the physical framework in terms of structuring the complexity of interrelated functions and movements of people, equipment and supplies by highlighting (94):

- The creation of a framework for multi-professional design
- A standardization of hospital processes
- An improvement of patient safety and a reduction of medication errors and hospital-acquired infections
- Enhancement of hospital accessibility and ergonomics
- Ease of navigation and way finding
- Visualization of work processes

The highlighted aspects become the guidelines for the standardization of procedures, improvement of way-finding and reorganization of the interrelated functions. The latter relates to the extensive research into lean in hospitals (95,96) from a logistical perspective analyzing the production lines as supply chains. There are several studies of lean and best practice in hospital design and organization (97-100) along with studies of innovation in technology and workflows (63,65,66,68,101-114).

Studies of patient experiences suggest quality improvements for the patients (115) and streamlined procedures for minimizing the risk of errors, as well as less personnel involved and fewer different places (116). The criteria are also outlined in the introduction as terms of efficiency and cost benefit (9-16).

Management literature and hospital design literature encourage using patients and patient procedures as the central object for the design generation.. One way to achieve that is through improved patient flows. Studies of patient flows along with modeling and simulation have been a central element in management literature over the past few decades (84). Design approaches with based on patients and patient procedures are encouraged, but a clear design approach and methodology is still lacking.

The physical framework of the healthcare facility needs to correspond with treatment, technology, diseases and demography. The interdisciplinary design approach encourages an examination of healthcare as an integrated system (117,118) for the development of a design methodology. Hillier et al. (39) introduces space syntax as an understanding of space and its configurations that provide a framework for defining, creating and modifying the built environment. Space syntax is a design approach for the definition of spaces and their configurations based on relations. It is applicable as a methodology for evidence-based functional design, as evidence can potentially describe the relationships of spaces as the qualities of spaces to be configured.

2.1.3. Hospital design framework

Treatment, medical procedures and technologies are under continuous development. The hospital design framework of the present project derives from state-of-the-art research and reflects the current state of treatment procedures and technology implemented in hospital design. A qualitative analysis outlines the design framework of current practice. The qualitative analysis is based on material from the design competitions of hospital constructions (42,43,45,46,74,75,77,116,119).

The goals for state-of-the-art hospitals are better organization and coherent patient treatment, increased patient safety and streamlined procedures. The hospitals focus on the patients and their experience of the health facilities. In general, focus is on the patient and the primary hospital functionality of diagnosing, treating and nursing the patient (38). This general focus creates a reduced need for the transportation of patients, staff and goods between hospitals and better utilization of technical equipment and administrative and technical function. The following six performance evaluators outline the parameters describing the state-of-the-art health facilities in tender documents and governmental recommendations (42,43,45,46,74,75,77,116,119):

- Construction Costs
- Operating Costs
- Functionality
- Patient Procedures
- Flexibility
- Healing Surroundings

In the tender documents and the evaluations of design competitions, realizability and economics are recurring elements. Economics is related to the constant economic pressure on hospitals. Moreover, the political circumstances of The Quality Reform, the Regions owning the hospitals and the Government’s block grant cause that the construction and operation of the hospital are two different and discreet sets of economy. The operation is a Regional economy issue, and the Quality Reform finances the construction. The Quality Reform presents an economic straitjacket to maintain control of several simultaneous construction projects. Consequently the economic perspective of this design model is divided into construction costs and operating costs.

In the evaluations of the design competitions, the committee judged the architectural, engineering and functional solution. All three solutions focus on hospital and patient procedures as the essence of the solution. Hospital procedures are the functionality of the hospital along with an optimal flow of patients, personnel and goods. This perspective is a recurring element in the evaluations of hospital designs (74,75,119).

Patient procedures cope with a broad understanding of the patients’ experience of the treatment. This is an essential part of the architectural and functional solution to a hospital (74,119). Continuity in personnel is weighted highly along with improved communication between sectors, departments and hospitals. These perspectives are central in describing improved patient experiences and procedures, because it is generally a negative experience to be involved with several departments and hospitals (116).

Flexibility is a necessity in today's hospitals in order to correspond with the continuing developments in demography, treatment and technologies (119). The hospital constructions of The Quality Reform prioritize diagnostics over care. The hospitals are equipped with fewer and smaller wards and more diagnostics, while the occupancy rate is increased (42,43,45,46,74,75,77,116). Today's hospitals are constantly reconstructing 8 to10 % of the area (ALECTIA A/S) because of the changes internally and externally. The changes will continue so flexibility is a necessity. Flexibility is needed in the individual rooms and in the combining areas as part of being future-proof. Flexibility means possibilities of extension or conversion to other uses without major expenses (1).

Healing architecture and patient safety are closely related. Practice uses a practical approach to healing architecture based on patient safety. It consists of instructions for hygiene, routes of infections etc. (120). The guidelines are professional requirements for hospital design in addition to the central elements of evidence-based design as approaches of health innovation (74,75).

2.1.4. Hospital functionalities

Diagnosis, treatment and care of the patients are the purpose of the hospital (89). Several functionalities support this. Some are patient-related and others are not.

Qualitative studies of hospital operation and organization outline the primary, secondary and tertiary functionalities. The primary functionalities are the diagnosis, treatment and care of the patient as outlined above. The secondary hospital functionalities are the patient related services, and the tertiary functionalities are the patient remote services. The secondary functionalities support the primary functionalities of the hospital. They are patient-related, and they include medical care and non-medical care. The tertiary hospital functionalities likewise support the primary functionalities. The tertiary functionalities consist of the non-patient related services, such as logistics and supplies.

The functionalities, the inherent technologies, relations and spaces (39) define the facility that is the hospital (65). The primary, secondary and tertiary functionalities are the large number of factors influencing each other. Together they describe the facility and their functions, like an interrelated supply chain (98,106,121). In supply chain management the facility and its supply chain are partitioned into the large number of factors that influence each other. In design modeling it is beneficial to partially describe the factors that influence each other (26). In the case of hospital design the relation between the primary, secondary and tertiary functionalities is an interrelated performance loop. The tertiary functionalities provide a framework for the secondary functionalities. The primary functionalities require the secondary functionalities while they influence the framework of the tertiary functionalities. When there are changes at one of the levels, the others must adhere to this. The parametric design model operates with these interdependencies (26). It attempts to capture design history while producing alternates (33).

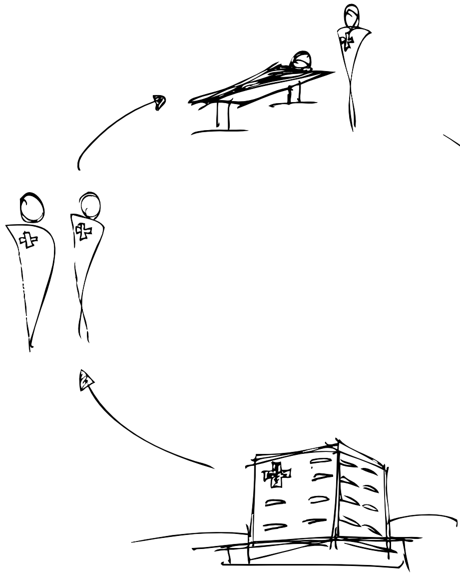


Figure 2-3 Performance loop illustrating the interdependencies of the primary, secondary and tertiary functionalities.

The functionalities of the hospital are decomposed into the secondary and tertiary functionalities that support the primary functionalities of diagnosis, treatment and care. The performance loop binds the functionalities together. The parametric design model applies to generating design through rules and relations.

This approach relates the theory of space of Hillier et al. (39). According to Hillier et al. (39), the organization of space relies on the inherent relations of the building including the relations between people and spaces. The people in the hospital context represent different perspectives and different levels of the functionalities. The patients and relatives are primarily related to the primary functionalities. The personnel is related to both the secondary and tertiary functionalities. The organization of spaces according to the inherent relations can secure the functionality of the built environment. The patient and personnel flows can be the rules and relations that define the interdependencies in this facility with a variety of characteristics (10). Space syntax, as defined by Hilier et al. (39), is a theory for designing by rules and relations. Architectural design modeling is a method for designing by rules and relations.

This research contributes with knowledge of architectural problem solving. The following subsection defines the framework of architectural modeling by the development, potential and paradigms.

2.2. Architectural design modeling

It is evident in today's architecture to apply computation for handling parameters and facilitating the design generation. Much of todays' remarkable architecture depends on the use of computation to handle the complexities. Architecture has been through a transformation from a manually driven tool-based design with pen and paper to a digitally driven form-based design (25). Table 2-1 illustrates some examples of today's architecture that are results of the available computational potential.

Table 2-1 Architecture developed by active computational usage.

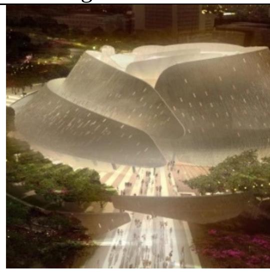
30 St Mary Axe 2001-2003	Beijing National Aquatics 2004-2007	Beijing National Stadium 2003-2008
		
Foster and Partners and Arup	PDT Architects and Arup	Herzog & de Meuron and Arup

In the design of 30 St Mary Axe, a parametric software was developed to convert the curved surface into panels to maintain the overall design and to secure buildability. The Beijing National Aquatics as well as the Beijing National Stadium encompass such complexity that parametric management of the components was necessary for managing the design.

The application of computation is using the available technologies, which has been decisive for the architectural development throughout history (34). Today's architecture explores a high degree of freedom, freedom in geometry, freedom in construction and freedom of gravity. This follows the computational potential. Computer usage in the design process provides a three-dimensional space freed from physical constraints and representational constraints. This allows freedom to explore new configurations. Moreover, the computer provides an enormous calculating power in terms of arithmetic, which allows following simple rules quickly and reliably (122).

Different approaches to computer usage classify the different architectural styles that derive from the computational methodologies. Table 2-2 illustrates the different influences of computation in the architectural styles.

Table 2-2 Computational architectural typologies.

Bubble BMW Pavilion 1999 Bernhard Franken and ABB	Üstra Office Building 1999 Frank Gehry	Massar Children's Discovery Centre, 2013 Henning Larsen Architects
		
Isomorphic architecture.	Metamorphic architecture.	Parametric architecture.

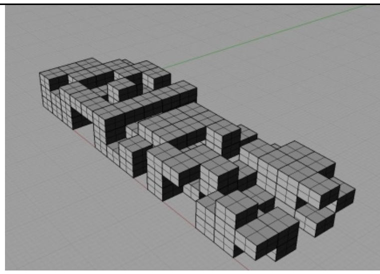
The topological typologies have shown particular potential in the form explorations from particular forms or expressions towards non-Euclidean geometries (23), as illustrated in Table 2-2. Isomorphic architecture is the architectural typology, where force fields develop the form as an interpretation of ‘form follows forces’. Metamorphic architecture is similar. It is the transformation of form through the addition of a temporal dimension to the deformation processes. The geometry morphs into a new form. Animate architecture utilizes movement in the form generation in order to engage with and respond to different dynamics (23). Parametric architecture develops from rules and definitions of the inherent parameters and components. Much parametric architecture is form explorations (23,123), but the methodology possesses an appropriate flexible framework for the present approach to hospital design.

2.2.1. Architectural modeling techniques

Genetic algorithms are the key concept in the architectural typologies. Genetic algorithms define the expression of the architectural concepts by a set of rules based on evolution. Parametric architecture is the architectural typology based on computer usage for the handling the parameters by a procedural description of geometry by rules and mathematical formulations (50). The computational potential handles the complexities and new territories for conceptual, formal and tectonics are explored (23).

The range of parametric models includes the visual parametric models as illustrated in Table 2-1 and Table 2-2. The functional parametric models are illustrated in Table 2-3, where the behavior of the procedures is illustrated.

Table 2-3 Computational architectural approaches

	
Shape grammars	Cellular automata

Shape grammars are the parametric approach where models are defined by performances. Algorithms use a composition of rules for the generation of shapes. The methodology has been used broadly for the generation of architectural and other spatial designs (111). Cellular automata use algorithms of procedural descriptions to define the generation of design.

Research into the contemporary non-visual parametric approaches is extensive. Khalafallah (124,125) introduces an approach for minimizing hazards in an airport context. Khalafallah and El-Reyes have developed an approximate dynamic programming model for identifying a global optimal location and orientation (124-126). Turrin (127,128) elaborates on the parametric design model to combine visual perspectives with functionality and performances. Other bare mathematical methods for visual parametrics are seen in combination with Bayesian statistics and visual styles (129).

The potentials in the computational techniques are extensive. Several forms have been explored and new architectural typologies have been established. However, the functional explorations are closely related to the programming techniques.

Design is the iterative process, where designs are generated on the basis of the chosen parameters and performances. Several variations are produced by activating and adjusting the predefined relationships iteratively (33). During the design process, partial definitions of the design as a response to the design requirements and preferences are present iteratively. The iterative process facilitates a development according to the actual design requirements and preferences, whereby the design integrates an enlarged set of performances. Design assessments in the early stages enhance the interdisciplinary design and reduce poorly performing design solutions. It allows for an elimination of the barriers between different professions and assists collaboration through digital technologies (122).

Consequently, the design is a result of a synergic approach. This is very useful for hospital design, where several professions collaborate in the design process, which, according to Hoof et al. (130), is a prerequisite for developing designs of hospitals, where the product balances the different professional input.

Combining architectural, engineering and functional perspectives is the essence of creating a synthesis in the conceptual design phase. Functional requirements are a central element in architectural layout design and configuration. Layout design is an established design approach for manufacturing companies (55-60). It concerns the identification of feasible locations and dimensions for a set of interrelated rooms, while meeting the design requirements. It relates closely to the computational processes (55,101,131-133). Layout design contributes to the architectural design of plans while the parametric model provides a broader framework. It facilitates a three-dimensional geometric approach with several requirements and preferences.

The complexity of the hospital provides a framework of several requirements and preferences. The complexity necessitates a translation of the functionalities to design requirements and preferences to achieve a highly functional hospital. The design of the layout according to the functionalities will reduce supply shortage, queues and delays, bottlenecks, waste of resources, lengthy stays, low levels of productivity, inappropriateness of clinical settings and workload variability.

2.2.2. Systemized models for layout design modeling

Layout configuration or layout design is concerned with finding feasible locations and dimensions for a set of interrelated rooms, meeting design requirements and maximizing design preferences. The last few decades have brought several proposals for layout design and an automated configuration of layout design (54,55,65,105,109,112,133-135). Advances in computational potential allow for emergent approaches.

Layout configuration is closely related to spatial configuration and spatial synthesis. Spatial configuration refers to the way spaces in a built environment relate to everything else which is relevant in terms of logistics, flows as well as wayfinding (102,136). Spatial synthesis is a derivative of this.. It concerns the configuration of spaces or two-dimentional rectangles, where the locations are variables and a constraint satisfaction problem defines the layout of the variables by algebraic constraints (137).

Much research has been conducted within spatial configuration especially within the broad understanding of logistics. Spatial configuration, layout planning, and component layout are terms covering the same objective: the placement of components in an available space, so that a set of objectives is optimized while spatial or performance contraints are met (138). Spatial configuration is mostly used in industrial production where a set of components or procedures are configured while the processes are optimized within the given contraints. Component packing (101,139-141), route path planning (53,54), and process and facilities layout design (55-60,108,142-147) are subject to spatial configuration. Spatial configuration has mainly concerned industry, where processes are important and the building framework is purely a functional framework, which is why the optimization objectives are easily defined and closely relate to the processes.

In terms of hospitals, many parallels can be drawn to industry. Prioritization of production lines or processes is prioritization of diagnosis, treatment of care related to patient treatments. Hospital design, compared to industrial production, encompasses an extensive complexity, as the production lines of patient treatments influence each other extensively. There is a high frequency of comorbidity of two, three and more diseases simultaneously. This influences the treatment procedures differently each time. Industrial production succeeds in separating the production lines in order to simplify the optimization objectives.

The participants in layout configuration are the components to be configured, the objective and the constraints of the configurations, as well as the requirements of the context. Cagan (67) describes the requirements of the context as the topological connections. They define the constraints of the geometric entities derived from the production lines. The locations and orientations of components are design variables to be defined through objective cost functions. The cost functions may reflect costs, quality, performance, and service requirements. Various constraints define the relationships between the components. The layout problem is the specification of the components, objectives, constraints and topological connections.

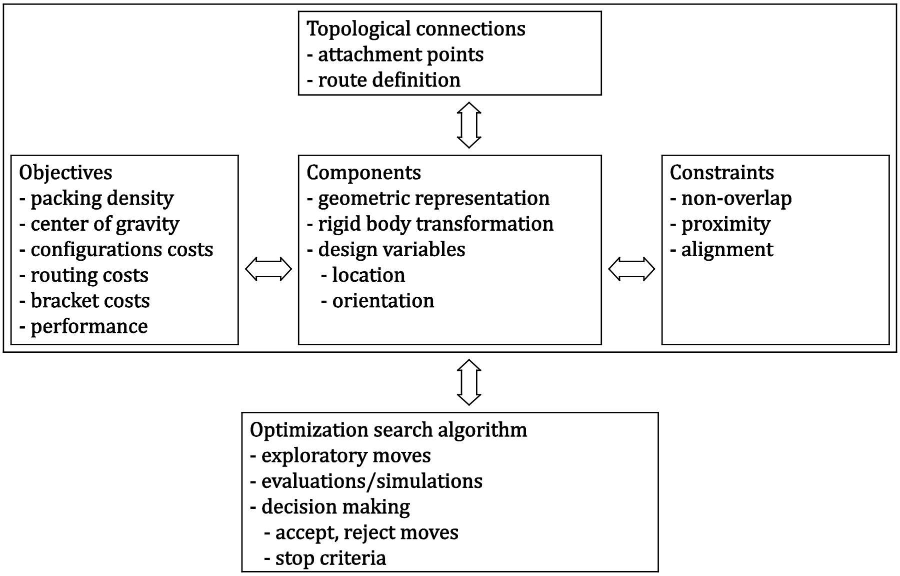


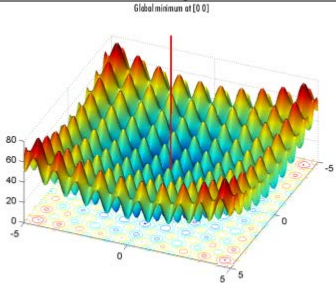
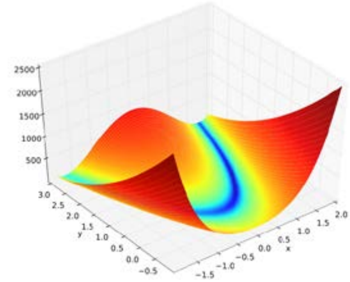
Figure 2-4 The main parts for layout synthesis (67).

The layout configuration develops according to the objective search algorithm. The objective search algorithm searches for solutions in the design space defined by the constraints. The design space is a mathematical representation of the space. It is non-linear and multi-modal (67). It is multi-dimensional and cannot be visualized. The configuration of costs defines the dimensions of the design space, i.e. for six costs with 46.656 (6^6) configurations the dimension of the design space is 46.656.

Deterministic algorithms cannot navigate in such design spaces, which is why stochastic algorithms are usually required for qualitative results (67). Deterministic algorithms consist of a particular procedure of e.g. a mathematical operation, whereby it will always produce the exact same output to a given input. Stochastic algorithms consist of a degree of randomness. The different algorithms and their use are described in Chapter 6 in section 6.2.3 Metaheuristics.

The multi-dimensional design space is a challenge. Because it is non-linear and multi-modal, several local minima and maxima exist, see the exemplification of Rastrigin's function in Table 2-4. The function is a general test function that describes a general two-dimensional problem with several local minima and maxima. In comparison to the Rosenbrock's function in Table 2-4, where the global minimum is easily identifiable, because the local and global minimum is the same.

Table 2-4 Rastrigin's function has several local minima and maxima. Rosenbrock's function with the same local and global minimum.

	
Rastrigin's function	Rosenbrock's function

The deterministic searches often converge to local/interior minima or globally near optimal solutions. By application of some degree of randomness within the search, such as stochastic algorithms, the search avoids the interior local optima. However, extensive randomness can cause too exhaustive searches and thereby impede convergence. Heuristics define the overall approach of approximations. Heuristics are, along with the algorithms, further described in Chapter 6. Heuristics tend to be domain-dependent, which is why it is important to match the requirement to the heuristic capabilities. The heuristic rules often derive from the experiences and insights of the actual mechanisms (67).

The objective search functions consist of two overall strategies: the constructive initial placement strategies and the iterative improvement strategies (148), which will be described in detail in Chapter 6. The explorations and developments of mathematical models for layout modeling will likewise be described further in Chapter 6.

2.3. Hospital layout design

The two previous subsections establish the framework for hospital layout design. Evidently, there is extensive development and research in architectural design modeling for form explorations. Research into the computational potential describes the search techniques for layout design. However, they primarily relate to the geometric constraints.

Hospital design consists of a range of objectives. The engineering objectives such as cost and performance are easily described by quantitative input parameters. On the other hand, the architectural design parameters concerning aesthetic and usability qualities are more difficult to describe formally. However, usability is closely related to the functionalities. Research in layout design exemplifies the description of functionalities as components, objectives and constraints.

Research into hospitals emphasizes this perspective by several proposals of discrete-event simulation as an analysis method or tool for different hospital procedures (61-64,149-152). Discrete-event simulation is the method of modeling a system of discrete sequences of events, where each event occurs at a particular instant in time and marks a change of state in the system. This research addresses primarily singular perspectives in the hospital system. In order to address a holistic perspective in hospital design, this research proposes a design model for the optimization of the architectural design of hospitals. The framework of this hospital design model defines the context and thereby the topological connections. The hospital functionalities define the components and the objectives. According to the theory of heuristics, the search algorithms require some insight into the actual mechanisms of the design space. Consequently, this research investigates how to solve the architectural design problem by using computational potential.

2.4. Summary

This chapter describes the introduction to the research project of Chapter 1 by the two areas of hospital design and architectural design modeling. This chapter sets the framework for this thesis by the state-of-the art of hospital design and architectural design modeling.

The state of the art of hospital design is defined based on the governmental framework and recommendations. Concurrently with The Quality Reform, the Danish Government established an expert panel to define the state of the art within hospital design and hospital construction. This chapter outlines the standardized principles and variables, the components that define the design framework. Moreover, six performance evaluators describe the objective of the hospital.

Architectural design modeling is the other perspective of this thesis. The state of the art in architectural modeling defines the framework for the knowledge contribution of this thesis. State of the art does not take performance objectives into account in the architectural modeling.

Using computers has produced new design methods within architectural design modeling of especially form exploration. Simulations and analyses drive the performance-based design models that contain the ability to act directly upon the physical performance properties of the specific design. The work of this thesis contributes to this perspective.

The synthesis takes place when form and function support each other in the creation of integrated design (153). This chapter sets the framework for using state-of-the-art technological and architectural methodologies for solving the architectural design problem. The following will go into detail with the architectural design problem of hospitals.

Chapter 3. Conceptual Design of Hospitals as Building Entities Responding to Functionalities

This chapter introduces the second part of the thesis where the first research question is dealt with. The chapter is based on the framework of hospital design and architectural design modeling of Chapter 2. The parametric design model is the foundation for the definition of conceptual design.

The chapter defines the design model of this research project. The construction of the design model consists of three levels: the principal drivers, the intermediate construction and the resulting geometry. This chapter defines the principal drivers in terms of the typologies described in Chapter 1.

The typologies derive from a qualitative study of Scandinavian hospitals, describing the different phenomena of hospitals. The building typologies, the organization typologies and the layout typologies define the principal drivers of the design model.

The worldwide trend of consolidating hospitals into few and larger entities relies on theories of economies of scale as well as of scope (4-8). This is introduced in Chapter 1. The consolidated hospitals are met with expectations of increased productivity. Increased productivity means faster and more efficient patient treatments that are reliable and decrease the time of hospitalization and the amount of re-hospitalizations. In terms of achieving the expected productivity, the functionalities cannot be distributed arbitrarily. It is necessary to understand the framework, constraints and potentials within the functionalities to achieve especially the scope efficiencies.

The scope efficiencies are the shared inputs to different types of outputs. Economies of scope in hospitals represent e.g. cheaper operating systems for several outputs rather than several separate systems. Mergers generally combine scale and scope effects in e.g. more efficient administration due to increased volumes and services across categories (7).

The phenomenon of hospital design as a health facility hosts the health-related facilities, but it also works as constructers and constrains to them as a building framework (80). The design of hospitals is the design of the framework of the facility. The facility frames the functionalities of diagnosis, treatment and care for the patient as a coherent patient procedure. The health-related services are linked to the overall well-being of patients. This is the purpose of the hospital (89).

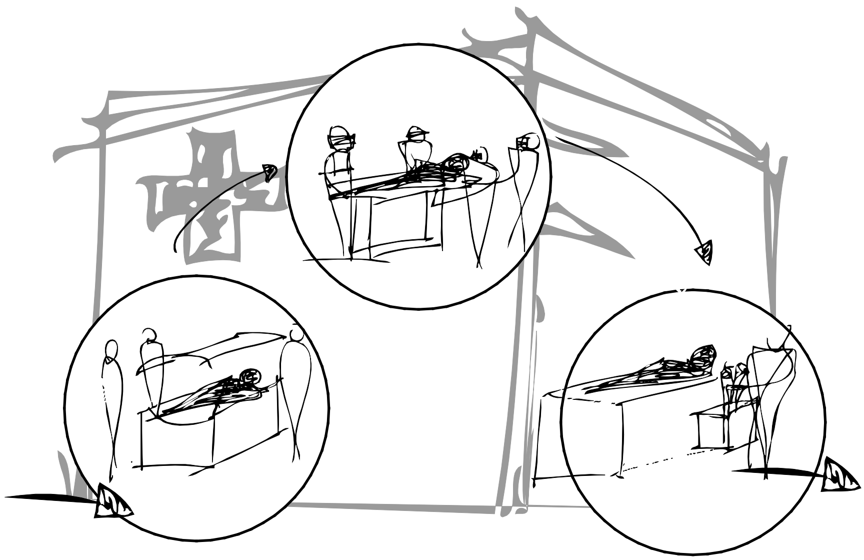


Figure 3-1 The hospital as a building frame with several layers of functionalities. The primary functionalities are diagnosis, treatment and care of the patient.

For hospital design, the inherent technologies, relations and spaces regard the variables associated with the processes of patient procedures defining the primary functionality of the hospital (38). The facility itself encompasses further variables concerning the inherent technologies and relations.

3.1. Theory of the design model

The framework of the design model influences on the structuring of the design problem. The structure of the design problem must apply the framework of the design model. For the current design problem the framework is the parametric design model.

The parametric model facilitates transparency of the facility design by its hierarchical construction describing the relationships and rules explicitly. The hierarchical construction implies a differentiation of the influencers and drivers of the design. The design drivers have the highest impact in the hierarchical design model. The hierarchical construction of the design model provides transparency of the different configurations and the influencers of the model. This facilitates a scientific design approach that is replicable and possible to analyze with respect to specific parameters in terms of correlation and sensitivity (71).

The hierarchical construction consists of three levels. One level derives from the input in the former level, thus the design model captures design history and returns it in an editable form during exploitation in the resulting level (33). The design process is a three-step procedure as outlined in Figure 3-2: the first level is the principal drivers that define the overall drivers for the design. The second level is the intermediate construction. It outlines how the design model operates. Finally, the third level is the resulting geometry that proposes design concepts for further exploration.

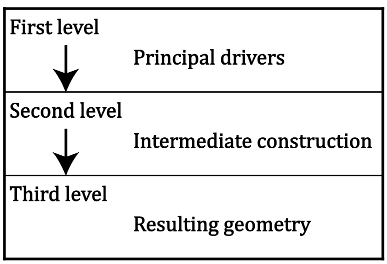


Figure 3-2 In the hierarchical construction, one level derives from the former

The principal drivers define the highest hierarchy of the model. The principal drivers are the initial choices and settings that drive the design. The intermediate construction derives from the principal drivers. It consists of numerical coding of the relationships of the organization of the hospital and its building attributes.

Finally, the resulting geometry reflects the design alternates (26). The intermediate construction defines the design configuration. It is a necessity to initially identify the primary drivers with the highest impact and most decisive for the design. In terms of hospital design, the parameters defining the respective design level relate to the physical and functional context.

The principal drivers define the highest hierarchy of the model in terms of contextual constraints defined by the demographic, physical and cultural context, as illustrated in Figure 3-3. The principal driver at the highest hierarchical level outlines the framework, which implies the design generation in all following levels with a predefined varying intensity at all detail levels.

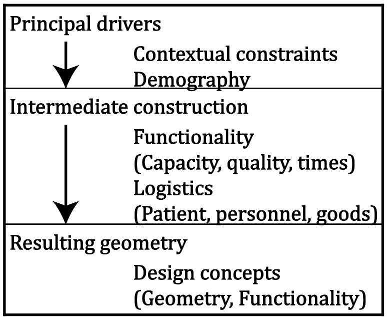


Figure 3-3 Principal drivers derive the intermediate construction in terms of functionalities, logistics and bonds that are defined quantitatively with respective perspectives.

The intermediate construction describes the functionalities in terms of logistics or bonds. Capacities, qualities and times define the data for the intermediate construction linking the principal drivers to the resulting geometry. The intermediate construction has two main input parameters: the hospital functionalities defined through capacities, qualities and times, and logistics correlating the functionalities, see Figure 3-3. The two perspectives are combined into an understanding of functionalities and correlations. These are geometric elements defined and dimensioned by the needed hospital functionalities based on the principal drivers. The hospital functionalities closely relate to the logistics and the interrelationships of the functionalities for personnel, goods and patients, likewise defined by the principal drivers. The resulting geometry is the simulation of the geometric design objectives, defined on a local basis relating the global structure. The resulting geometry derives from the intermediate construction as variable layout designs. The resulting geometry is the foundation for the design concept defined through several alternates of configurations designed in the intermediate construction.

The following outlines the definition of the principal drivers of the design model. The principal drivers define the overall dimensioning of the functionalities of the hospital, derived by the demography, health records and treatment procedures. The functionalities are typically dimensioned and described in tender documents (45,46). Along with the dimensioning, the principal drivers also define the overall design strategy. Consequently, the following outline of the principal drivers is a formal architectural description of the hospital and its characteristics. It defines the data for the design model of architectural typologies, as outlined in Chapter 1. The formal descriptions combine the qualitative and quantitative definitions of the typologies, while it relates the functionality and the architectural qualities of the typologies.

The principal drivers are described by the building typologies, the organization typologies and the layout typologies. The typologies define the overall constraints for the hospital design at the different levels. The following subsection elaborates on the outline of the typologies in Chapter 1. The building typologies define the overall design approach for the hospital as a design strategy for the building composition. The organization typologies define the organization of the hospital, and the layout typologies define the design approach for circulation and function areas and the relationship thereof.

3.2. Building typologies

As outlined in the introduction, Danish hospitals (and worldwide, for that matter) can generally be divided into the three typologies outlined below, relating to the local context and area of the construction site.

The building typology conveys the external relations at the available site, the relations to the surroundings and the cultural understanding of a hospital as a building. Especially the latter can be influenced by the developer's approach of either horizontal or vertical architecture, site costs or local regulations. The building typologies respond to the immediate constraints on the construction while forming the basis for design alternates, whereas internal constraints define different design typologies.

3.2.1. High-rise

Figure 3-4 Building Typologies, High-rise

The high-rise building typology is a compact building often applied in a compact city structure, where efficient area usage is required because the plot ratio is limited. To compensate for the delimited plot ratio the construction is high. The building typology encompasses a high degree of proximity in the overall hospital. The vertical connectors allow similar proximities for stories next to each other as well as stories separated by several stories. The building complex is one entity and an uniform experience of the building quality is present throughout the complex.

A simple constructive system of beams and columns and stabilizing cores allows an efficient area usage. The operational efficiency is high according to the vertical proximity. The proximity eases way-finding. However, attention is required in terms of the uniform indifferent building experience throughout the complex. The complex is inflexible in relation to expansion, as the complex represents a high degree of completion. It is complicated to add extra stories as the most natural possibility for expansion because of the dimensioning of the structural system.

The structural system of loadbearing columns, beams and cores encompasses flexibility in terms of changes in layouts, as the inner walls are non-load bearing. This assures flexibility for changes in treatment technologies as well as changes in the division of diagnostics, treatment and care.

There are daylight limitations in the compact building, because the distance from the center to a façade or opening is long. This also complicates the integration of natural settings. The building scale that rises high above the ground with an authoritarian sense emphasizes this.

3.2.2. Urban

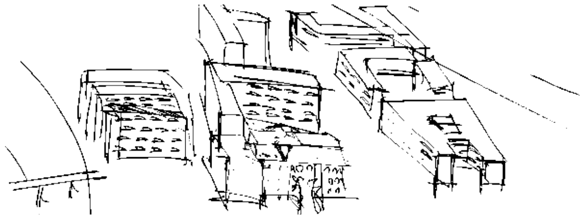


Figure 3-5 Building Typologies, Urban

The urban building typology consists of a building composition of several volumes within the urban scale. The building typology is present in cityscapes and integrates itself in the city with street connections. The typology consists of a configuration of several individual buildings. The buildings and the corresponding composition are in accordance with the cityscape.

Local proximities are present within the individual buildings. The individual buildings facilitate a differentiated experience through the hospital by variances in the qualities and experiences in the individual building. The configuration of several buildings cause a semi-efficient area usage. Consequently, this requires a plot of a certain size for this hospital typology.

There is a high degree of operational transparency in the construction by the differentiated buildings. The composition of several buildings within the complex calls for a professional unison within the individual buildings. Each building has a horizontal and vertical proximity. However, the proximity is hampered in-between the buildings. The human scale contributes to a healing architecture by the sense of the scale. The differences within the buildings likewise contribute. It facilitates way-finding and thereby the individual ability to participate and take charge in especially the care-processes. Navigation within the buildings and in-between consists of different levels. This allows differentiation in way-finding. Thus, the buildings can facilitate targeting way-finding for specific patient groups. The construction facilitates integration of surroundings and natural settings as well as possibilities for expansion.

3.2.3. Campus

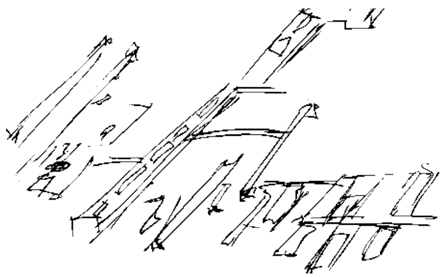


Figure 3-6 Building Typologies, Campus

The campus typology is a building composition of several volumes with a high degree of proximity within the buildings. The individual buildings are limited in scale. The scale of the composition refers to campus architecture where the human scale is decisive. There is a high degree of difference in the building qualities within the components. It is essential for the typology to enhance the human scale, relation and differentiation.

The several constructions cause an inefficient area usage with a high degree of local operational transparency in the construction. The scale causes long distances across the hospital. Meanwhile the delimited components create short distances within the individual buildings, which encourages professional unison. There is limitless potential for integration of nature, landscape and other types of surroundings. This is evident in terms of healing architecture and rehabilitation for patients. The composition entails a high degree of freedom for expansion while the individual layouts represent inflexibility in relation to changes because of the limited sizes.

It is often an initial decision which building typology to apply. It is given by the local context in terms of construction place and area as well as traditions. Each building typology contains advantages as well as disadvantages. Some relate directly to the three functionalities: the primary, secondary and tertiary, and others relate to the evaluators of Construction costs, Operational costs, Functionality, Patient procedures, Flexibility and Healing architecture.

3.3. Organization typologies

The principal drivers also consist of typologies that describe the organizational perspective. Currently two categories characterize the organization of hospitals: the functionally split model or the traditional sectorized model. The organization typologies derive from state-of-the-art research in hospital organization as the two most represented approaches for achieving efficiencies of scope and scale in the consolidated hospital (115,154).

The functionally split organization describes a hospital with a functionalistic division, with departments of different functions e.g. diagnostic facilities, operation facilities, laboratory, etc. where each department services the entire hospital.

The sectorized hospital is like several hospitals within one hospital. Each department is profession-related, e.g. oncology, neurology, etc. and it has all the relevant facilities within the department or professional cluster e.g. diagnostic facilities, operational facilities, wards, etc. that are required for patient treatment within the individual profession.

3.3.1. Functionally split

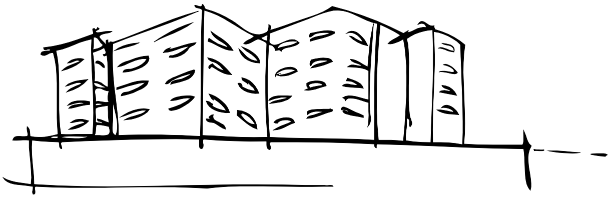


Figure 3-7 Organizational typology, Functionally split

The organization typology encourages a professional, functionalistic handling of treatments. It facilitates economies of scale. The scale of each function is enlarged because every function is only present once in the hospital. The personnel are organized around functions so there is transparency in relation to the functionalities.

In terms of construction costs, the division encourages a construction where complicated installations are limited to the areas of the given functionalities. There is a differentiation in the installations according to the given functionalities. The operating costs are efficient in terms of economies of scale, where the entire hospital population must use the facilities. However, more transportation within the hospital is required, as the patients are on the move for the different steps of their respective procedures.

The organization allows flexible working conditions within each function across the professions. This facilitates function-specialized professional cluster but not clinical professional cluster There is a high degree of flexibility in terms of increase and decrease of treatments, because the functionalities are liberated from the treatment but deals with the functionality. However, the structure is inflexible for changes in the division or focus of diagnostics, treatment and care.

The dimensioning of the functions causes a lack of relations and intimacy as a healing perspective.

3.3.2. Sectorized

Figure 3-8 Organizational typology, Sectorized

The organization derives from the patient treatments, and so the physical framework depends on the technology and the patient treatment. The typology consists of small organizations regarding the specific patient treatments from diagnosis to discharge. It causes a mixed construction typology, where areas requiring complex installation for e.g. diagnostics and operation are in close relation to the less-demanding areas such as wards and patient hotels.

The personnel are specialized and thereby closer to the patient. This improves the general experience to be coherent. However, the organization and construction is complex. All functionalities are present several times in the hospital and parallel operation occurs. For specialized functionalities, this causes inflexible working conditions for the personnel because the functional specializations are distributed.

The typology is inflexible in terms of changes in the demographic combination of patient treatments. Where patient treatments change is size or existence shortages or surplus in functionalities may occur. However, the typology is less exposed to changes in focus or division into diagnostics, treatment and care, because the proportions of the functions are smaller.

The functionally split organization consists of departments servicing the entire hospital, whilst the sectorized hospital consists of several hospitals within the one. Both organizational typologies are applicable in all building typologies.

3.4. Layout typologies

The last typology defining the principal drivers is the overall layout typology. There are five general layout typologies: 1) Single corridor, exterior, 2) Single corridor, interior, 2) Double corridor, 3) Courtyard, exterior, and 4) Courtyard, interior. More layout typologies exist, but for the present project, the general layout typologies are based on Scandinavian hospitals, because of similarities in the regulations for workspaces, demands for natural daylight, etc. This framework limits the layout typologies to the five typologies described.

The layout typologies derive from a qualitative analysis of hospitals and tender documents outlining the design approach for layouts. As a principal driver, the layout typologies influence the overall design approach. The typologies consist of different qualities and requirements. They influence the design on an overall level in terms of functionalism, net-gross factor, integration of nature, human scale and dimensioning.

The layout typologies are applicable across the building typologies and organizational typologies. Each typology consists of advantages as well as disadvantages according to the three functionalities: the primary, secondary and tertiary. Likewise, each performs differently according to the evaluators of Construction costs, Operating costs, Functionality, Patient procedures, Flexibility and Healing architecture.

The following will illustrate the typologies and describe them. The functional areas are white and circulation areas are hatched. Chapter 5 gives numerical definitions of the typologies, and Figure 7-2 illustrates a digital representation of the typologies.

3.4.1. Single corridor, exterior

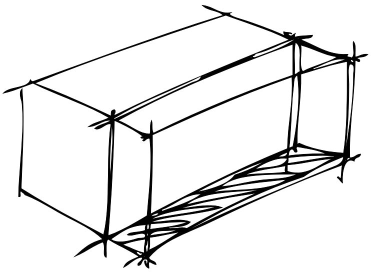


Figure 3-9 Layout Typologies, Single corridor, exterior

The layout typology consists of exhausted integration of natural daylight. The functional rooms are at one side of the circulation area, whereby all functionalities are exposed to natural daylight, even the corridor. It causes long distances, inefficient space usage and a limited unit size. The unit’s long intra-unit distances mean that the size of the unit is limited. The operational efficiency is low because the distance to the center of mass is long.

The simplicity of the unit gives easy accessibility and way-finding in each unit. The organization is simple and transparent, and the exterior corridor allows transparency in the facade. The units are flexible for addition because the natural daylight exposure is extensive

3.4.2. Single corridor, interior

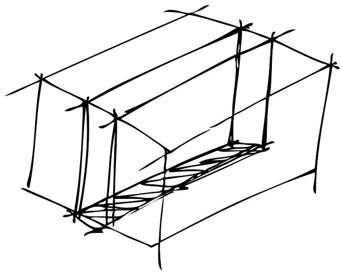


Figure 3-10 Layout Typologies, Single corridor, interior

This typology is mased on the former, but the efficiency is increaced in terms of operational costs and construction costs. The corridor is central and there are two rows of functional rooms. Consequently, the distances to the same quantity of functionalities are reduced. It is a simple construction with a minimal building envelope.

The operational efficiency is high due to the short distances, and the accessibility and transparency are eased, because of the shorter discances. The corridors without natural daylight poses a generally negative experience of institutionalization. The typology is semi-flexible for addition, because daylight issues can occur.

3.4.3. Double corridor

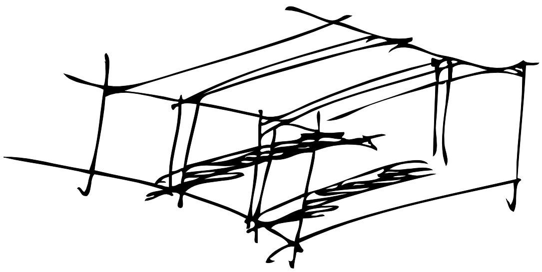


Figure 3-11 Layout Typologies, Double Corridor

This typology represents the most area-efficient organization. It reduces the distances to a minimum, because it implements an area for the non-daylight requiring functions central in the composition.

The compact, simple construction has an efficient space usage, which is semi-flexible for addition. The typology has a minimal building envelope and the distances are minimized. It gives a high operational efficiency, as long as there are functions that can be placed without natural daylight.

3.4.4. Courtyard, exterior

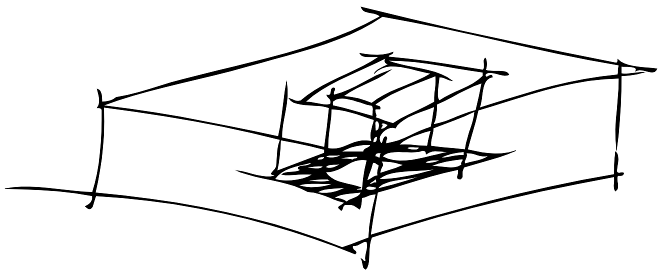


Figure 3-12 Layout Typologies, Corridor exterior, Courtyard

This layout typology represents another layout approach, i.e. the one based on an integration of natural settings in terms of courtyards, etc.

The typology is based on an integration of outdoor space and natural daylight. There is a substaantial orientation towards the unit with medium to long distances around the courtyard. The organization of function rooms and circulation areas becomes less transparent as in the former typologies, because the direction shifts. As a consequense of the exterior corridor, an inefficient space usage is present, even though this unit is remarkably larger than the single corridor, exterior typology.

There are flexibility limitations in the composition because of the courtyard, but the exhaustive exposure of natural daylight creates some flexibility. This typology closely relates to the principles of healing archtiecture with integration of courtyards, gardens etc. The integration of outdoor spaces is inherent in the typology. However, the integration of the outside causes more facades and thereby a maximal building envelope. This causes an operational complexity and medium distances.

The typology is oriented towards itself and it is very patient-flow oriented, giving a different experience throughout the building complex, which corresponds to the human scale.

3.4.5. Courtyard, interior

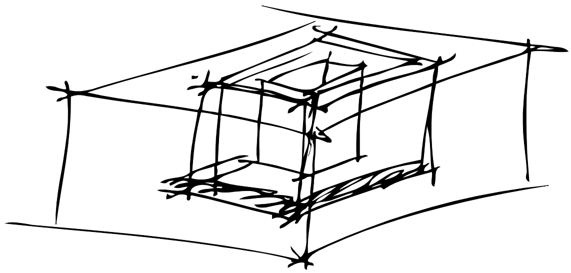


Figure 3-13 Layout Typologies, Corridor interior, Courtyard

This layout typology continues the principle from the former, but it consists of an increased area efficiency and organizational efficiency. When the efficiency increases, the integration of outdoor space decreases. The typology encompasses an interior corridor without natural daylight and views. The organization is orientated towards the unit and towards the patient and patient treatment.

The typology is orientated towards itself and encompasses relations between patient and physical framework. This is in acordance with the principles of healing architecture, emphasizing the orientation towards the patient.

The organization around the courtyard and the shifts in directions cause a complex organization of medium distances. The complex construction entails a large unit size, which is why an operational complexity is inherent. However, the interunit distances are small. The typology facilitates and encourages different experiences throughout the building complex by integration of outdoor space. Because of the interior corridor, there are limitations in flexibility along with natural daylight.

3.5. Summary

The principal drivers at the highest hierarchical level in the design model inform and contribute with overall principles for design generation. This chapter contributes with a definition of the principal drivers.

The principal drivers influence the design on all scales and throughout the design process. With the highest hierarchical position in the design model, they have to cope with the outer framework of the hospital design.

The framework is defined by the typologies that characterize the Scandinavian hospitals. The typological framework is essential for the configuration of building entities, as it defines different patterns for the configuration, while is contributing with different qualities. The typologies are the framework for the design configuration and for the design evaluation.

The resulting geometry is defined as a reflection of different configurations within the typologies. The intermediate construction defines the configuration of the design alternates by rules. The resulting geometry is a representation of a design concept for further development. With the typological construction, alternatives can easily be produced, because each typology consists of a range of predefined rules, relations and preferences. The typologies pool a range of design requirements and preferences as a reflection of the built environment.

Chapter 4.
Intermediate Construction

This chapter outlines the model definition based on the model theory described in the former chapter. The model definition is within the intermediate construction of the hierarchical design model. This chapter is a description of the model generation and the information that define the design model. The information defining the design model is derived from the hospital context and the principal functionality of the hospital: diagnosis, treatment and care of the patient.

The data of this definition of the intermediate construction originates from hospital operation in terms of contacts and patient treatment processes. The data defines prioritizations, requirements and preferences.

The procedures of hospital requirements are based on qualitative analyses of hospitals, hospital operation and hospital designs. The procedures and requirements drive the processes of finding feasible locations and dimensions for a set of interrelated rooms and functions according to the definition of the design model.

It is the intermediate construction of the design model that arranges and defines the internal relations. The intermediate construction defines the construction of the design model. The model generation is defined by construction of the intermediate construction. The resulting geometry is *an exemplification of a design concept according to the principal drivers defined by the intermediate construction.*

The principal drivers, as defined in Chapter 3, define the framework of the hospital and the hospital functionalities and so they are the basis for the model generation. The evaluators are essential in the construction of the intermediate construction, as they reflect quality of the conceptual design of the hospital as a building entity that responds to the inherent functionalities. The six evaluators outlined in Chapter 2 defined the point of departure for the response of the functionality and quality.

This chapter describes the model definition by combining the architectural design model as described in the former chapters. The architectural requirements and preferences and the primary and supportive functionalities drive the processes of the hospital design model. By doing so, the hospital design model is rooted in the two perspectives: architectural design modeling and hospital design.

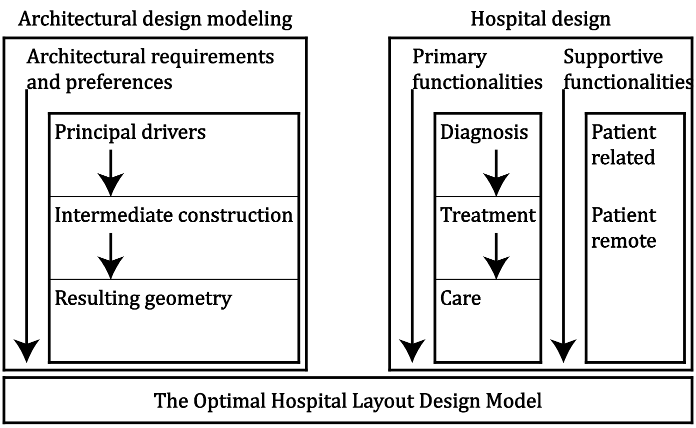


Figure 4-1 Definition of the architectural design model for hospital design

The architectural requirements and preferences are perspectives in the architectural design model determined by the design object. The functionalities of the hospital, the primary functionalities and the supportive functionalities, drive these requirements and preferences. A hospital decomposition into primary and support functionalities defines the architectural requirements and preferences, which drive the design generation, as illustrated in Figure 4-1.

The primary functionality of a hospital is defined as the diagnosis, treatment and care of the patient. This refers to the general focus in hospital design, namely the patient treatment. The patient treatment is the general focus in hospital design. Next comes better organization, related to the patient treatment, coherent patient treatment, increased patient safety and streamlined procedures (1). This chapter analyzes patient treatments in order to outline the architectural requirements and preferences in terms of design parameters and required facilities, which the intermediate construction is built on.

The following subsections decompose the hospital into primary and supportive functionalities in order to define the architectural requirements and preferences, as illustrated in Figure 4-1. This approach transforms patient treatments, as the focus of hospital design and as the source for evaluation, into data relating the functionality and the architectural understanding. This decomposition is the definition of the intermediate construction of the design model on patient treatments. Hence, this chapter is a definition of the data defining a formal description of the architectural understanding in terms of hospital functionalities.

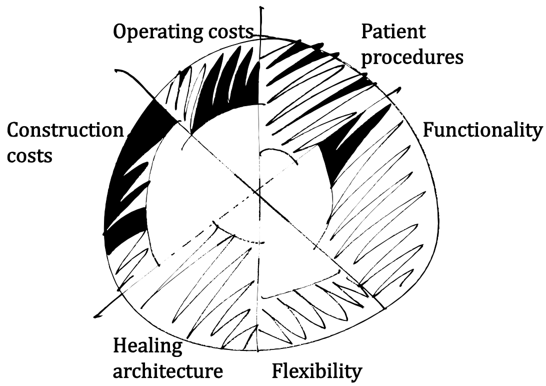


Figure 4-2 The six performance evaluators consist of two perspectives, a function of an evaluation in terms of the patient treatment (the hatched area) and an evaluation in deliberated from the patient treatment (the white area).

The patient treatments influence all six performance evaluators, as illustrated in Figure 4-2. The patient treatment deals with the coherent procedures in relation to the treatment.

‘Patient procedures’ is the performance evaluator that most directly describes the evaluation of the patient treatment, from the patient’s perspective. ‘Functionality’ represents the overall functionality of the hospital, and so it evaluates the patient treatment from the hospital’s perspective. To take the hospital’s perspective, efficiency is a derivative of increased cohesion, which is an emphasized focus and purpose of the innovative organization of the procedures (1). ‘Flexibility’ relates the patient treatment and opposes the patient treatment at the same time. Flexibility is the preparation for future changes, including changes in the patient treatments. ‘Healing architecture’ closely relates to coherence as a way towards higher patient safety, increased patient motion and fewer errors, because continuity increases the general information level on the specific patient and its treatment (85,89,155).

'Operational costs' consists of one part in relation to the patient treatment and another part, separated from the patient treatments. According to ALECTIA A/S data on hospital operation, the majority of expenses in hospital operation are the salaries, see Figure 4-3. The salaries are related to the patient and the patient treatment as reflections. Salaries reflect the personnel of the hospital who are closely connected to the patient treatments and thereby reflect the patient treatments. The costs regarding medicine and goods are difficult to influence in the hospital design, they mostly contribute to the increased economic pressure. Service/unit costs are the costs regarding the service of the hospital and costs relating to the different units. When planning sustainable hospitals, the traditional approach is to decrease these costs. According to Figure 4-3, the greatest impact on operating costs are on salaries and not service costs.

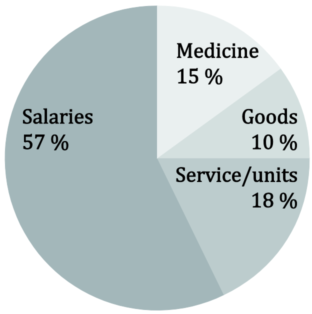


Figure 4-3 Average cost distribution for operational costs from Herlev Hospital, Aarhus Hospital and Glostrup Hospital (ALECTIA A/S).

'Construction costs' mostly reflect the patient treatments in the dimensioning of the different functionalities.

With this approach, where the patient treatments are essential to the objective of the hospital, and in the evaluation of the hospital, the following decomposition is based on the patient treatments. A qualitative study of patient treatments and procedures define the intermediate construction. By focusing on the patient and relating the organization to this, quality improvements are expected along with the introduction of new ways of organizing the work. Hence, this approach is expected to correspond to the motivations of the consolidated hospitals.

4.1. Prioritization

A hospital consists of several patient treatments, some of which occur with a high frequency and others with a low. Likewise, there is a high dispersion in terms of frequencies, and a parallel dispersion in the respective time requirement and severity within the patient treatment. In order to prioritize, it is necessary to analyze the patient treatment and contacts.

The existing data on patient treatments is medical data derived from the extensive mapping hospitals perform. Transforming the patient treatment into entities manageable in a design model requires a transformation of the medical data and description into facility entities or components. Definition of the facility entities is the essence of the intermediate construction, as it is the definition of the design model parameters. Moreover, the definition of the facility entities is one of the major contributions of the present research project. It is the definition of the formal description of the architectural requirements and preferences derived from functionalities.

In the formal definition of an architectural design approach, information and data on the functionalities inform the approach. Historical data of hospital contacts determines the prioritization of the hospital functionalities. The data of hospital contacts are combined with descriptions of the respective patient procedures. Table 4-1 below shows a frequency table of the 20 most frequent hospital contacts in the regional hospital. A hospital contact is the patient's contact with or entrance to the hospital in the emergency ward, outpatient clinics and in-patient clinics.

Table 4-1 Frequency table of the 20 most frequent hospital contacts, number of contacts and bed days. Data from the regional Hillerød Hospital in Denmark.

#	Code	Action diagnosis	Contacts	Bed days
1	DR100	Abdominalia acuta	1.548	2.104
2	DO800	Partus spontaneus unifoetatio, praesentatio capitis	1.534	2.788
3	DJ189	Pneumoni without specification	1.495	6.309
4	DI489	Atrial fibrillation	960	2.503
5	DR108	Abdominalia, other and without specification	890	1.340
6	DE869A	Dehydratio	806	2.491
7	DJ441	Chronically Obstructive Lung syndrome with acute exacerbation, without specification	636	2.685
8	DI639	Infarctus cerebri without specification	619	6.293
9	DJ159	Bacterial pneumoni without specification	563	3.041
10	DO802	Partus unifoetatio after initiation, praesent capitis	557	1.392
11	DI489B	Atrial fibrillation	550	1.481
12	DN390	Urinary tract infection without localization	503	2.135
13	DK590	Obstipatio	490	1.186
14	DK802	Cholecystolithiasis without cholecystitis	473	952
15	DR079	Chest pain without specification	462	713
16	DN300	Cystitis acuta	461	1.483
17	DR559	Lipotymi and collaps	456	1.082
18	DM171	Arthrosis genus primaria, other form	440	1.495
19	DI209	Angina pectoris without specification	436	1.074

20	DJ301	Rhinitis allergica saesonalis (pollen caused)	432	441

Table 4-1 shows how the hospital contacts respond to different codes and action diagnoses. There is a high variance across the diagnoses in bed days and number of contacts. The hospital contacts are described by action diagnosis and a code of letters and numbers. The code reflects the groups of relating diseases or diagnoses. Table 4-2 below shows, how the contacts and bed-days are distributed across the hospital with respect to the groups of diagnoses, and not the specific ones as in Table 4-1.

Table 4-2 Frequency table of hospital contacts, number of contacts and bed days. (Contact descriptions maintain the Danish definitions, because the data is from a regional hospital in Denmark. English translations are in *Italic*.)

Code	Description	Contacts	Bed days
DA	Visse infektiøse og parasitære sygdomme [DA00-DB99] *Certain infectious and parasitic diseases*	1.893	9.498
DB	Visse infektiøse og parasitære sygdomme [DA00-DB99] *Certain infectious and parasitic diseases*	543	1.318
DC	Neoplasmer [DC00-DD48] *Neoplasms*	1.728	12.980
DD	Sygdomme i blod og bloddannende organer og visse sygdomme, som inddrager immunsystemet [DD50-DD89] *Diseases of the circulatory system*	1.597	4.910
DE	Endokrine, ernæringsbetingede og metaboliske sygdomme [DE00-DE90] *Endocrine, nutritional and metabolic diseases*	2.145	7.869
DF	Psykiske lidelser og adfærdsmæssige forstyrrelser [DF00-DF99] *Mental and behavioural disorders*	1.163	2.679
DG	Sygdomme i nervesystemet [DG00-DG99] *Diseases of the nervous system*	1.531	6.192
DH00-59	Sygdomme i øje og øjenomgivelser [DH00-DH59] *Diseases of the eye and adnexa*	216	314
DH60-95	Sygdomme i øre og processus mastoideus [DH60-DH95] *Diseases of the ear and mastoid process*	604	927
DI	Sygdomme i kredsløbsorganer [DI00-DI99] *Diseases of the circulatory system*	7.622	32.580
DJ	Sygdomme i åndedrætsorganer [DJ00-DJ99] *Diseases of the respiratory system*	7.756	26.047
DK	Sygdomme i fordøjelsesorganer [DK00-DK93] *Diseases of the digestive system*	5.918	20.496
DL	Sygdomme i hud og underhud [DL00-DL99] *Diseases of the skin and subcutaneous tissue*	915	2.346
DM	Sygdomme i knogler, muskler og bindevæv [DM00-DM99]	3.269	8.556

	Diseases of the musculoskeletal system and connective tissue		
DN	Sygdomme i urin- og kønsorganer [DN00-DN99] *Diseases of the genitourinary system*	3.165	9.856
DO	Svangerskab, fødsel og barsel [DO00-DO99] *Pregnancy, childbirth and the puerperium*	5.565	12.088
DP	Visse sygdomme, der opstår i perinatalperiode [DP00-DP96] *Certain conditions originating in the perinatal period*	478	4.362
DQ	Medfødte misdannelser og kromosomanomalier [DQ00-DQ99] *Congenital malformations, deformations and chromosomal abnormalities*	174	407
DR	Symptomer og abnorme fund IKA [DR00-DR99] *Symptoms, signs and abnormal clinical and laboratory findings, not elsewhere classified*	8.150	16.523
DS	Læsioner, forgiftninger og visse andre følger af ydre påvirkninger [DS00-DT98] *Injury, poisoning and certain other consequences of external causes*	4.212	15.044
DT	Læsioner, forgiftninger og visse andre følger af ydre påvirkninger [DS00-DT98] *External causes of morbidity and mortality*	2.473	6.902
DX	Ydre årsager til skade [DX60-DY09] *Factors influencing health status and contact with health services*	15	22
DY	Ydre årsager til skade [DX60-DY09] *Factors influencing health status and contact with health services.*	5	5
X	*Codes for special purposes*	155	857

Table 4-2 groups the related contacts into disease related contacts for prioritizing the hospital functionalities formally. This table includes all hospital contacts (emergency, in-patient and outpatient) of the hospital, except the psychiatric contacts.

It is seen how the DR codes for ‘Symptoms, signs and abnormal clinical and laboratory findings, not elsewhere classified’ process most hospital contacts and DI codes for ‘Diseases of the circulatory system’ cause most bed days. Meanwhile, the DP codes for ‘Certain conditions originating in the perinatal period’ have the most bed days per contact, with a mean of 9.1 for all hospital contacts.

This gathering of hospital contacts contributes with the formal description in the prioritization and weight of the functionalities. The analysis combines the frequencies in the number of hospital contacts, both for the individual diagnoses and for the groups of related diseases, and balance the contacts with the bed days with an understanding of the functional requirements and preferences according to the hospital contacts and patient treatments. The following section will outline the functional requirements and preferences according to the hospital contacts and patient treatments. The study will combine the frequency tables above with the requirements of the most frequent patient contacts (116,157-169) to define the facility requirements and preferences. Consequently, this analysis is based on a qualitative analysis on patient contacts coded for facility requirements and preferences.

4.2. Patient procedures

The following subsections will outline the analysis and coding of the patient treatments in two examples. The present examples outline the most frequent hospital contact and a severe hospital contact with several requirements to the physical framework.

4.2.1. Acute abdomen

The most frequent patient contact is acute abdomen. Acute abdomen discloses the state of sudden pain in the abdomen. It is not an organ specific diagnosis, but it includes a variety of diseases involving the specialties of surgery, gynecology, vascular surgery, urology and internal medicine. Patients are typically from the primary sector or the emergency department (ED). After primary surgical exploration possibly including imaging and clinical biochemistry, a tentative diagnosis forms the basis for further treatment and e.g. referral to another specialist/department responsible for concluding the treatment (157). The hospital is able to treat one third of the patients as outpatients, another third can be treated within the emergency department within the time limit of 48 hours. The last third of the patients demand admission to the ward with a mean 4.82 days hospitalization (for the analyzed population) (157).

Through the qualitative analysis of the patient treatment, coding on requirements for the facility entities outlines the requirements to the facility. Thus, the analysis provides data for the architectural solution to the patient treatment. The coding relates to evaluation parameters in terms of the facility to the patient treatment. It relates to the physical framework of the building composition to patient treatment. The functionalities and requirements focus on facility entities for a decomposition or parameterization of the hospital functionalities described by components. Data definition through analysis of patient treatment focuses on defining input for solving the architectural design problem and on informing this process.

Table 4-3 Facility requirements relating to the patient treatment of Abdominalia acuta.

Function	Description	Relation		[0-4]
Emergency medical service[Lægevagt]	Location of the emergency medical service relative to the emergency department	Emergency Department	Prox Acces	4 4
Diagnosis, Imaging/endoscopy	Prerequisite to facilities and equipment of endoscopy and radiology in ED. Laboratory in department	Laboratory	Prox	4
Anesthesia, Intermediary	Critical patients shall be in an intermediate section if they do not have respiratory problems, but demands observation under the anesthesiology auspices.		Prox	2
Examination and treatment facilities	ED close to examination and treatment facilities		Prox	2

Table 4-3 outlines the requirements regarding acute abdomen to the physical facilities. The requirements primarily involve proximity and accessibility. The requirements reflect general requirements for proximity and accessibility to the emergency department and the related diagnosis. The requirements and preferences define the accessibilities and proximities by a variable [0-4] of the respective functionalities. These variables are local, because they describe the relation with respect to this local, specific patient treatment. The variables derive from the qualitative analysis of the patient treatment (157), where the description of the treatment is coded for requirements and preferences in terms of proximity and/or accessibility.

4.2.2. Apoplexia

Apoplexia is a widespread disease affecting 12-14,000 Danes each year. Apoplexia is the collective term for thrombus in the brain and cerebral hemorrhage. It is a serious disease, potentially life threating, and often results in significant disabilities. Immediate treatment is required to reduce disabilities and mortality. The current mortality rate within the first month is only 11 %. This improvement is due to an increased focus in recent years (159). The illness requires immediate evaluation and treatment, and even mild symptoms should prompt immediate hospitalization. The physicians should administer thrombolytic therapy or antiplatelet drugs within three hours. The assessment of the patient must occur in departments of neurology or internal medicine at the hospital within two hours after symptoms occurred. The particularly important specialties are intensive, cardiology, parenchyma surgery, radiology and internal medicine. The hospital must prevent and treat any medical complications and clear the causes for the stroke. Rehabilitation starts during admission and continues in outpatient clinics by specialized teams. Interdisciplinary design is crucial to succeed along with stimulating surroundings, which in addition to doctors consist of nurses with specific skills, therapists and dieticians. The long-term rehabilitation targets intensive training and rehabilitation with a specially trained staff. It is not appropriate to have rehabilitation together with the acute patients in the emergency department. Moreover, a very short course can be completed in the emergency department (159).

Parallel to the most frequent hospital contact of acute abdomen, the qualitative analysis of the patient treatment outlines the requirements for the facility entities. The coding conveys the evaluation parameters in terms of the facility to the patient treatment and respective requirements. For apoplexia, the requirements to physical framework must correspond with the severity of the disease and the requirements to immediate diagnosis and treatment.

Table 4-4 Facility requirements relating the patient treatment of Apoplexia cerebri

Function	Description	Relation		[0-4]
		Emergency Department		
Diagnosis CT/MRI scanner, Carotid scanner, echo cardiograph	Prerequisite to diagnosis facilities and equipment in ED.	CT/MRI scanner	Prox	4
Diagnosis Biochemical diagnosis	Prerequisite to diagnosis facilities and equipment in ED.	Biochemical diagnosis	Prox	3
Intermediary beds			Prox	2
Examination and treatment facilities	ED close to examination and treatment facilities		Prox	2
		Rehabilitation		
Training facilities	Training facilities integrated with or in close relation to wards	Wards	Prox	3
Kitchen		Wards	Prox	3
Patient schools		Wards	Prox	3

The facility requirements for apoplexia involve the emergency department and rehabilitation. Within the emergency department, the requirements strengthen the general requirements of accessibility and proximity. Moreover, the patient treatment requires more technical equipment, i.e. MRI scanner or CT scanner, than other patient treatments. The requirements for rehabilitation likewise expand as the disease often causes serious disabilities. Hence, rehabilitation concerns the physical rehabilitation in physiotherapy and occupational therapy, but also the practical rehabilitation and patient schools that require kitchens and other training facilities.

The requirements and preferences define the required proximities by a variable [0-4] of the respective functionalities. These variables are local and regard this specific treatment of apoplexia. The variables derive from the qualitative analysis of the patient treatment (159), where the description of the treatment is coded for requirements and preferences in terms of proximity.

The outline of apoplexia and acute abdomen in this subsection illustrates the procedure of the qualitative analysis of patient treatments. The 10 most frequent patient treatments have been analyzed to define the input data of the intermediate construction of the design model, this research project concerns. All 10 patient treatments have listed a number of functionalities with specific local requirements and preferences according to the given treatment. These variables are in the range of [0-4].

4.3. Facility requirements

The following combines the hospital contacts with the frequencies and weight and respective treatments into a global matrix. The global matrix describes all functionalities of the hospital in requirements and preferences, by global variables. The global matrix consists of the interrelated requirements in terms of proximities and accessibilities. The requirements and preferences outline all hospital functionalities and define the required or preferred relation from one functionality to another. The definition of the global matrix is a general framework for an abstract hospital with all patient treatments regarding the classification of diseases and related health problems in Table 4-2.

The global matrix representing an abstract hospital is combined with the size requirements derived from a demographic dimensioning of the functionalities. The size requirements reflect the required numbers of functionalities combined with space requirements, respectively (46). The dimensioning of the functionalities is project-specific, and so the dimensioning variables of the matrix are project-specific.

The following outlines the definition of the global matrix as a result of the qualitative analysis of the patient procedures and treatments. Coding of proximities has defined the formal description of the relations across the hospital and in-between the functionalities in parallel to the traditional architectural bubble diagrams. The bubble diagrams outline the area by a bubble-size and the correlation of one functionality to another by a line emphasized in thickness or the like, cf. Figure 4-4.

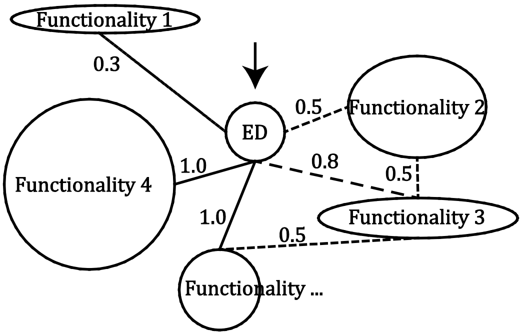


Figure 4-4 Traditional architectural description of correlations between functionalities.

The principles of the bubble diagram are transformed into the formal description of a matrix, applicable in a design model. The matrix thus has a basis in qualitative analyses of patient treatment and procedures, coded for facility requirements and preferences. The requirements and preferences are defined on a local basis for each patient treatment. The locally defined requirements transform into global variables reflecting all the hospital contacts and the most frequent patient treatments. Hence, the analysis applies the prioritization of the frequencies and weight to the coding of patient treatments exemplified in Table 4-3 and Table 4-4. The requirements and preferences define the accessibilities and proximities by a variable [0-4] of the respective functionalities.

In the definition of the global matrix the local variables [0-4] for all patient treatments are combined. The combination applies the frequencies and weights according to the hospital contacts. This procedure makes a global matrix as a reflection of the traditional architectural bubble diagram in Figure 4-4. It defines the correlations between all hospital functionalities by a global variable [0-1]. The variable describes the correlations between all functionalities of the hospital, parallel to the numerical values emphasizing the relations in the bubble diagram, Figure 4-4. As a principle, the global matrix is parallel to the bubble diagram, but the format makes it more formal and applicable in a design model. The correlation matrix exemplified in Table 4-5 outlines a section of the matrix with 10 functionalities and their respective correlations.

Table 4-5 Correlation requirements for 10 functionalities.

#	Description	m^2	1	2	3	4	5	6	7	8	9	10	…
1	Exterior		-										
2	Acute, somatic bed	2,070	0.8	-									
3	Acute, psychiatric bed	90	0.8	0.0	-								
4	Acute treatment, diag, ER	2,720	1.0	0.8	0.8	-							
5	Acute, admin	2,474	0.0	0.8	0.8	1.0	-						
6	Intensive, ER	3,730	1.0	0.3	0.0	0.0	0.0	-					
7	OR	5,550	0.0	0.5	0.0	0.8	0.0	1.0	-				
8	Post OR	1,024	0.0	0.0	0.0	0.0	0.0	0.5	0.8	-			
9	Intensive, admin	3,372	0.0	0.0	0.0	0.0	0.5	0.8	0.8	0.5	-		
10	Diagnostics	4,270	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	-	
…	…	454	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.5	-

The correlations in Table 4-5 outline the requirements relating to the design variables for the functionality of the hospital. Table 4-5 is a section of Appendix A outlining the full correlation matrix. Appendix A and Appendix B outline the two full correlation matrices representing the two organization typologies. The different organization typologies require different correlations across the hospital.

The correlation matrix can be seen as a transformation of the architectural understanding of a hospital and its functionality. It represents the architectural design approach of drawing diagrams and relating the functionalities to facilities.

The variables outline the coordinated collaborations (according to the organization typology) within the hospital. It is closely related to the logistics. The requirements involve the primary, secondary and tertiary functionalities of the hospital in terms of correlations needed for the patient treatments as the primary functionality. The diagnosis, treatment and care of the patient equally relate the secondary patient-related supportive functions and the tertiary patient-remote supportive functionalities. In this way, the correlations and not the functionalities become the design objective.

During the last few years, designing hospitals while respecting supportive facilities has increased as well as design respecting automated supportive systems (80,98,121). A correlation approach weighs the correlations by functionalities, frequencies and severity and facilitates a systematic operation. Moreover, qualitative and quantitative data define the correlation, facilitating an evidence based design approach. The correlations given in the present correlation matrix, are defined based on evidence of patient treatments. Thus, it is evidence from patient treatments that defines the treatment-based correlations and requirements for the facility.

Having the correlations explicitly defined as the design objective facilitates the ongoing update of the design model according to current research. The decomposition of the hospital as presented encompasses large potential in ongoing update and changes in the field. It is easy to update the requirements and preferences of the correlations according to trends and shifting focus on logistics, supportive functions, collaborative efforts etc. by weighing or changing the correlations. The correlations become the data informing the intermediate construction of the design model.

In terms of architectural modeling, the date of the correlation matrix defines the intermediate construction. Thereby, the intermediate construction derives from functionalities and the primary drivers defined by typologies. The intermediate construction defines the generation of design concepts as resulting geometries reflecting hospital functionalities.

Using the correlations between functionalities as generators of the design is a design approach that emphasizes a functionalistic approach to the design rather than an approach rooted in the existing departmental division and collaboration on a personal level. The approach attempts to elevate the perspective on the functionalities to a holistic level covering experience and collaboration in general. The starting point is the data from the hospital operation rather than personal experiences from one or more stakeholders (cf. Figure 2-1) who advocate their own or related perspectives in the hospital design process.

4.4. Model generation

The model generation begins with the correlation matrix. The correlation matrix formally describes qualitative and quantitative data on hospital functioning. It represents the architectural approach of bubble diagrams. Model generation with this approach takes place in the architectural understanding of design by functionalities. Consequently, the design approach involves formulation of the framework of a facility by the functionalities and their relations as defined in the correlation matrix.

The traditional architectural design approach consists of geometric studies and studies of volume in the early form generation. The design approach combines the geometric studies with the functional requirements in the form making. The design model of this paper reflects the traditional architectural design approach. Therefore, it combines geometric studies and studies of volume with functionalities by combining the typologies with the correlation matrix.

To make a design model for conceptual design of hospitals, where the design responds to the functionalities, the functionalities must define the geometric constraints. The model generation responds to this approach by an initial loading of the correlation matrix. Subsequently, there is a definition of the geometric constraints and an exploration of the configuration of volumes.

The design model generates design concepts by mathematic formulations. Initially there is an elaboration of the functionalities in the correlation matrix, and a definition of the principal drivers in terms of typological design choices. This leads to the definition of design concepts as a resulting geometry.

The basis of the model is several iterative processes and optimizations with varying objective. Overall, the design generation consists of a four-step procedure, to which the functionalities, described as correlations and dimensions, are input data. The design model processes data of the functionalities through the framework defined by the building typologies, organization typologies and layout typologies. This leads to geometric studies, where geometric units, defined by overall geometric constraints, typological definitions and inherent functionalities, describe the hospital. The geometric units are conceptual design configurations of the hospital. Accordingly, the architectural and structural exploration begins in the geometric units and the building, organization and layout typologies.

4.4.1. Generation of geometric units

As already mentioned, generation of the geometric units follows a four-step procedure initiated by loading input data in terms of the correlation matrix.

1. Define a number of geometric units.

   A qualitative study of recent hospital construction in Scandinavia reflects the number of units as defined by collaboration and culture within the hospital. The number of units is defined as a number of combined specializations. For the analyzed projects, the number is within the range of 5-10 units per hospital.

2. Define the layout of the geometric units.

   The layout typologies define the layout of the units as a derivative of the design strategy. Layout typologies 1-5 define the layout of the units with the respective constraints.

3. Define the area of each geometric unit.

   Each geometric unit consists of a variable number of layout units. The number of layout units in each geometric unit is generated randomly according the geometric units and the total area of the hospital.

4. Define the content of each geometric unit.

According to the correlation table as exemplified in Table 4-5, the content of the geometric units is defined. The content is restricted to the constraints of the geometric units defined in step 1-3. Chapter 7 outlines the definition of the content in the geometric units, where the numerical implementation of the design model is outlined.

The geometric units define the baseline for the design of the hospitals as conceptual designs reflecting functionalities. Typological visualizations and outline of the inherent functionalities create the conceptual designs. The geometric units are defined on the inherent requirements relating to the functionalities. Geometric constraints define the parameters for the design configuration.

4.5. Summary

This chapter has defined the architectural requirements and preferences in terms of hospitals. The driver of architectural modeling in terms of requirements and preferences are defined by the functionalities of the hospital, thus the performance of hospital functionalities defines the design model. This perspective has driven the definition of the correlation matrix. This chapter describes the definition of the correlation matrix. The correlation matrix is defined as the input data of the design model. It is defined on state-of-the-art analyses of patient treatments, and with that foundation it defines the requirements and preferences for the design generation. By having the correlation matrix as a separate element loaded into the design model, ongoing update of knowledge, evidence and practice is facilitated. The definition of the correlation matrix is an approach for the implementation of evidence in the design generation. The definition of the correlation matrix is an essential part of this research project, as it facilitates an approach of evidence-based design.

Evaluating hospital design is as mentioned in the introduction according to the perspectives of the six performance evaluators. As this chapter describes the patient treatment are essential as the objective of the hospital design and in the evaluation of the hospital design. All performance evaluators consist of perspectives regarding the patient treatments, which argue for the patient treatments as the driver in the model definition and the model generation. The patient treatment defines the correlations of the functionalities of the hospital, and so the design objective is the correlations and not the functionalities. The definition of the geometric units focuses on the operational ability of the hospital functionalities rather than the building functionalities.

A traditional design approach for hospitals begins in the relatively fixed entities or departments. The prime focus while designing hospital facilities is on optimizing the arrangement of hospital departments with respect to shared functionalities and collaborations across departments. The purpose is parallel to the present research project by streamlining logistics in terms of minimizing travel or transportation, which represent a primary cost in hospital operation. Analyses of interaction between departments outline expressions of travel frequencies and relationships. They define the efficient placement of departments with respect to adjacency. This approach relates to the traditional understanding of the departmental constraints in the exploration of new ways of organizing work and procedures. The definition of the correlation matrix and designing by correlations allow exploring new ways of organizing work, because it liberates itself from departmental constraints.

The optimization perspective is inherent in the mathematical operation of the correlation matrix and thereby an essential driver in the process of finding the best location and size for the geometric units. The geometric units and the performance objectives define the hospital design by a set of defined parameters and rules. The resulting geometry is a reflection of the performance objectives and the geometric units.

Procedures of optimizing functionalities and relations by the respective correlations define the geometric units. The definition of the framework of the geometric units is subject to the building typologies, organization typologies and layout typologies. Processes of adjusting the constraints of the geometric units in accordance with the dimensioning of the individual functionalities define the geometric constraints. Consequently, the units possess individual sizes defined by the requirements for correlations within the functionalities.

Chapter 5. Evaluators

The intermediate construction consists of a definition of the geometric entities according to the initial design choices by the principal drivers. The definition of the geometric entities consists of a functionality distribution allocating all hospital functionalities according to the data of the correlation matrix within the given framework of the principal drivers. The following section will outline the framework by the principal drivers numerically as input for the evaluation of the performances. The evaluation of the hospital design configurations consists of two parts. One part reflects the performances relating to the principal drivers. Another part reflects the performances as a function of the functionality distribution.

This chapter elaborates on the definition and description of the performances relating to both the principal driver and the functionality distribution. The definitions of the principal drivers in Chapter 3 are in this chapter elaborated by two numerical definitions, which determine the influence on the performances. Accordingly, the numerical definitions drive the definition of the performances while reflecting the principal drivers.

Subsequently, this chapter defines tables for implementation in the design model, outlining the six performance evaluators in terms of the principal drivers and the functionality distributions. They reflect the six *performances for the design configurations described by principal drivers and the functionality distribution respectively.*

The functionality distribution derives from the correlation matrix. It describes the interdependencies within the hospital as a model for performance. Relativity exists between the functions for design requirements and preferences and the function for the functionality distribution. The functionality distribution emerges through iterations of various performances with focus on patient treatment, as described in Chapter 4.

The principal drivers have the highest hierarchical level in the design model, and so they generate the framework for the design configuration by defining and dimensioning the geometric units and the performances. The choice of principal drivers closely relates to the geometric studies and studies of volume characterizing the traditional architectural design approach. The output of the principal drivers becomes the input parameters defining the intermediate construction.

The six performances are defined as performance objectives, respectively, to facilitate implementation in a design model. The performance objectives and design requirements and preferences all are defined as cost functions in the range [0-1]. The higher the cost function the better performance.

5.1. Numerical definition of typologies

This subsection elaborates on the typological definition in Chapter 3. Contextual premises found several of the numerical constraints that define and distinct the typologies. Table 5-1 outlines the dimensions for the building typologies. The dimensions are derived from qualitative analyses of hospitals in Scandinavia as described and exemplified in Chapter 1 and Chapter 3. The dimensions derive from the plots as exemplified in Chapter 1 and the requirements defined in the tender documents for the construction projects (45,46).

Table 5-1 Physical dimensions of the building typologies defining the framework for the building composition

Index	Max length of plot [m]	Max width of plot [m]	Number of story	Default story height [m]	Max height of plot [m]	Plot ratio [%]	Total built area [m^2]	Total plot area [m^2]
1	150	100	25	5	125	2,500	375,000	15,000
2	1,000	600	5	5	25	62.5	375,000	600,000
3	2,000	1,250	3	5	15	15	375,000	2,500,000

The building typologies define the landscape of the architecture of the hospitals. The physical dimensions define the differentiation between the typologies. The dimensions are variables reflecting existing hospitals. These variables can be updated with project specific dimensions for the plot, the story height etc. The main contribution of the specification is the differentiation in total plot area, given by the length of the plot times the width of the plot. The plot ratio is given by the built area dived by the total plot area. The number of stories is given by local regulations or politics. In the project-specific adjustment of these dimensions, it is important to maintain the differentiation.

The numerical definition of the layout typologies are likewise derived from the examples in Chapter 1, the specifications in tender documents (45,46) and ALECTIA A/S design guidelines. The dimensions of the layout typologies are derived from design principles of flows, daylight and room organization involving requirements and preferences in walking distances, work environment, natural daylight etc. Table 5-2 numerically defines the dimensions of the typologies based on the typological definitions exemplified in Chapter 1. The numerical definitions can be updated according to project-specific dimensions, as long as the principles in the definitions are maintained. The principles regard the differentiation with/without courtyards and functional rooms on one or both sides of the corridor.

Table 5-2 Physical dimensions of the layout typology defining the framework for the building and unit composition

Index	Max length of section [m]	Max width of section [m]	Max sectional depth [m]	Daylight depth [m]	Hall width [m]	Max length of courtyard [m]	Max width of courtyard [m]	Area of section [m^2]
1	75	9	9	6	3	0	0	675
2	75	15	15	6	3	0	0	1,125
3	75	15	15	6	3	0	0	1,800
4	75	27	9	6	3	9	57	1,512
5	75	45	15	6	3	15	45	2,700

The building typologies and layout typologies define the variables for the physical dimensioning for the design composition. The organization typology indexes the correlation requirements according to the functionally split or the sectorized models. Accordingly, the organization typologies influence the correlation matrix directly by different correlation requirements and preferences. The correlation matrices are outlined in Appendix A and Appendix B as a derivative of organization typologies 1 or 2, respectively.

In the geometric studies or studies of volume, some evaluations can be applied directly. However, most evaluators are defined as functions of the functionality distribution. The following subsection defines the definition of the performance evaluators as functions of the physical framework and the functional distribution.

5.2. Performance evaluators

Several performance evaluators exist in the hospital facility of multiple production lines and performance objectives. Some of the performance evaluators are even contradictory. The evaluators of Chapter 2 represent the perspectives of state-of-the-art hospitals, which define the framework of this thesis. The evaluators represent architectural, engineering and functional perspectives, as illustrated in Figure 5-1.

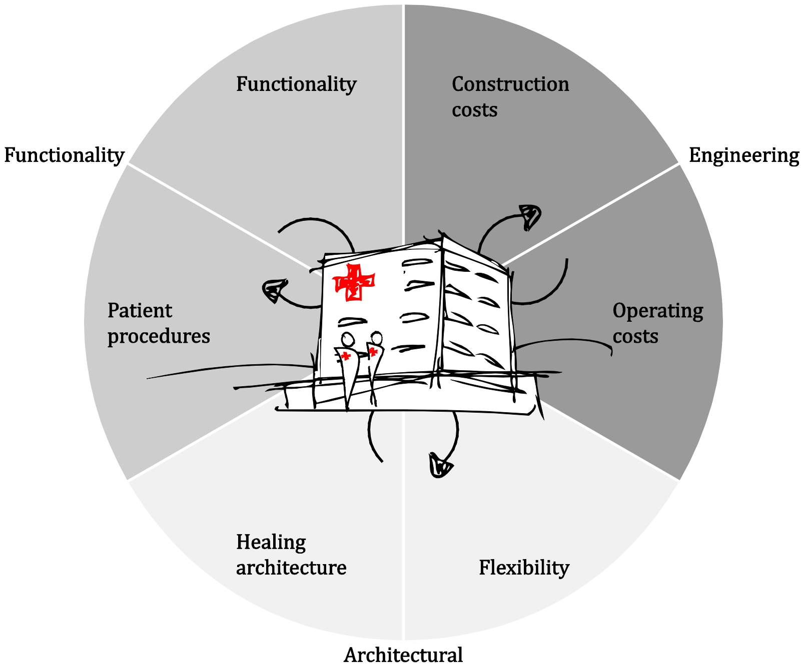


Figure 5-1 The performance evaluators influence the hospital design differently. Together the performances describe the architectural, engineering and usability perspectives.

The following subsections will define and describe the six performances and their influence on hospital design. The physical dimensioning, as defined in the previous section, influences the performances in terms of the principal drivers, by a performance indexation. The physical dimensioning also influences the performances in terms of the functionality distribution. Consequently, the performances are also defined as a function subject to the functionality distribution.

The following subsections introduce the performance evaluator initially. This introduction is based on qualitative analyses of tender documents and governmental recommendations (42,43,45,46,74,75,77,116,119). These references define the framework of the qualitative studies, for supplemental references these are given, explicitly. Following, each subsection defines the numerical performances of the evaluators. The numerical performances combine the numerical definitions from the previous subsection with the individual performance evaluators. Each performance evaluator consists of a subsection of a performance indexation by principal drivers and a subsection of the performance evaluator as a function of the functionality distribution.

5.2.1. Construction costs

The ability to realize a given project economically is a central and recurring element in the evaluation of the engineering, architectural and functional solution of the hospital construction. It is a client focus and for The Quality Reform projects it is non-negotiable and fixed.

The overall construction typology, the choice and amounts of materials influence the construction costs. Larger distances and larger spans increase the construction costs in terms of increased construction material, installations etc. The size of the built area is decisive for the construction costs – more construction means more costs.

A focus on construction costs is present from the initial design concept. However, knowledge of construction costs increases throughout a project's phases, and several of the Quality Reform hospital constructions have shown difficulties in sticking to the budgets throughout the project phases (170,171). This has caused several cost-savings, and for some of the cost savings, the construction cost savings are paid for by operational costs (170,171). This is a negative sub-optimization, because the operational costs are much higher than the construction costs in the total economics of the hospital, and so the economic consequences are serious (171).

The cost functions are defined only to relate the typologically dependent costs. The construction costs reflect the investment capital costs relating the building design, and they do not include costs regarding furnishing, equipment and installations that are the same within the different typologies. The construction cost functions as constructors reflect the choices of principal drivers and the distribution of functionalities according to the correlation matrix. Overall, the construction costs include the amount of materials and the construction typology. The construction cost function consists of a term representing the indexation by the principal drivers, reflecting the amount of materials and the construction typology. The other term is a function of the functionality distribution as the design variable.

5.2.1.1 Principal drivers

The next part outlines the construction costs as an indexation according to the principal drivers. The indexation in terms of building typologies refers to the three building typologies of 1) high-rise, 2) urban, and 3) campus. The indexation of layout typologies refers to the five typologies of 1) single corridor, exterior, 2) single corridor, interior, 3) double corridor, 4) courtyard, exterior, and 5) courtyard interior. The indexation of organization typologies refers to 1) functionally split and 2) sectorized.

The construction costs are given by the built area, cf. 5.2.1. The differentiation according to the principal drivers is defined by the gross-net area. The Gross-net area is given as the functional area divided by the total area for a given layout typology. Because all cost functions refer to a value in the range [0-1], the gross-net areas are normalized to be within the range [0-1], with [1] as the better cost function.

Table 5-3 Construction costs related the principal drivers.

	Building Typology	Layout Typology	Organization typology
Referring	Typological cost of construction	Gross and net areas according to typology	Influences the functional costs
Index	Not indexed typologically	[1:5]	Not indexed typologically
1		0.84	
2		1.00	
3		0.94	
4		0.93	
5		0.99	

The building typologies do not imply the construction costs on an overall level (ALECTIA A/S). The decisive costs according to the building typologies relate to the price of a given site. This parameter is not included in the model, as it varies significantly from place to place, and for most construction projects the site is a given prerequisite.

The layout typologies imply the cost by the gross and net factor following the typological dimensions.

The organizational typologies imply, as described, the functional distribution by separate correlation matrices.

5.2.1.2 Functional distribution

The construction costs as a function of the functionality distribution consist of variables regarding the geometric unit area, GU_A, the effective geometric unit area, reflecting the area provided by typologies and the functionally required area, and finally a functionality cost index for the unit.

Table 5-4 Construction costs related the functional distribution.

	Unit area	Effective area	Functional cost index
Referring	[m^2]	Occupied area in unit, [%]	Highest functionality cost index for unit [%]
[1:10]	GU_A	[1-100]	[1-100]

The functional cost index is a function of the functionalities within the unit. It reflects the construction and the technical demands for the given functionalities. Therefore, the index reflects the construction costs of the highest indexed functionality in each geometric unit. It is given by the experience figures of Table 5-5.

Table 5-5 Functional construction costs per m^2, categorized by type of functionalities. The costs are company experience figures (ALECTIA A/S).

Functionality	e.g.	New construction [DKK]	Cost Index
Secondary areas	Basement, Technical rooms, deposits, archives etc.	12,800	1.00
Non clinical areas	Offices, teaching, foyer, etc.	20,000	0.64
Clinical areas	Wards, out-patient clinics, etc.	28,100	0.46
Special clinical areas	Operation, laboratories, imaging, etc.	36,300	0.35

As described earlier, the performance objectives are defined as cost functions in the range [0-1]. The higher the cost function the better performance. The cost index of the construction costs is therefore calculated as the lowest price divided by the price of each functionality category.

The construction costs closely relate to the design configuration of the geometric units, and so the cost index multiplies the area of the geometric unit.

5.2.2. Operating cost

The operating costs are highly weighted in the evaluations of the hospital designs. It is a parameter for all design phases. However, it often lacks focus initially because there are too many unknowns, and so it is too difficult if not impossible to estimate and include the operating costs in the development of the design concepts.

The design teams focus on the operating costs in terms of sustainability, personnel conditions, and logistics in a broad sense. The operating costs are difficult to concretize and incorporate, and so focus becomes general considerations and intentions. Numerical implementation is a method of concretizing the operational costs, but the traditional method of developing the design does not combine this perspective. In the later design phases where focus on construction costs intensifies, several occasions of compromises on operating costs occur, probably because of the lack of numerical implementation (170,171). Solutions with initiatives for sustainable operation and low operation costs are rejected to achieve investment capital.

Operating costs have parallels in sustainable operational procedures. However, they reflect approximately 18 % of the operating costs while the salaries reflect a majority. The operating costs closely reflect transportation and distances across the hospitals, both locally and globally.

5.2.2.1 Principal drivers

This subsection outlines the indexation according to the principal drivers. The operating costs are defined similar the construction costs as a reflection of the costs derived from the design configuration, and so the general costs are not included, i.e. equipment, energy usage regarding equipment, lighting etc. Personnel costs, functional costs and building operating costs describe the operating costs.

The personnel costs reflect salaries, which in terms of the design configurations regard transportation requiring personnel, locally and globally. Moreover is regard as accessibility for patients for minimizing the required assistance. The functional costs are independent of the design configuration and consequently they are not included.

The building operating costs reflect energy consumption as a result of the building geometry, envelope and surface areas, it reflects orientations and energy utilization because of the overall building design with regard to installations.

Table 5-6 Operating costs related the principal drivers.

	Building Typology	Layout Typology	Organization typology
Referring	Typological cost of construction	Gross and net areas according to typology	Influences the functional costs
Index	[1:3]	[1:5]	Not indexed typologically
1	1.00	0.84	
2	0.65	1.00	
3	0.25	0.94	
4	-	0.93	
5	-	0.99	

The operating costs in terms of the building typologies reflect the global distances across the hospital. The construction costs in terms of layout typologies relate to the relationship between the net and gross areas as an expression of the local distances for transportation and energy consumption for e.g. installations. The organizational typological implication is inherent in the functional distributed operating costs.

The typological cost according to building typology is derived from the plot ratio. The plot ratio is divided by the number of stories to describe the built area and thereby the extension of the built area. This number is normalized to be within the range [0-1].

The typological cost according to layout typology is the normalized gross-net area.

The organization typology influences the cost according to the correlation matrix.

5.2.2.2 Functional distribution

The operating costs as a function of the functionality distribution supplements the approach of the indexation, but as functions of the defined geometric units. The operating costs regard the mass of the geometric unit, M_{GU}, as a term describing functional and building costs. The effective area also reflects functional and building costs, while the functional cost index relates to the inherent correlation, *cf* and thereby the conditions for personnel and transportations.

Table 5-7 Operating costs related the functional distribution.

	Center of mass	Effective area	Functional cost index
Referring	[m]	Occupied area in unit, [%]	Unit-wise correlation factor
[1:10]	M_{GU}	[1-100]	*cf*

The functional construction costs depend on the geometric configuration of the geometric unit and the correlations within the units. The correlations reflect the personnel costs in terms of transportations, walking distances and accessibilities. The correlation factor, *cf* is a summarized factor of the achieved correlations within the respective units. The correlation factor is calculated by iterations of optimizations according to the four-step procedure described in Chapter 4 and numerically defined in Chapter 7.

The center of mass is given by the actual size of the defined geometric unit. It is based on the distance to the center of mass of the actual geometric unit.

The effective area is the percentage of occupied area in the geometric unit. Each unit has a fixed framework according to the typologies. The definition of the geometric units allows some waste areas. The effective area is the occupied area divided by the total area.

5.2.3. Functionality

The overall functionality of the hospital reflects the hospital procedures. The engineering solution, architectural solution and functional solution in a hospital design regard this perspective.

Optimal flow of patients, personnel and goods describe the functional hospital. It encompasses patient safety and professional and technical conditions for operating the hospital.

Functionality is an architectural and engineering focus area throughout the design process. Solving the functionality problem in practice is done based on experience. Architects and engineers as advisers represent expert knowledge in solving the hospital procedures within a built environment. The user involvement as described in Chapter 2 contributes with health professional experience and opinions. Both contributions are essential in the definition of the design. However, the integration of the contributions is not formalized, and the knowledge contributions from the different professions are handled intuitively and not systematically.

The initial design sets an overall plan for the hospital procedures and standardization thereof. The plan copes with perspectives of working environment and patient safety, including hygiene, acoustics, daylight etc. Some of these perspectives address the design in the late phases, as they represent a high detail level. These perspectives are not taken into account as their qualities are independent of the overall design configuration. Daylight and working environment are decisive drivers and so they have defined the different layout typologies.

5.2.3.1 Principal drivers

This subsection outlines the indexation according to the principal drivers. The hospital procedures involving the building typologies reflect the global distances across the hospital as an expression of the adjacency and the distances globally. In terms of the layout typologies the functionality is closely related to daylight and views in terms of the working environment and legislation. Therefore, the indexation in terms of the layout typology refers to the relationship between area and façade.

Table 5-8 Functionality performance related the principal drivers.

	Building Typology	Layout Typology	Organization typology
Referring	Typological cost of construction	Relation between area and facade	Influences the functional costs
Index	[1:3]	[1:5]	Not indexed typologically
1	1.00	1.00	
2	0.65	0.64	
3	0.25	0.44	
4	-	0.89	
5	-	0.53	

The functionality is given by the normalized global distances across the hospital.

The functionality in terms of layout typologies is given by the area of the façade divided by the area of the layout typology. Like before, the number is normalized by the typology with the largest number for the index to be within the range of [0-1] with [1] as the better performance.

The organization typology influences the functionality by the correlation matrix.

5.2.3.2 Functional distribution

The hospital procedures are closely related to the functionality distribution and the correlation factor. The functionality in terms of the design configuration can be described by the correlation factor, *cf*, as a definition of the coherence of the different functionalities. The configuration of the individual geometric units is likewise of importance in describing the adjacency and proximity by the mass of each unit M_{GU} and the actual size of the unit.

Table 5-9 Functionality performances related the functional distribution.

	Unit area	Center of mass	Functional cost index
Referring	[m^2]	[m]	Unit-wise correlation factor
[1:10]	GU_A	M_{GU}	*Cf*

The variables influencing the functional distributions have been defined in the previous subsections.

5.2.4. Patient procedures

The patient procedures reflect the other perspective of the hospital functionality. They take the patient’s perspective. Patient procedures are in focus from all involved participants in the design process, and the process of working with the patient procedures is similar to the hospital functionality. Involvement of different professions and user groups clarifies the perspectives of the patient procedures. Improved patient procedures and continuity in personnel are prioritized parameters together with improved communication between sectors, departments and hospitals.

The patient procedure is especially an initial focus area that contributes to the definition of the design concept. Configuration of design concepts often begins with connecting the flows of the hospital for assuring continuity in care and reducing the patient transportations and shifts. Anti-institutionalization is a driver in the conceptual design, it concerns minimizing the pacification of the patient by activating the patient and its relatives in the patient treatment.

Patient satisfaction is another perspective of the patient procedure. Minimizing delays and waiting times is a priority along with avoiding unpleasant waiting rooms. Furthermore, a shortage of staff, little face-to-face contact with physicians and direct care time are important elements. Incorporating these perspectives in the design configuration requires a transformation of the foci into perspectives related to the design configuration.

The improved patient satisfaction forms part of the late detailed design of decoration. This perspective is not incorporated at a detail level of the design configuration. For the initial and overall design configuration, the improved patient procedures are within the close contact to the personnel, minimization of distances and transportation for both patients and personnel, and improvement of accessibility.

5.2.4.1 Principal drivers

The patient procedures relating the building typologies reflect the global distances across the hospital in terms of accessibility and way-finding. Accessibility and way-finding also characterize the performance of patient procedures in terms of layout typologies. The patient procedural performances involving organizational typological implication are inherent in the functional distribution.

Table 5-10 Patient procedures related to the principal drivers.

	Building Typology	Layout Typology	Organization typology
Referring	Typological cost of construction	Gross and net areas according to typology	Influences the functional costs
Index	[1:3]	[1:5]	Not indexed typologically
1	1.00	0.84	
2	0.65	1.00	
3	0.25	0.94	
4	-	0.93	
5	-	0.99	

The typological cost of the building typology as the normalized global distances across the hospital and the layout typology as the normalized gross- net factor have been defined above.

5.2.4.2 Functional distribution

The patient procedures deal with the accessibility and proximity, and so, the function of the functionality distribution consists of the following three terms. The area of the unit, GU_A, proposes the proximity. The center of mass, M_{GU}, reflects the accessibilities and way-finding for the patient. Finally, the coherent patient treatment is defined as the functional cost index by the correlations factor, *cf*.

Table 5-11 Patient procedures related the functional distribution.

	Unit area	Center of mass	Functional cost index
Referring	[m^2]	[m]	Unit-wise correlation factor
[1:10]	GU_A	M_{GU}	*cf*

The variables influencing the functional distributions have been defined previously.

5.2.5. Flexibility

Flexibility is present from the initial definition of the design concept to the late decoration and furnishing. Flexibility is an expertise area of the advisers, as it requires overview of the hospital, design principles and in the construction principles.

Flexibility is a decisive parameter. In the longer perspective, it is a parameter of operational costs, because of the constant 8-10 % reconstruction of hospital mass (ALECTIA A/S). The economic potentials in flexibility are massive.

Grouping-related functions and relating the load-bearing constructions are common approaches to flexibility. This approach reflects the traditional preparation for changes along with a standardization of rooms. The values of flexibility are accessibility, standardization and preparedness for future changes.

Accessibility includes two perspectives: the local accessibility for local, interior changes and the global accessibility across the hospital. The local accessibility reflects access for changes in equipment, which often is large, heavy and hard to maneuver. The global accessibility is for accessing the hospital with new equipment and for reconstruction, but it also takes the internal reshuffling into account.

Standardization is another perspective. Standardization prepares the hospital for demographic changes, changes in the patient’s mental and physical capabilities and universal reconstructions. Along with standardization comes the independent functionality. Independent functionality secures sustaining the functionalities in an area near reconstructions.

Technology preparedness includes the above categories of grouping-related functions, load-bearing cores and achieving flexibility in facades and rooms.

5.2.5.1 Principal drivers

The indexation reflects the accessibility for the building typology and thereby the open structure. The indexation for the layout typologies reflects the compactness as a reflection of the internal accessibility.

The organizational typological implication is indexed by a factor. The functionally split model is more flexible for demographic changes, because the functionalities are gathered and so changes in dimensions are facilitated.

Table 5-12 Flexibility related the principal drivers.

	Building Typology	Layout Typology	Organization typology
Referring	Typological accessibility and flexibility	Typological accessibility and flexibility	Typological preparedness for changes
Index	[1:3]	[1:5]	[1:2]
1	0.25	0.84	1
2	0.38	1.00	0.70
3	1.00	0.94	-
4	-	0.93	-
5	-	0.99	-

The indexation of the building typologies encourages the accessibility of the built environment from the outside. Therefore the typological indexation is normalized by the most open structure.

The indexation of the layout typology is normalized by the gross and net areas. The indexation is normalized by the most compact typology.

The indexed factor of the organization typology is a variable, derived from the correlation matrix. The correlation requirements operate with +/- 20-30 %. The variable is subject to changes.

5.2.5.2 Functional distribution

Flexibility according to the functional distribution reflects the same principles of accessibility and inverted correlations as described for the principal drivers. Flexibility as a function of the functionality distribution refers to the mass, M_{GU} as a perspective of proximity and accessibility. The inverted correlation, *cf*, is the other term referring to the requirements of correlation for the functionalities. The flexibility performances entail the inverted correlation factor, since the higher the correlation, the higher the dependencies across the functions. The center of mass represents the local accessibility along with the unit size.

Table 5-13 Flexibility related the functional distribution.

	Unit area	Center of mass	Functional cost index
Referring	[m^2]	[m]	Unit-wise correlation factor
[1:10]	GU_A	M_{GU}	$\frac{1}{cf}$

The variables have been defined previously.

5.2.6. Healing architecture

The design practice focuses on evidence-based design on healing architecture. Healing architecture is a consistent evaluation objective in tender documents. However, practice operates with an abstract understanding of healing architecture and healing surroundings.

Healing architecture represents a concept grounded in research. It encourages daylight, green facilities, the indoor environment, and the general atmosphere. Practice, clients and tender documents emphasize healing architecture in terms of patient safety and the sanitation of hospitals (120) to which there are specific design guides.

Research focuses on initiatives for healing surroundings primarily regarding atmosphere and holistic settings. These perspectives can be incorporated in the overall design configuration. The perspectives of patient safety and sanitation influence the design on a more detailed level.

The natural settings focus on natural lighting as a healing element and on views. The relation between functional areas and facades reflect these perspectives. The integration of plants in the hospital settings is not incorporated. This perspective is based on the more detailed design of decoration, and must be closely linked to the principles of sanitation, spread of infectious diseases and the indoor climate and the patients.

Patient safety as confidence is related to the size of the built environment and the relation to personnel.

5.2.6.1 Principal drivers

The healing surroundings in terms of the principal drivers reflect the integration within the natural settings and the daylight exposure. This is defined as the openness of the building typology and the relation between area and façade of the layout typology.

The organization typology indirectly implies healing in terms of the coherent patient treatment. This perspective is inherent in the correlation matrix.

Table 5-14 Healing surroundings related the principal drivers.

	Building Typology	Layout Typology	Organization typology
Referring	Typological cost of construction	Relation between area and facade	Influences the functional costs
Index	[1:3]	[1:5]	Not indexed typologically
1	0.25	1.00	
2	0.38	0.64	
3	1.00	0.44	
4	-	0.89	
5	-	0.53	

The indexation of the building typologies encourages the openness of the built environment, and so the typological indexation is normalized by the most open structure, which also applies to the flexibility indexation.

The relation between the area and facade has been defined for the functionality, 5.2.3.

5.2.6.2 Functional distribution

Healing surroundings, according to the functional distribution, concern patient safety, integration in natural settings and rehabilitation with respect to the geometric composition. The compactness of the unit is decisive for a close relation to the exterior together with the area of the unit. M_{GU} defines the close relation to the exterior and GU_A is the area of the unit. The coherent patient treatment is important for improved patient safety. This is described by the correlation factor, *cf* as the second term of the function. The correlation factor represents the coherent patient treatment for knowledge about the patient and patient treatment for minimizing errors, an important issue in patient safety.

Table 5-15 Healing surroundings related the functional distribution

	Unit area	Center of mass	Functional cost index
Referring	[m^2]	[m]	Unit-wise correlation factor
[1:10]	GU_A	M_{GU}	*cf*

Previous subsections have described the definition of the variables.

5.3. Summary

This chapter defines a method for evaluating the performances with two perspectives: evaluation subject to the principal drivers, and evaluation as a function of the design variables defined in the functionality distribution.

The evaluators with respect to the design configuration, as they are defined, derive from the numerical definition of the typologies as the principal drivers. The numerical definitions are an elaboration of the qualitative definitions in Chapter 3. The numerical definitions are variables, schematically listed, for implementation in the design model. The variables can be updated with project specific information within the framework of the typologies. For the building typologies, the typological differences are in scale and not principle and changes will just influence the indexation with increased or decreased differentiation in the performance according to the project specific variables.

The performances in terms of principal drivers clearly visualize the contradictions of the evaluators. The study shows how some of the evaluators encourage dense and compact typologies. Meanwhile, others require spacious and light typologies. Listing the evaluators in tables facilitates implementation in the design model for discussing the contradicting performances of the evaluators. Moreover, it facilitates evaluating design configurations on an informed basis with an illustration, because it visualized the respective qualities.

The evaluators described as a function of the functionality distribution also outline the principles in the evaluation. Likewise, they emphasize the contradicting perspectives of the respective performance evaluators. However, the impact of the evaluators as a function of the functionality distribution is not visually clear, as they are defined by variables and not scalars. However, outlining variables provides insight into which variables imply which performance evaluators.

This chapter concludes the first research question of how hospitals can be designed conceptually as building entities that respond to functionalities.

The decomposition provides a method for operating systematically with functionalities in architectural design. The decomposition and definition of the correlation matrix is a transformation of the architectural design approach of bubble diagrams, broadly recognized and valued in practice. The correlation matrix provides a formal description of functionalities in comparison to the bubble diagrams. It encompasses of a formal transformation of the requirements to the patient treatment and the hospital functionality.

The analysis of patient treatments outlines the required functionalities and dependencies for each patient treatment in terms of the primary functionality of the hospital and the secondary and tertiary functionalities of the hospital. With the correlations as the design objective and not the building functionalities, the design configuration focuses on the operational ability of the hospital functionalities rather than the building functionalities.

The decomposition is the first step in understanding hospitals as a response to functionalities. Decomposing the hospital transforms it into entities of the hospital's inherent functionalities and correlations. The decomposition is essential because it liberates operation from traditional thinking, while it facilitates exploration of new patterns, when the design aims to respond to the inherent functionalities.

The typological approach provides a framework by rules for configuration. The typologies represent a decomposition of the building entities of the hospital.

In the definition of the performance evaluators, the functional, engineering and architectural perspectives on design configuration contribute. A qualitative analysis of hospitals provides an architectural understanding, which coding formalizes into applicable requirements and preferences, similar to the engineering and functional requirements and preferences. The tables of performance evaluators are formal definitions of the architectural, engineering and functional requirements and preferences.

This concludes the definition of a conceptual design model for hospital design, where the conceptual design of building entities responds to functionalities. The following part of this PhD thesis elaborates on the numerical implementation of the design model.

Chapter 6.
Use of Systemized Numerical Design Models

This main part of this thesis consists of Chapters 6, 7, 8 and 9 outlining the numerical implementation of the design model and thereby the second research problem of the thesis. This chapter outlines the current research into the topic and defines the numerical methodological framework for the model definition.

The model definition is based on current mathematical models. The overview of this chapter defines the methodologies framework. Current research has elaborated on mathematical optimization models for architectural design from a computational perspective. The research conducted for this thesis attempts to implement contextual premises in the existing models. Consequently, focus is on applying the complex hospital context in the existing models.

This chapter introduces the numerical models in architectural design and the definition of numerical optimization models. Finally, the chapter will describe three different approaches for setting the framework for the model definition in the following chapter.

A numerical model can facilitate the design generation by functionalities, because it is able to handle the complexities while generating design. The design is derived from the framework of standardized parameters and principles, programmed into the model. It is easy to program research and evidence into the standardized parameters and principles.

The point of departure for the mathematical formulation of the design model is the four-step procedure from 'Model generation' in Chapter 4. It described the functionality distribution that follows the generation of geometric units. The functionality distribution is subject to optimizing the correlation within each unit.

6.1. Numerical design models in architectural design

Numerical design models take two strategies, as outlined in Chapter 2: the constructive initial placement strategies and the iterative improvement strategies (148). The constructive initial placement strategy locates activities one by one by stepwise making a solution from scratch. The iterative improvement strategy begins with an initial arrangement followed by iterations of incremental improvement attempts. Computer scientists have made the most development in the fields with a focus on making things work and minimizing computation time (172). The constructive initial placement strategy, where e.g. decision trees locate activities one by one, is an expensive model for complex problems. The iterative improvement strategy, on the other hand, is appropriate for complex problems, because of the iterative incremental improvements (148).

With hospital design as the applied context, the current research takes the practical context and applies the relevant functional constraints and framework in the mathematical models. This perspective is barely seen in hospital design research. Research in application of computational modeling takes the computer scientist's perspective of making things work (61,63,65). In research examples regarding hospital design, the hospital is merely a complex general case (65,131,151).

6.1.1. Construction of numerical design models

Research has explored component packing (101,139-141), route path planning (53,54), and process and facility layout design (55-60) for spatial configuration with the aim of finding feasible locations and dimensions for a set of interrelated rooms. Exhaustive searches commonly cause expensive computation, why researchers have developed decision tree-based combinatorial representations (137,173). To reduce computation time the in-expensive iterative improvement strategies have proven their worth through heuristic strategies for general layout problems.

However, exhaustive search still causes expensive computation, which is why attention must be paid to the problem from practice in order to avoid the reduction in complexity based on limited information whereby the traditional patterns are maintained (91) and the potential in computational architecture is not honored.

This study explores the application of numerical design models for hospital design in the initial phase of 'Planning & Design', as outlined in Chapter 1, because it is in this phase the final design qualities are most difficult to identify.

6.1.2. Use of numerical models for design functioning

The numerical design models can apply quantitative and qualitative knowledge and thereby include a broad understanding of performances as generative parameters or evaluators. The performance-based models intend to act directly upon analysis and simulation for the specific design (153). The chosen performances or functionalities actively generate the design. Oxman (50) defines the performance-based design models, as illustrated in Figure 6-1, by a generic schema of components, relationships and properties. The models contain four basic components of the traditional design activities of *Representation*, *Generation*, *Evaluation* and *Performance* (50).

In the performance-based design models, performance data drives the form generation. The designer interacts with the three modules, defining the respective criteria in the respective modules, while interacting directly through the digital representation (153).

The generic design model The performance-based generation model

Figure 6-1 D: Designer in center interacts with the activities of R: Representation, G: Generation, E: Evaluation and P: Performance (50).

The ability directly to modify design according to analysis and simulation implies the ability to incorporate functionalities and performances. The performance-based design model builds upon the parametric design model. The construction of the models is the same, and so this model is applicable for design problems related to complex layout designs with several requirements and preferences (25).

In general, engineering objectives such as cost and performance are easy to transform into quantitative input parameters. Meanwhile, the architectural design parameters concerning aesthetics and usability are more difficult to describe formally. The work of the second part of the thesis in Chapter 3, Chapter 4 and Chapter 5 concerns this formal description of architectural, engineering and functional perspectives and performances. Chapter 3 formally describes the architectural understanding and approach to hospital design in typologies. Chapter 4 concerns the transformation of the functional understanding of the hospital into a formal matrix of design parameters in terms of usability, collaboration and relations. Chapter 5 formally defines a combination of the architectural, engineering and functional perspective on the performance of the hospital.

The formalization of the functional, architectural and engineering objectives defines the framework of performances and evaluations in the design model, as illustrated in Figure 6-2.

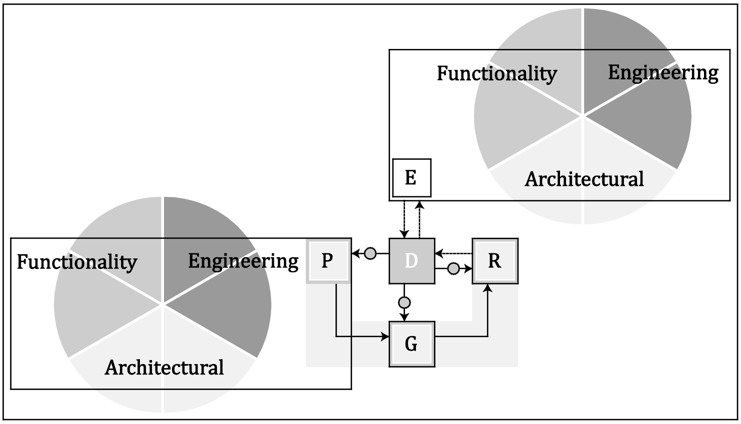


Figure 6-2 The performance-based generation model based on functionality, engineering and architectural parameters formally described as performance input parameters in the correlation matrix and as evaluation parameters as constraints.

6.2. Optimization in numerical design models

The numerical models use the potential in scientific computing to handle variables and procedures. Researchers have used several problem representations and solution search techniques to describe and solve the problems. The methods are based on the classical optimization methods for single-objective optimization rooted in Sir Isaac Newton based on differential calculus. The later non-classical methods of non-linear programming use random guided searches. This method attempts to counter the weaknesses of the classical optimization methods in high-dimensional search problems. Several researchers have solved the layout problem in terms of geometry (65,113,139,174,175). Some researchers have also solved the layout problem with respect to diverse and potentially conflicting constraints (66,124-126).

6.2.1. The general optimization problem

The general optimization problem is a process of finding the conditions giving a maximum or minimum of a function. It is the act of obtaining the best result under given circumstances (172). The circumstances defined by constraints determine the restrictions which the objective function must fulfill. It is setting the boundaries for the solution space, and so it is optimization for a constrained problem. The constraints can consist of the various requirements facing real-life, functionally related conditions and design requirements. The general mathematical geometry optimization problem can be formulated as:

$$\begin{aligned} \text{minimize} \quad & f(\boldsymbol{X}) \\ \text{subject to} \quad & h(\boldsymbol{X}) = 0 \\ & g(\boldsymbol{X}) \leq 0 \\ & \boldsymbol{X} \text{ in } R^n \end{aligned} \qquad \text{Equation 1}$$

where $\boldsymbol{X}$ is the vector of design variables, n is the number of variables, and $h(\boldsymbol{X})$ and $g(\boldsymbol{X})$ are vectors of equality and inequality constraints.

If several objective functions $f(\boldsymbol{X})$ are given, the optimization problem in Equation 1 can be used solving multiple-objective optimization problems. The multiple-objective functions can be combined into a single objective function using a weighted sum of the individual objective functions:

$$f(\boldsymbol{X}) = \sum_{i=1}^{N} w_i \, f_i(\boldsymbol{X}) \qquad \text{Equation 2}$$

where $f_i(\boldsymbol{X})$ is the i^{th} objective function. w_i is the weight of relative importance of the i^{th} objective function. N is the total number of objective functions and $\boldsymbol{X}$ is the design variables.

6.2.2. Classical and non-classical optimization

Optimization has a long history with roots in Newton and Leibniz's development of differential calculus in the 17^{th} century. Differential calculus defines the foundation of optimization, into which there has been a huge amount of research and development of several methods (172). The methods of optimization can be divided into the classical and the non-classical optimization methods, where recent research in optimization prioritizes investigation in the non-classical methods and the non-linear programming methods to solve complex problems, see Figure 6-3.

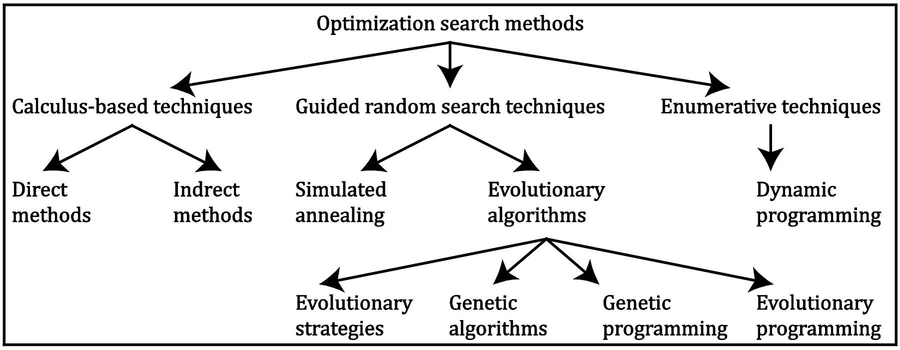


Figure 6-3 Optimization approaches

The classical methods are rooted in differential calculus followed by Euler's method of calculus of variations and minimization of functionals and the Euler–Lagrange equations for extrema of functionals. Lagrange represents today's method for constrained optimization problems, where the necessary condition is in the form of a differential equation, which the extremal curve should satisfy. For constrained optimization problems, the augmented Lagrangian methods are applicable. They are a class of algorithms for solving constrained optimization problems by replacing a constrained optimization problem by a series of unconstrained problems. The augumented Lagrangian methods add an additional term to the unconstrained objective with similarities to penalty methods (52).

The simplest optimization problem consists of finding an extremum of a function. Once the objective function surfaces are subject to the constraint, the optimum point can be determined. When the number of design variables exceeds two or three, the constraint and objective function surfaces become complex and the problem has to be solved purely as a mathematical problem.

The method of optimization for constrained problems, which involves the addition of unknown multipliers, became known by the name of its inventor as the Lagrange multipliers. It consists of a strategy for finding the local maxima and minima of a function subject to equality constraints. Cauchy made the first application to this approach by the steepest descent method to solve unconstrained minimization problems (172). Despite these early contributions, the progress in optimization methods was relatively modest until the middle of the twentieth century when high-speed digital computers enabled the implementation of optimization procedures (172).

The classical techniques such as gradient-based, response surface models or simplex optimization can be very efficient when the underlying assumptions are fulfilled. If the assumptions are correct, the methods are fast and reliable. These classical techniques are ‘strong’ methods. The methods are gradient-based formulated on calculus. The main problem with the methods is that if the assumptions are not correct, then the methods will not find the global optimum.

With the advent of computational potential, new optimization techniques arose for the gap between the ‘strong’ methods and the ‘weak’ methods, where hardly any assumptions are made. The methods arose in the intermediate, not with a guarantee of the optimal result but in almost all cases a very good solution. The new strategies such as simulated annealing, genetic algorithms, etc. are the non-classical search methods not anchored in calculus but in guided searches. Some of the guided random searches simulate evolutionary processes. Researchers have conducted much further research into the new non-classical optimization methods as countering the weaknesses of the classical optimization methods in high-dimensional search problems and in non-linear problems (52).

6.2.3. Metaheuristics

Metaheuristics is a higher-level procedure designed to find, generate or select a lower-level procedure for finding a sufficiently good solution to an optimization problem. The metaheuristic procedure attempts to find a good solution dependent on a set of random variables with less computational effort than algorithms, iterative methods, or simple heuristics. As such, they are useful for optimization problems in design with wide solution spaces.

A range of metaheuristics are adapted and tuned for their application to the layout design problem. There have been several heuristic strategies attempting to find solutions without searching for the design space exhaustively. A variation of this is by allocating space for rooms one at a time, based on the best probable design move. The procedure follows the constructive placement strategy succeeded by an iterative improvement strategy (148,176).

The most important methods for metaheuristic searches are Simulated Annealing (SA), Genetic Algorithms (GA), Evolutionary Strategies (ES), hereunder Genetic Algorithms (GA), and Swarm Algorithms as illustrated in Figure 6-3 and Figure 6-4. The methods are not developed nor guaranteed to give the optimal result, but in almost all cases, they find very good solutions.

The methods follow the same optimization cycle with different selection criteria and generations. The optimization cycle is typically iterative starting with a random position according to the sample seed. The evaluation will assess the quality of the point. If no stopping criteria apply, the next stage is to accept the solution as a starting point for the generation of a new solution.

The principles of the non-classical methods of Simulated Annealing (SA) are analogous to the physical cooling of a liquid, and so it is part of the family of Physical Algorithms, as illustrated in Figure 6-4. Darwin's theories of evolution and processes of natural selection apply the Evolutionary Algorithms (EA). Genetic Algorithms (GA) and Evolutionary Strategies (ES) are elements of the Evolutionary Algorithms (EA). Tabu Search (TS) is another guided search method that represents the learning processes as part of the Stochastic Algorithms.

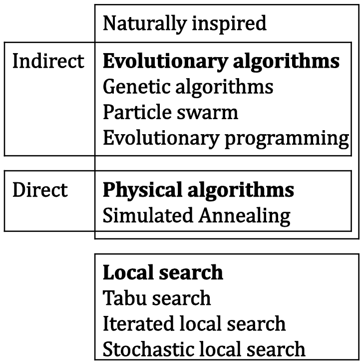


Figure 6-4 Metaheuristic algorithms

Metaheuristics encompass an general algorithmic framework that can be applied to different optimization problems with relatively few modifications for adapting to specific problems (177). The heuristic methods concern precision, quality, and accuracy in favor of the computational effort, in terms of space and time efficiency, and they manage the application of an embedded neighborhood exploration (177).

Metaheuristics encompass a large range of non-classical optimization methods, from evolutionary algorithms to simulated annealing and tabu search as well as iterated and stochastic local searches, as categorized in Figure 6-3.

Simulated annealing as a physical algorithm is inspired by the process of annealing in metallurgy. It has proven itself powerful for up to 200 locations within the facility layout problem (175). Simulated annealing starts with an iterative improving strategy, where it eliminates many of the disadvantages of the of the strategy by the inspiration from physical annealing. The new solutions are accepted at each stage of the optimization even if they actually increase the cost of the plan, because an exchange can be accepted if the probability of the resulting cost is lower than a control parameter. The use of simulated annealing makes it less likely falling into local minima and local optima, because of the braod acceptance of solutions in the process.

Genetic algorithms rely on analogies in natural processes and so, they relate to the improvement procedures. They are based on evolution and survival of the fittest.

The population undergoes a sequence of unary mutations or crossovers striving for survival by a biased selection scheme towards fitter individuals. After a number of generations, convergence towards the best individuals hopefully represents the optimum. Jo (111) and Gero (68) propose genetic algorithmic approaches with outstanding results for office and hospital layout problems, where the evolved genes are used for optimal or near-optimal design proposals.

Stochastic algorithms are the globally predominant optimization algorithms. They apply random search as a direct search method by the strategy of sampling solutions across the entire design space using a uniform probability distribution.

Stochastic algorithms lack of an inspiring system or a metaphorical explanation in terms of the descriptive elements in the standardized algorithm description (177). They apply random search across the entire design and so, the advantage is the broad search in the design space for avoiding local minima. Stochastic algorithms have been used successfully when implementing in layout design generation (111,178,179). A stochastic programming problem is an optimization problem in which some or all of the design variables and/or preassigned parameters are probabilistic, nondeterministic or stochastic. Stochastic programming deals with the solution of the optimization problems in which some of the variables are described by probability distributions.

The basis of the primary methods of heuristics and metaheuristics is algorithms, and evolutionary algorithms are central. Genetic or evolutionary algorithms look for a population related to improvement procedures. The simple genetic algorithm includes the procedures of selection, crossover, mutation and fitness, with the goal of undergoing sequences of mutations or crossovers towards fitter individuals.

The first actual algorithmic contribution to research came in 1980s followed by evolutionary multi-objective optimization. The commonly adopted notion of optimality is the Edgeworth-Pareto optimality, originally proposed by Edgeworth (1888) and later generalized by Pareto (1896). Today, the commonly accepted notion is the Pareto optimality, describing the state in which all individuals are distributed in such a manner that it is not possible to improve a single individual without causing at least one other to become worse than before the change. The Pareto optimal front is a non-dominated solution set. No member of the solution set dominates all the solutions (52). The boundary defined by the set of point mapped from the Pareto optimal set is the Pareto optimal front.

6.2.3.1 Evolutionary algorithms

Genetic algorithms are the most popular type of EA. The algorithms consist of parameter values encoded into binary strings of fixed and finite length as genes, chromosomes and individuals. Genes consist of each bit of the binary string (elements), and chromosomes are binary strings (in genotype space). Individuals are a set of one or multiple chromosomes, a prospective solution to the given problem. By applying operators such as recombination and mutation (or both), genetic algorithms are useful in optimization problems. The best representations are usually those, where operators reflect something about the problem to be solved.

The development in methods based on evolutionary algorithms is currently evolving because of increased computer power. The nature of the equations in research involves the nonlinear programming problem (180), the geometric programming problem (114,181), the quadratic programming problem (65) and the linear programming problem.

Genetic programming is an evolutionary algorithmic-based methodology that presents solutions in the form of computer programs. Their ability to solve a computational problem determines their fitness. Evolutionary programming is similar to genetic programming, but the structure of the program is fixed and it allows its numerical parameters to evolve. Evolutionary strategies work with vectors of real numbers as representations of solutions and typically they use self-adaptive mutation rates. Differential evolution is based on vector differences and is, therefore, primarily suited for numerical optimization problems. Common for the evolutionary algorithms is the simple genetic algorithmic form with different criteria of selection, mutation and crossover.

In the selection process, individuals are chosen from the current population to constitute a mating pool for reproduction. The fitness proportional selection methods can be based on each individual selected and copied in the mating pool with the probability proportional to fitness as well as i.e. tournament selection, roulette wheel selection, proportionate selection, rank selection, steady state selection, etc. The following mutation is applied gene-wise, thus each gene undergoes mutation. The fitness evaluation assigns each individual with a fitness value as the measure of performance. The objective function can be the fitness function itself.

Inspired by findings from the single-objective optimization literature, researchers realized that the selection could benefit from elitism. Elitism uses a plus selection by the issue of imposing a total order, rather than a partial order, on the population. An absolute ranking can be found for the selection, which is solved in the selection mechanism of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) (52). The algorithm is based on elitist search, as the elite preservation is found important for proper convergence in SOEAs & MOEAs. The first MOEA from the mid-1980s: the Vector Evaluated Genetic Algorithm (VEGA), designed by David Schaffer consists of a simple genetic algorithm with a modified selection mechanism (52). With three tasks in MOEA of elite preservation towards the

Pareto-optimal front, several elitist algorithms have been developed cf. Table 6-1 by some remarkable algorithms based on non-dominating sorting and elitism (177).

Table 6-1 Elitist MOEAs (52)

Distance-based Pareto GA (DPGA)	(Osyczka and Kundu, 1995)
Thermodynamical GA (TDGA)	(Kita et al., 1996)
Strength Pareto EA (SPEA)	(Zitzler and Thiele, 1998)
Non-dominated sorting GA-II (NSGA-II)	(Deb et al., 1999)
Pareto-archived ES (PAES)	(Knowles and Corne, 1999)
Multi-objective Messy GA (MOMGA)	(Veldhuizen and Lamont, 1999)

The diversity among non-dominated solutions advances the elitist algorithms by use of a crowding procedure. The elitism protects an already found Pareto-optimal solution from being deleted. Newly found non-dominated solutions are compared with the existing external population, while the resulting non-dominated solutions are preserved. The non-dominated solutions are stored externally, and by tournament selection and recombination, the solutions combine current and elite populations by a clustering technique. This procedure maintains the diversity in the updated external population. The algorithm has to balance between the regular population size N and the external population size N. If N is too large, the selection pressure for the elites is too large and the algorithm may not converge to the Pareto-optimal front. On the other hand, if N is too small, the effect of elitism will be lost (52).

Research in GAs for traditional facilities (68,111) has showed excellent results, especially because of the easy interpretation (68). Moreover, the advantages of extending the GAs (68,111) to use genes for the original problem cause faster convergence (182). This is very beneficial for genetic engineering.

Gero and Jo (68,111) explore application of GAs in layout design with a simple approach of emphasis on activities and distances. It starts with the quadratic assignment problem in the finding of optimal locations for a set of interrelated objects by an activity interactions matrix, a distance matrix and a cost function (68). The approach defines the foundation for later layout proposals where complexity is increased.

6.3. Application of optimization on architectural layout models

The following subsections outline how the approaches have been applied to geometric architectural design.

6.3.1. Optimization of topology and geometry

Optimization of topology is a basic engineering problem of distributing a limited amount of material in a design space. The first applications concern optimization of structural topology, shape and material. By decomposing a problem into topology and geometry, the topological decisions define constraints for the geometric design space in terms of the logical relationships between layout components. The geometry refers to the position and size of each component in the layout. It is the topological decisions that define constraints for the geometric design space.

Michalek et al. (66) defined a design model able to enumerate solutions for a studio apartment and for a nine-room building by topology and geometry optimization (66). The model is based on the general mathematical optimization formula in Equation 1 with several design variables and constraints. The optimization concerns grouping units into categories based on functionalities. A unit is defined as a rectangular, orthogonal space allocated for a specific architectural function. The units are represented as a point in space *(x, y)*, see Figure 6-5.

Representation of a unit   Sample of fixed grid allocation layout

Figure 6-5 Definition of unit and layout grid for allocation for topology and geometry optimization (66).

The architectural requirements concern light, heating, etc. The units along external walls may also have windows for natural lighting. The windows and window variables in the work of Michalek et al. (66) are quite decisive in the optimization procedures, as the windows entail variables for optimization of the geometric objectives. The variables for each unit include a reference point location (x, y), distances to each wall (N, S, E, W), and the size of any windows added to each unit ($\omega_N, \omega_S, \omega_E, \omega_W$) i.e. the vector of design variables is given as:

$$\boldsymbol{X} = \{x_i, y_i, N, S_i, E, W_i, \omega_{N_i}, \omega_{S_i}, \omega_{E_i}, \omega_{W_i}\} \quad i = 1, 2, \ldots, n \qquad \text{Equation 3}$$

where i is the set of n Units.

The geometric design objectives are defined to be used independently or together depending on the designer’s goal. In the example by Michalek et al. (66), several optimization objectives control the optimization. Minimizing Heating Cost, f_{heat} (Equation 4) and Minimizing Lighting Cost f_{light} (Equation 5) are some of the decisive design objectives involving the real-life functional conditions.

$$\min f_{heat} = \frac{\kappa_{gas} Q_{heat}}{\eta_{heater}} \qquad \text{Equation 4}$$

where κ_{gas} is the cost of gas, Q_{heat} the annual heat loss and η_{heater} the efficiency of the heater, and

$$\min f_{\mathrm{light}} = \Gamma_{\mathrm{elec}} - \left(\sum_i \Theta_i\right) \beta_H 10^{-3} \qquad \text{Equation 5}$$

where Γ_{elec} is the total required costs if all light is electric lighting, and β_H is the number of hours of available light per month.

The model has proved its worth by enumerating all topologies capable of producing at least one feasible geometry and subsequently reviewing the topological possibilities for selecting some for geometric exploration (114). The technique reduces computation dramatically and it has been successful for up to twenty rooms.

6.3.2. Quadratic assignment problem (QAP)

The quadratic programming problem is a nonlinear programming problem with a quadratic objective function and linear constraints. The quadratic programming problem formulates as:

$$\begin{aligned} &\text{minimize} && f(\boldsymbol{X}) = c + \sum_{i=1}^{n} q_i x_i + \sum_{i=1}^{n} \sum_{j=1}^{n} Q_{ij} x_i x_j && \text{Equation 6} \\ &\text{subject to} && \textstyle\sum_{i=1}^{n} a_{ij} x_i = b_j \;, \qquad j = 1,2,\dots,m \\ & && x_i \geq 0, \; i = 1,2,\dots,n \end{aligned}$$

where c, q_i, Q_{ij}, a_{ij}, and b_j are constants.

The quadratic assignment problem (QAP) is another strategy for architectural layout design. It is a fundamental, combinatorial optimization problem for facility layouts, with a set of facilities and a set of locations. The optimization problem is to minimize the sum of the distances multiplied by the corresponding flows, specified for each pair of facilities. The problem statement of assigning facilities to locations expresses a cost function in term of quadratic inequalities.

By using Equation 6 Hahn and Krarup (65) solve the facility layout problem using combinatorial optimization with integer programming. Hahn and Krarup take their point of departure in the so-called Spadille task from 1973 to find the layout with (*n*) facilities. With *n* within the range from 30 to 48, no algorithms in 1972 were capable of solving the problem. For 28 years researchers attempted to optimize the layout problem (Krarup 30a), and in 1999 Hahn and Krarup (65) solved the problem. The optimum was found after a runtime of 98.6 days and examination of 29,764,589 nodes. Much research has been performed subsequently in the area, but solving QAPs larger than Krarup 30a is beyond reasonable computing resources.

The method used to solve the optimization problem was a DP branch-to-bound algorithm. It generates a series of non-decreasing lower bounds to the QAP, to which it generates an equivalent QAP with a reduced cost function. The DP calculation is an iterative process that permits stopping early. This has proven itself very efficient in reducing branch-to-bound runtime (65).

Hahn (183) has refined the Branch-to-Bound solution and in 2008, Hahn (132,184) introduced the multi-story space assignment problem (MSAP) as an innovative formulation of the multi-story facility assignment problem that allowed modeling the location within multi-story facilities as a Generalized Quadratic 3-dimensional Assignment Problem (GQ3AP). In 2012, Hahn et al. (185) applied the level 3 reformulation-linearization technique (RLT3) to the quadratic assignment problem (QAP) and presented a method to calculate the lower bound approximates. Calculating for problem sizes larger than size 27 still presents a challenge because of the large amount of memory needed (185).

The work of Hahn et al. (65,132,185,186) gives expensive optimizations of layout problems of 27-30 units. The work is based on developing the method for QAP and testing it with respect to computing resources. The work only briefly relates to the actual design task and responds to the design requirements and preferences in the optimization procedure.

Helber et al. (131) give another proposal for hospital facility layout optimization, based on QAP. As facility layout problem typically contains a QAP, Helber et al (131) proposes solving a hospital layout problem based on QAP and a hierarchical modeling approach of two stages. By decomposing the problem into a Stage I problem, Helber assigns Organizational Units to locations, based on the QAP of Koopmanns and Beckmann (131).

Helber et al.’s (131) use of QAP does not reflect the real-world complexities of a hospital, but merely the locating of the OUs as a conceptual starting point. The Stage II optimization problem includes an objective function of minimizing total transportation time within the OUs, defined by physical constraints and placement strategies for lifts (131).

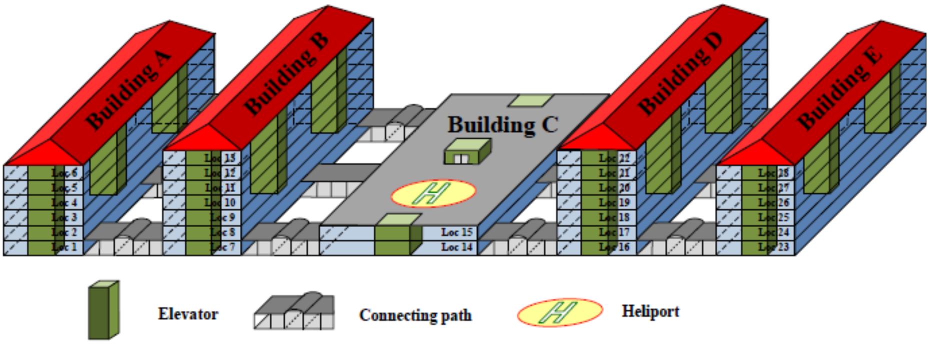


Figure 6-6 Result presenting the schematic design of a hypothetical hospital building (131).

The layout optimization performed by Helber et al. (131) consists of functional objectives in the Stage II optimization. However, Helber et al. (131) apply functional performances in a reduced form in the early design phase, which according to Joost et al (91) can be a limitation for emergence of interesting and valuable solutions.

The work of Helber et al. (131) introduces the hybrid methods of optimization that apply different methods in the appropriate part of the optimization. In the hybrid method, the indirect calculus methods are often applied for the last part of the optimization, where the approximate global optimum has been identified through the non-linear programming and the exact location still must be found (172). Division of the optimization problem in stages is exemplary for including more performance objectives than transportation times to and from lifts, as in the case of Helber et al. (131). This approach defines the framework for the following definition of a design model for hospital design.

6.3.3. Hospital design subject for optimization

According to the work of this thesis, there are six performances evaluators driving the optimization, see Chapter 5 for details. The performance evaluators consist of several variables as inputs in terms of the principal drivers and the design vector derived by the functionality distribution. The functionality distribution consists of processes of optimization of the correlations in definition of the geometric units as described in Chapter 4.

The input data of the design model is the correlation matrix. The number of design variables is the number of functionalities of the hospital design problem. For the present project, the data of the correlation matrix includes 66 functionalities. This is remarkably more than Michalek (66), Hahn (65) and Helber (131) operated with, where approx. 30 design variables caused extensive computation time.

6.4. Summary

This chapter has elaborated on the use and definition of architectural modeling as outlined in Chapter 2. The chapter sets the mathematic methodological framework of this PhD thesis.

Examples of application and results from research have outlined the advantages and disadvantages for relating the computational methods to the present project. The potential in scientific computing has developed many non-classical optimization methods for the implementation of architectural modeling. Research of non-classical methods, e.g. in GAs for solving the optimization problems shows excellent results in especially wide design spaces, which characterize much architectural design. GAs are easy interpretable and therefore applied broadly in computational architecture.

The hospital design problem for the present project consists of 66 functionalities and so 66 variables. This amount is higher than the applied examples and so search methods for wide design spaces are a prerequisite.

According to Equation 2, the six performance evaluators can be combined by the weighted-sum method in multiple-objective optimization. Utilizing the weighted sum method simplifies the problem solving remarkable, compared to six sets of solutions, which multi-objective optimization by the Pareto front will define.

Beside the six performance evaluators and the 66 design variables, several constraints characterize hospital design, especially when architectural modeling relates to practice. The Augmented Lagrangian method provides an approach for constrained optimization. Thereby, the additional optimization objectives are transformed into constraints.

This chapter has introduced a method for evaluating a set of interrelated functionalities by using the computational methods of GAs. Hospital performances, described by quantitative and qualitative knowledge, can be combined in a multi-objective cost function that drives the optimization processes.

Chapter 7. A Numerical Design Model in Hospital Design

This chapter defines a numerical design model for hospital design on the basis of the theory presented in the former chapter. The model making begins in established models and utilizes the advantages of genetic algorithms for wide design spaces. The conducted research within architectural layout design is founded, as previously described, in the context of computing resources and mainly performed by computer scientists. A lot of research transforms the functional context into generic geometric constraints. This chapter consists of a major contribution by the PhD projects: a contribution of model making that applies functionalities along with the geometric constraints in the attempt to solve the architectural design problem.

The model definition is based on the definition of the configuration of geometric units from Chapter 4.

The framework for the model definition is the numerical definition of the principal drivers in terms of building typologies, organization typologies and layout typologies, as defined in Chapter 3 and elaborated in Chapter 5. Design of the geometric entities is according to the framework defined by the typologies, and arranged as a respose to the *functionalities and their requirements and preferences in terms of the correlation matrix, as defined in Chapter 4.*

This chapter defines the numerical implementation of the hospital design model. The definition follows the construction of the parametric design model with the principal drivers defining the highest hierarchical level. The intermediate construction operates with the principal drivers from whom the resulting geometry is derived as design concepts.

This is a proposal of a numerical model that systematically generates design based on a broad understanding of performances and functionalities.

7.1. Definition of design model

The starting point is the framework of the quadratic assignment problem (QAP), optimization of topology and geometry, and metaheuristics using genetic algorithms.

The design model consists of three hierarchies:

1. Data definition and input,
2. Definition of the intermediate construction of the design model, based on the four-step procedure of the former section, and
3. Evaluation and visualization of design concepts by a cost function.

The numerical implementation follows the below procedures. This is an elaboration of the one defined in Chapter 4:

1. Data definition and input
   Based on the required functionalities for a given hospital, the correlation matrix is updated with the respective functionalities. The first variables to determine in the design model are given by the correlation matrix, as defined in 4.3.
   1.1. Define numbers N of hospital functionalities and requirements, i.e. functionality areas, A_i and correlations r_{ij}
2. Definition of the intermediate construction
   The intermediate construction is defined by the variables of principal drivers, as elaborated on in 5.1. This part of the design model consists of the mathematical definition of functionality distribution
   2.1. Define a number of geometric units, N_{GU}.
   For the analyzed projects the number is within the range of 5-10 units per hospital, see Chapter 1.
   2.2. Define the layout of the geometric units. Chose L_T.

The layout of the units is defined by layout typologies 1-5, as defined in 3.4, with the respective constraints. L_{TA} are the respective areas.

2.3. Define the area of each geometric unit, AGU_i.
The number of layout units in each geometric unit is randomly generated according the geometric units and the total area of the hospital.

2.4. Define the content of each geometric unit
According to the correlation matrix, the content of the geometric units is defined. The content is restricted to the constraints of the geometric units defined in step 2-4.

3. Evaluation, optimization and visualization of design concepts
This part concerns the application of cost functions of the evaluators, as defined in Chapter 5. The cost function is the objective function of the optimization. The cost functions optimize, evaluate and compare the design concepts.

3.1. Define performance indicators of the principal drivers, P_i.
The performance indicators reflect the cost index P_i of the direct impact of costs derived from the principal drivers. These are the ones defined for each evaluator in the first table.

3.2. Define the cost index by the functional distribution, C_i.
The performance objectives given the functionality distribution are functionalities of the respective definition of the geometric units. The correlation factor, cf_i, the functional costs, fc_i and the geometric constraints, AGU_i, $EAGU_i$, the effective area of the geometric unit and $NMGU_i$, the normalized mass of the unit, as defined in the last table, respectively for each evaluator.

The optimization model consists of several iterations. The objective function utilizes the weighted sum method for multi-objective optimization. By the advantages of non-linear programming, genetic algorithm searches for the optimal configurations when maximizing the summarized cost function.

Generation of form is based on the iterative improvement strategy within the overall iterative process, cf. Chapter 2. The generations substitute traditional sketching and the evaluation and modification become generators for the design. Concretization of the design starts while the requirements of all three aspects, the functional, architectural and engineering, are considered. The procedure develops architectural, engineering and functional perspectives in unison cf. Figure 5-1, both as performance drivers and in the evaluations.

The architectural understanding of the geometric composition and the geometric relationships is incorporated into the design process by geometric rationalization. Information is developed, incorporated and used as generative elements in the development of the design. Optimizing is inherent in the geometric rationalization, and it implies a formal description of the architectural understanding and a qualitative understanding of geometry.

The proposed generative design model operates with both the architectural, engineering and functional performances in the development of conceptual architectural design. This is a systematic approach subject to the functionalities of the building.

7.2. Numerical definition of design model

As initially described, the design modeling differs from current research as it encompasses the correlations of functionalities and generates design from actual functionalities and not generic geometries. Design modeling starts with decomposing the hospital. It is not just recombining predefined geometric elements. The proximities are described by correlations of relative weight, and so the correlation matrix defines the input data by a prioritization of functionality, connectivity and proximity. The following subsections will elaborate on operating with the data of the correlation matrix.

7.2.1. Data definition and input

The first procedure in the design model is the data definition and input. The procedure transforms the data of hospital operation, research in hospital design and patient treatment into a parametric operational entity in terms of a correlation matrix. By using an objective function to optimize the correlations of the matrix, the design model ensures that the design is derived from analysis and research, as described in Chapter 4, as an approach that facilitates evidence-based design.

The procedure consists of defining design variables from the correlation matrix. After the matrix is loaded, the procedure starts with the definition of N, the numbers of hospital functionalities and requirements, Ai, the respective functionality areas, and r_{ij}, the required correlations. All variables are in the correlation matrix. N and Ai are updated with project-specific information on the respective functionalities.

7.2.2. Definition of the intermediate construction

This subsection follows the sub-steps of the second step of the intermediate construction. This is the definition of the geometric units. Each geometric unit is unique and responds in the geometric definition to the requirements and preferences of the functionalities. The number of geometric units, N_{GU}, sets the framework for how many unique units are defined.

7.2.2.1 Define a number of geometric units, N_{GU}

The first step is defining the number of geometric units, N_{GU}. It is an initial choice. For the analyzed hospitals, as outlined in Chapter 1, the number is within the range of 5-10 units per hospital. This defines the constraints for N_{GU}, a number in the range of 5-10. Before the geometric elaboration, the geometric units are generic frameworks for the functionality distribution.

The number of geometric units represents the number of professional unisons present in hospitals. In practice, this number is often chosen initially as part of the design strategy for a given hospital. In the design model, the number defines the framework for the distribution. Parallel to practice, the number is chosen initially. However, the number is a variable which is easy to change for generating alternates.

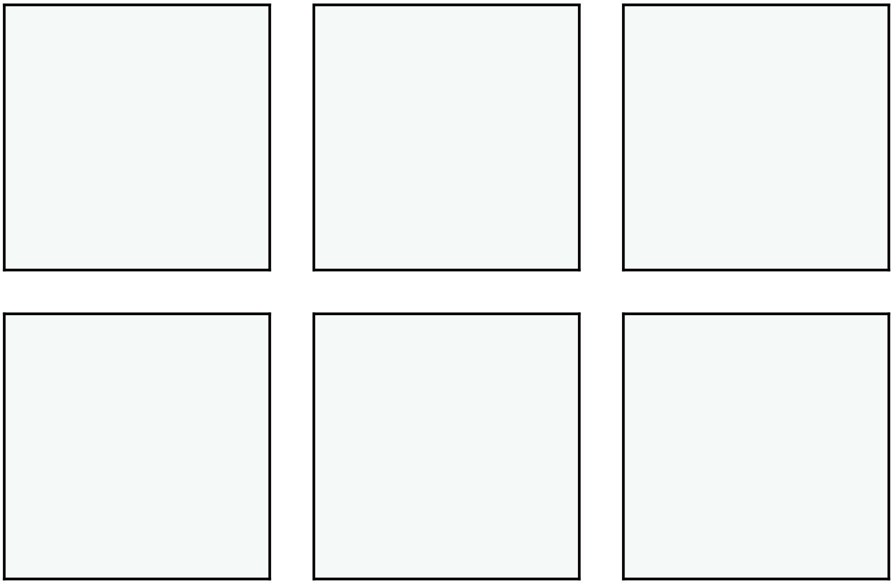


Figure 7-1 The initial choice N_{GU} = 6 is made. Hence, six frameworks are the basis for the following functionality distribution. The frameworks are initially empty, but through the process, a random number of layout units will populate them.

7.2.2.2 Define the layout of the geometric units. Choose L_T.

This step sets the framework for the geometric definition of the units that by number is defined above. The layout typology, L_T, is defined by the initial choice. The dimensions define the constraints of the layout typologies, as elaborated in 3.4 and illustrated in Figure 7-2. After choosing one of the typologies listed in Figure

7-2, L_{TA} follows as a variable of the layout typology, defining the area and qualities of the typology. This part of the model chooses the layout framework for the geometric unit and the following design configuration. The layout typologies are the modules forming, the geometric units.

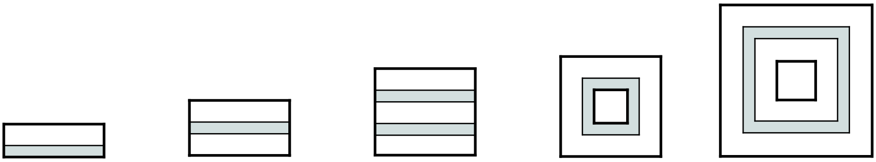


Figure 7-2 Layout principle of typologies, where the white outlines the functional area and the grey is the circulation area, as elaborated in 3.4.

7.2.2.3 Define the area of each geometric unit, AGU_i.

Each geometric unit consists of a number of layout typologies. The definition of the area of each geometric unit follows a random number generation of layout entities. Figure 7-3 exemplifies this and outline the area of the geometric units, AGU_i, by the red line. The area fits the area of a random number of layout typologies.

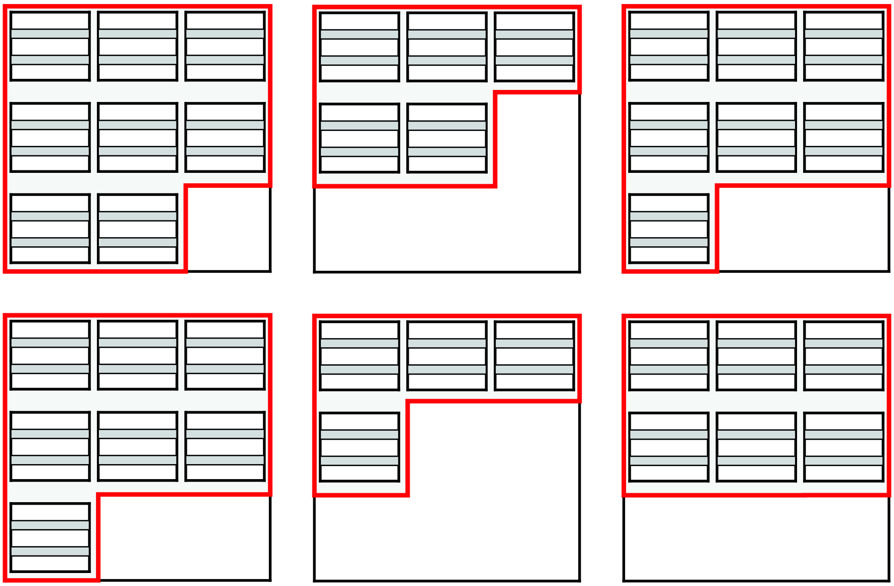


Figure 7-3 A random number of layout entities define the area of the geometric unit, AGU_i, as illustrated by the red demarcation.

The random number generation follows the below optimization subject to the constraints by the layout typology and the summarized area of all hospital functionalities.

$$\sum_{i=1}^{N_{GU}} AGU_i = \sum_{i=1}^{N_{GU}} N_{LT_i} L_{TA} \approx \sum_{j=1}^{N} A_i \qquad \text{Equation 7}$$

N_{LT_i} is the unit-wise numbers of layout typologies.

7.2.2.4 Define the content of each geometric unit

According to the correlation matrix, including the correlations r_{ij}, the content of the geometric units is defined, subject to the constraints of the geometric units, given by N_{GU}, L_T, L_{TA} and AGU_i. The distribution of functionalities into geometric units follows the objective function:

$$\begin{aligned} &\text{minimize} && f(\boldsymbol{X}) \\ &\text{subject to} && g_i(\boldsymbol{X}) = 0 \\ & && \text{i}=1,2,\ldots, N_{GU} \end{aligned} \qquad \text{Equation 8}$$

where $\boldsymbol{X}$ is the vector of design variables, N_{GU} is the number of geometric units, N the number of design variables, and $g_i(\boldsymbol{X})$ are vectors of equality constraints.

The objective function $f(\boldsymbol{X})$ is the weighted sum of the cost function, following the definition in Equation 2.

The optimization looks to find the conditions that minimize $f(\boldsymbol{X})$ given the circumstances of the constraint function of $g_i(\boldsymbol{X})$. It optimizes the weighted sum of the cost functions defined by the six evaluators. The correlations of the functionalities and the geometric configuration are the decisive variables. The design vector $\boldsymbol{X} = \{x_1, x_2, \ldots, x_N\}$ includes discrete values between 1 and N_{GU}, where N is the number of functionalities, and N_{GU} is the number of units.

The objective function is given by:

$$f(\boldsymbol{X}) = \sum_{j=1}^{N_{cost}} w_j \sum_{i=1}^{N_{GU}} C_{ji}(\boldsymbol{X}) \qquad \text{Equation 9}$$

where $\boldsymbol{X}$ is the vector of design variables, C_{ji} is the unit-wise cost function for j-cost. N_{GU} is the number of geometric units, and w_j is the weight vector. N_{cost} is the number of performance objectives or costs.

The overall cost function is formulated as:

$$C(\boldsymbol{X}) = \sum_{j=1}^{N_{cost}} \sum_{i=1}^{N_{GU}} C_{P_i} + C_{fd_{ji}}(\boldsymbol{X}) \qquad \text{Equation 10}$$

where N_{cost} is number of performance objectives or costs and N_{GU} is the number of geometric units. C_{Pi} is the costs by the principal drivers. C_{fdi} is the cost function of the functional distribution. $\boldsymbol{X}$ is the vector of design variables.

The constraint $g_i(\boldsymbol{X})$ defines the effective area of each geometric unit given as:

$$g_i(\boldsymbol{X}) = \sum_{j=1}^{N} A_i z_{ij} - AGU_i \qquad \text{Equation 11}$$

A_i is the area of each functionality and AGU_i is the demanded area for each geometric unit. AGU_i is generated prior the optimization as defined in Equation 7.

The optimization problem is formulated as an integer design problem, which is solved using the Genetic Algorithm solver in the Global Optimization Toolbox [52] in MATLAB®. The optimization problem is a constrained problem, solved by an elitist algorithm for in-expensive searching in the wide design space.

By the described definition, the intermediate construction of the design model is defined. The weighted sum method of multi-objective optimization of the costs defines the geometric units. The costs relate to the geometric configuration of the correlations of the functionalities as defined in Chapter 4, and to the principles of the building typology, the layout typology and the organization typology, as defined in Chapter 3 and dimensioned in 5.1.

All hospital functionalities are distributed into geometric units, and the basis is defined for visualization by typological designs. The following subsection outlines the definition of the cost functions of the objective function.

7.2.3. Definition of cost function

The geometric entities are defined by functionality distribution where all hospital functionalities are distributed according to the data of the correlation matrix within the given framework of the principal drivers. The functional distribution defines the geometric units of varying sizes and various functionalities.

In the unit definition, the objective function of maximizing the weighted summarized costs involves optimizing the correlations within the units subject to given geometric constraints.

The function defining the correlations is given by:

$$cf(\boldsymbol{X}) = -\sum_{i=1}^{N_{GU}}\sum_{j=1}^{N}\sum_{k=j+1}^{N} r_{jk}z_{ik} \quad \text{Equation 12}$$

r_{ij} is the correlation values given in the correlation matrix for N functionalities and z_{ik} is a decision variable equals 1 if functionality k is in unit i, and 0 otherwise.

The objective function driving the unit configuration is defined on the primary hospital functionalities of diagnosis, treatment and care, as described in Chapter 1. To frame the broad understanding of hospital performances, as elaborated in Chapter 4, a cost function is defined by combining the six performances evaluators of the hospital.

The performance evaluators drive the optimization processes, while they evaluate and visualize qualities and costs by the different design concepts. The cost function entails two main terms, as described in Chapter 5.

The first term, as outlined in Equation 10, is the performance evaluators directly influenced by the principal drivers: the Costs by principal drivers, C_{Pi}. The second term is the performance evaluator as a function of the functional distribution, Costs, by functional distribution C_{fdi}. The tables of Chapter 5 elaborate on the cost functions.

7.2.3.1 Performance evaluators by principal drivers

The performance evaluators by principal drivers reflect the six performances of hospital design directly influenced by the initial choices of principal drivers and the respective qualities.

As described in Chapter 2, Building typologies, Layout typologies and Organizational typologies, respectively, influence the performance evaluators. Chapter 5 describes the implications from a functional perspective. The typological constraints are applied to the functional perspectives and a parametric description of the performance evaluators by constraints is defined. In the following the descriptions of Chapter 5 are transformed into operational matrices, B_{TP}, L_{TP} and O_{TP}, as variables to imply the cost of the geometric unit, $x = \{1, 2, \ldots , N_{GU}\}$ for numerical implementation in a cost function. The matrices are defined by combining the tables of Chapter 5 with respect to the building typology, the layout typology and the organization typology, respectively. The (m x n) matrices consist of the columns of the tables are the rows, and the columns of the matrix are respective performances for each typology.

Building Typology

The first table of the respective performances in Chapter 5 lists the indexation of the performances in terms of building typologies. In the following, the indexation is combined in the B_{TP} a ($N_B \times N_{cost}$) matrix. N_B is the number of Building Typologies, and N_{cost} is the number of performance objectives.

$$B_{TP} = \begin{bmatrix} 1.00 & 1.00 & 1.00 \\ 1.00 & 0.65 & 0.25 \\ 1.00 & 0.65 & 0.25 \\ 1.00 & 0.65 & 0.25 \\ 0.25 & 0.38 & 1.00 \\ 0.25 & 0.38 & 1.00 \end{bmatrix} \qquad \text{Equation 13}$$

B_{TP} is a variable of discrete values as a function of the typology, B_T and the respective performances N_{costi}. B_{TP} defines the performances of the geometric unit responding the typological constraints and their implication. B_{TP} enters into the equation of C_{Pi}.

Layout typology

The tables of Chapter 5 likewise list the indexation in terms of the layout typologies for the respective performances. Parallel to the B_{TP} matrix, the typological constraints directly relating the performance indicator define the layout typological performance indicator, L_{TP}, a ($N_L \times N_{cost}$) matrix. N_L is the number of Layout Typologies, and N_{cost} is the number of performance objectives.

$$L_{TP} = \begin{bmatrix} 0.84 & 1.00 & 0.94 & 0.93 & 0.99 \\ 0.84 & 1.00 & 0.94 & 0.93 & 0.99 \\ 1.00 & 0.64 & 0.44 & 0.89 & 0.53 \\ 0.84 & 1.00 & 0.94 & 0.93 & 0.99 \\ 0.84 & 1.00 & 0.94 & 0.93 & 0.99 \\ 1.00 & 0.64 & 0.44 & 0.89 & 0.53 \end{bmatrix} \qquad \text{Equation 14}$$

L_{TP} is a variable of discrete values as a function of the typology, L_T and the respective performances N_{costi}. Like B_{TP}, L_{TP} defines the performances of the geometric unit responding the typological constraints and their implication, and it enters along with B_{TP} into the equation of C_{Pi}.

Organizational typology

The direct implication of organization typologies is limited to the performance indicator of flexibility as listed in the tables of Chapter 5. The typological constraints and implications are inherent in the definition of the correlations of the correlation matrix, and thus the typological constraints influence the performances of the design concept in terms of the functional distribution.

In the following section, the indexation is combined in O_{TP} a ($N_O \times N_{cost}$) matrix, where N_O is the number of Organization typologies, and N_{cost} is the number of performance objectives.

$$O_{TP} = \begin{bmatrix} 1.00 & 1.00 \\ 1.00 & 1.00 \\ 1.00 & 1.00 \\ 1.00 & 1.00 \\ 1.00 & 0.70 \\ 1.00 & 1.00 \end{bmatrix} \qquad \text{Equation 15}$$

O_{TP} is a variable of discrete values as a function of the typology, O_T and the respective performances N_{costi}. O_{TP} defines the performances of the geometric unit responding the typological constraints and their implication. Along with B_{TP} and L_{TP}, O_{TP} enters into the equation of C_{Pi}.

$$C_{P_i} = \frac{B_{TP_i} + L_{TP_i} + O_{TP_i}}{3} \qquad \text{Equation 16}$$

The following subsection defines the term of cost function relating the functionality distribution.

7.2.3.2 Performance evaluators by the intermediate construction

The performance objectives as a function of the functional distribution concern the respective performances as a cost function from 0 to 1. The higher the cost function, the better performance in terms of the objective related to the design requirements and preferences. The overall cost function is formulated as:

$$C_{fd}(\boldsymbol{X}) = \sum_{j=1}^{N_{cost}} \sum_{i=1}^{N_{GU}} EA_{GU_{ji}}(\boldsymbol{X})z + NM_{GU_{ji}}(\boldsymbol{X})z + FC_{GU_{ji}}(\boldsymbol{X})z + cf_{ji}(\boldsymbol{X})z$$

Equation 17

where N_{cost} is number of performance objectives or costs and N_{GU} is the number of geometric units. $\boldsymbol{X}$ is the vector of design variables for the respective units. EA_{GU} is the effective area of each unit, NM_{GU}, the normalized center of mass of each unit, FC_{GU} the functional costs of each unit, and cf is the correlation factor. z is an ($5\times N_{cost}$) identification matrix, defining the implication of the geometric constraints according to the respective performances, according to the tables of Chapter 5. $C_{fd_{ji}}(\boldsymbol{X})$ is thus the unit-wise respective costs.

As stated in the tables of Chapter 5, the geometric constraints imply the various performances differently. The identification matrix is defined on information of the tables of Chapter 5 outlining the implication of the geometric constraints in terms of the respective performances.

$$z = \begin{bmatrix} 1.00 & 0.00 & 1.00 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 & 1.00 & 0.00 \\ 1.00 & 0.00 & 0.00 & 1.00 & 0.00 \\ 0.00 & 1.00 & 0.00 & 1.00 & 0.00 \\ 0.00 & 1.00 & 0.00 & 0.00 & 1.00 \\ 0.00 & 1.00 & 0.00 & 1.00 & 0.00 \end{bmatrix}$$ Equation 18

The last column in the identification matrix reflects the inverted correlation factor affecting the costs of flexibility.

The first term in the cost function is EA_{GU}, given by the effective area of the geometric unit by the following definition:

$$EA_{GU_i} = \frac{A_{GU_i} - \sum_{i=1}^{n} A_i\,(\boldsymbol{X})}{A_{GU_i}}$$ Equation 19

where $\boldsymbol{X}$ is the vector of design variables for the respective units and n is the number of functionalities within the unit.

NM_{GU} is given by the normalized center of mass, by the following:

$$NM_{GU_i} = \frac{\sqrt{\frac{A_{GU_i}}{\pi}}}{\max\sqrt{\frac{A_{GU_i}}{\pi}}}$$ Equation 20

where $\max\sqrt{\frac{A_{GU_i}}{\pi}}$ returns the maximal value for a geometric unit.

FC_{GU} is given by the functional typological costs within the unit. The functional typological costs follow the most demanding functionality within the unit, as elaborated in the tables of section 5.2.1.2, which outlines the cost index according to the functional cost as:

$$FT = \{1.00\ 0.64\ 0.46\ 0.35\}$$ Equation 21

FT refers to the values of the inherent functionalities being the design variables: {Secondary areas, Non-clinical areas, Clinical areas, Special clinical areas}.

The functional typological cost, FC_{GU} is given by:

$$FC_{GU_i} = \max FT(\boldsymbol{X})_i$$ Equation 22

FT reflects the discrete values of $\boldsymbol{X}$, the vector of the design variables, as a function of the inherent functionalities.

It is the max FT in each unit that defines FC_{GU}, as it is the most demanding functionality in terms of technical requirement that defines the functional cost of the unit. Hence, it is the presence of the most demanding functionality of Secondary areas, Non clinical areas, Clinical areas or Special clinical areas, respectively that define FT.

cf_{GU} the last term in the cost function is given by the unit-wise correlation factor, defined by Equation 12. The correlation factor is normalized by a max correlation for the cost function to range from 0 to 1.

7.3. Summary

This chapter outlines the numerical definition of the design model, as described in 7.1. The model definition follows the three main procedures of 1: Data definition and input, 2: Definition of the intermediate construction, and 3: Evaluation, optimization and visualization of design concepts. This chapter deals with the processes of 2: Definition of the intermediate construction and 3: Evaluation, optimization and visualization of design concepts.

Physical constraints and functional requirements and preferences define the functionality distribution into geometric units. Through iterations, the functionalities are distributed as a configuration searching for maximizing the objective function of optimizing the weighted summarized cost function. The correlation factor derived from the functionality distribution is a decisive variable in the cost function.

The procedures of optimizations provide geometric optimization into the design process. The procedure develops the correlations and geometries through iterations of increased information. It develops and implies information as a generative element in the development of the design rather than a late modification. Optimizing the design from geometric rationalization is a perspective that implies a qualitative understanding of the geometry and the geometric construction, defined in terms of hospitals in Chapter 3. The proposed design model is constructed as a generative design model relating engineering and architectural knowledge as described in the performance-based models by Oxman (50) in Figure 6-1 and outlined for the present project in Figure 6-2.

The procedure transforms the engineering objectives of cost and performance into quantitative input parameters, described by typologies. The definition of typologies also includes definition of architectural design parameters concerning aesthetics and usability by the formal definitions of the correlation matrix.

This chapter has outlined the numerical implementation of these principles into a design model, as a proposal of a systemized design model for architectural modeling. The approach aims at organizing the several contradictory input parameters into manageable concepts for hospital design. It aims to improve the design process and thereby the quality of hospital designs in terms of cost and functionality.

Chapter 8.
Implementation of a Hospital Design Model

This chapter elaborates on the design model of Chapter 7. Firstly, the design model will be exemplified, and next this chapter will modify and evaluate the intermediate construction of the design model to improve the design configuration. The construction of the design model, as defined in Chapter 7, remains, and the modifications are applied in the evaluation of the model.

Chapter 4 describes how the input data combines functional requirements and data from a Danish hospital's operation and transforms into the correlation matrix. In this way, the dataset for the present design configuration originates from the requirements to a regional hospital in Denmark. The combination of the two dataset facilitates evidence-based design and systematic numerical design modeling.

Because the data originates from Danish hospital construction, the terminology of medical functionalities is Danish, and the terminology has not been translated. Therefore, the tables as outputs of the design model will entail functionality descriptions in Danish. The exemplifications of the design generations analyze the sensitivity of the principal drivers in the design generation.

Firstly, subsection 8.1 outlines how to understand the representation of the results. Subsequently, three examples represent the result of the design model. Next, subsection 8.3 analyzes and elaborates on the design model, firstly by analysis of the correlation factor driving the objective function. The correlation factor is essential, because it refers the input to the output of the model; meanwhile, it drives the design generation. Secondly, subsection 8.3.2 defines and applies additional constraint functions. These constraint functions reflect the inherent inexplicit perspectives from practice. Lastly, the chapter analyzes the behavior of the functional distributions for pattern configurations. This analysis outlines the sensitivity of the principal drivers, as initially presented in this chapter.

The following subsections outline the design configurations, generated as resulting geometries, as described in Chapter 3. The tables illustrate the generated design concepts visualizing the design by building typology and layout typology. Along follows the configuration of the geometric units defined and illustrated as a configuration of a number of layout typologies with respective functionalities. The functionalities are listed by a number and the Danish description. The design configuration entails evaluation of the configurations for comparing the initial choices and discussing the consequences of the initial design choices. The evaluations list the respective cost functions, with a cost factor of [0-1]. The costs are listed in a column in the table, with 1) Construction costs, 2) Operational costs, 3) Functionality, 4) Patient procedures, 5) Flexibility and 6) Healing architecture.

The first subsection of this chapter describes the representation of the results generated by the design model. The following subsections elaborate on the results of the design model.

8.1. Definition of the representation of the results

Tables present the resulting geometry as the result of the design model defining the design concept. First, the building typology illustrates the framework for the following architectural exploration.

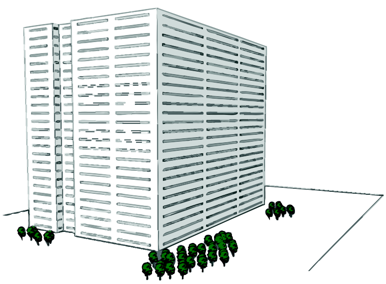


Figure 8-1 Illustration of the building typology, High-rise

The building typology illustrates the framework for the architectural configuration of the hospital design by geometric units. As illustrated in Figure 8-1, the architectural exploration and so the configuration of the geometric units have to follow the high-rise typology. The geometric units ought to be stacked on top of each other to fulfill the high-rise framework as illustrated.

Following the building typological framework, a configuration of the layout typologies illustrates the geometric units. In the subsequent design process of architectural exploration the geometric units will be configured according to the building typology, e.g. stacked on top of each other following the building typology.

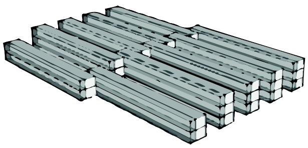


Figure 8-2 Illustration of the geometric unit consisting of several layout entities

Figure 8-2 exemplifies how the geometric unit consists of a given number of layout entities. The configuration of layout entities into geometric units is part of the architectural exploration following the procedures of the design model. The given number of layout entities (as defined in 7.2.2.3) defines the area of the geometric unit. Parallel to the illustration of building typology, the illustration sets the framework for the following architectural exploration.

The representation of the results captures the illustration of the geometric unit with a number of the geometric unit and the area of the unit. The number of the geometric unit is used in coordination with the cost diagrams, where the cost is a function of the unit and the six performance evaluators. The number is not relevant in terms of the design, and so there is no prioritization in the numbering.

The illustration below of the geometric units (as exemplified in Figure 8-2) outlines the functionalities inherent in the geometric units by index numbers (1 to 66) and by the Danish description. Moreover, it lists the costs of the six performance evaluators for each geometric unit. The costs are listed in a column, where the first row concerns the construction costs; the second row the operational costs etc. The six performance costs are listed for each geometric unit, referring to the costs of the given unit.

	Functionalities in unit	Costs
14	Kardiologi, seng	0.7188
18	Reumatologi, us	0.4785
21	Ortopædkirugi, seng	0.4919
22	Ortopædkirurgi, us	0.8703
23	Arbejdsmedicin, us	0.7453
…	…	0.7587

Figure 8-3 Illustration of list of functionalities defining the content of the geometric unit

The list of functionalities as illustrated in Figure 8-3 outlines the functionalities inherent in the geometric unit. The design model correlates the functionalities according to the principal drivers, the intermediate construction and, most importantly, the correlation matrix. As exemplified in Figure 8-3, three different types of examination rooms correlate with two types of wards. The correlation of the functionalities follows the requirements and preferences given by the correlation matrix and the design model. The costs listed in Figure 8-3 illustrate the high cost of patient procedures, medium high construction costs, flexibility and healing architecture. Meanwhile, the cost functions of operating costs and functionality are average.

The listed costs describing each geometric unit, as illustrated in Figure 8-3, represent the evaluation of the design configuration. The overall result is illustrated as a function cf. Figure 8-4, where the cost function is expressed as a function of the geometric unit and the six performance objectives.

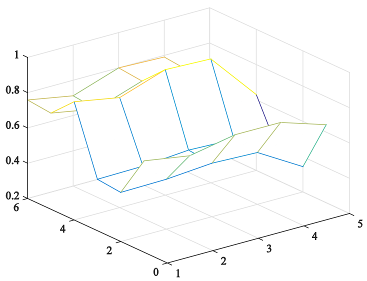


Figure 8-4 Illustration of the geometric unit consisting of several layout entities

Figure 8-4 illustrates how the cost function is visualized as a function of the geometric units along the x-axis and the six performance evaluators along the y-axis. The function is the costs written for each geometric unit. The surface plot illustrates the sensitivity of the costs with respects to the geometric units and the six performance evaluators.

The illustration of the costs is at the bottom of the tables presenting the results, showing the costs as a function of the performance evaluators and the geometric units for each design configuration.

The following subsection shows the generation of three design concepts of the different building typologies: the high-rise, the urban and the campus. A table of each individual configuration will represent the configurations. The following subsection analyzes the configurations, firstly, with respect to functional distributions, and secondly with respect to the cost functions. Additionally, the quality of the design configuration is analyzed.

8.2. Design configuration by principal drivers

This subsection illustrates the resulting geometry. The design configuration consists of a general design concept to be elaborated on architecturally within the framework of principal drivers.

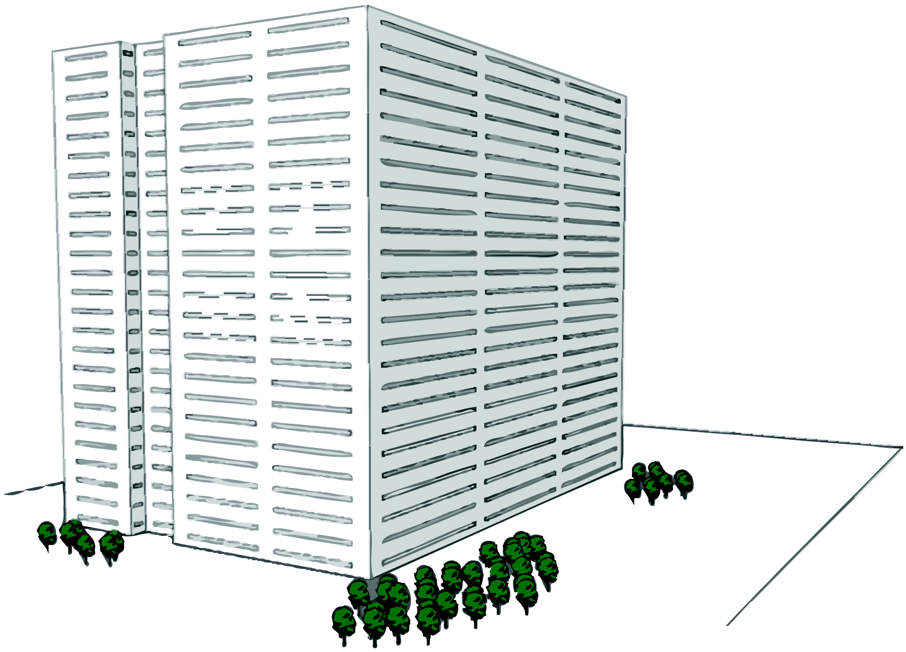
The following exemplifies how the design configurations differ according to different building typologies, and so it illustrates the sensitivity of the model.

The model operates with four initial choices reflecting the principal drivers. These are the building typologies, the organization typologies, the layout typologies and the number of geometric units, as described in 7.2. This example visualizes the sensitivity of the building typologies; consequently, the other principal drivers remain the same.

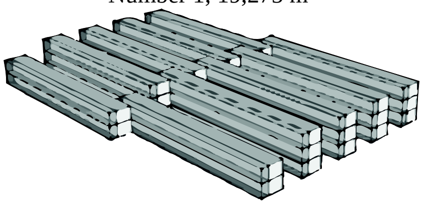
Each of the following exemplifications of a design configuration should be seen as the resulting geometry. It is an example of several alternates of design configuration by the intermediate construction and principal drivers of the design model. This means that the following exemplifications constitute one out of a set of design concepts.

The following three spreads illustrate three design configurations by first the high-rise typology, followed by the urban typology and finally the campus typology.

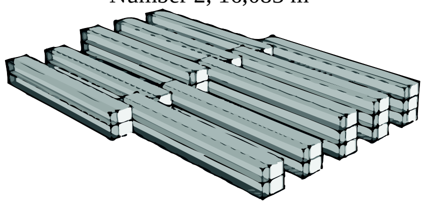
Table 8-1 Example of design concept generated by B_T=1 (High-rise), L_T=1 (Rectangular with exterior corridor), O_T=1 (Functionally split), N_{GU} = 5 units.



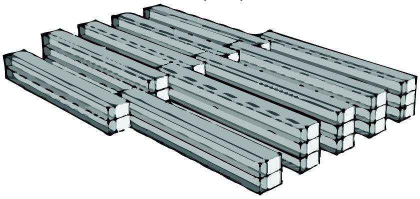
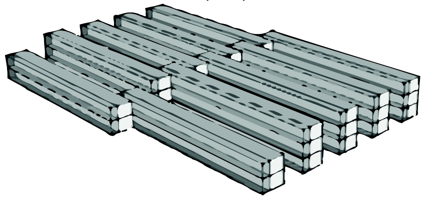
Number 1, 19,275 m^2

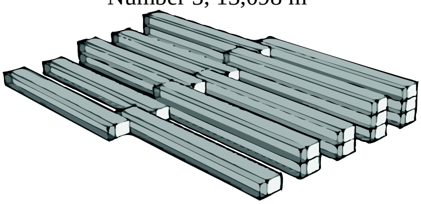
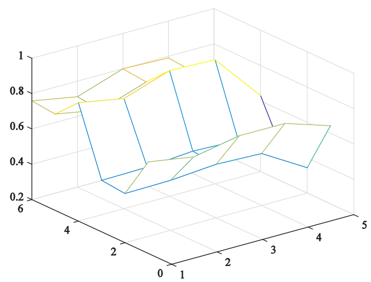


Number 2, 16,083 m^2



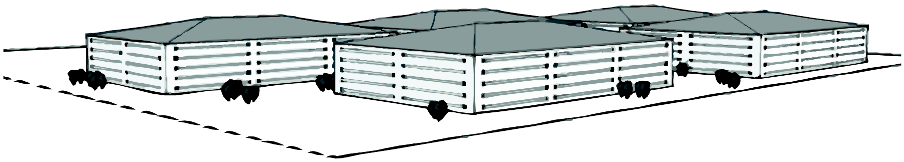
	Functionalities in unit	Costs		Functionalities in unit	Costs
14	Kardiologi, seng	0.7188	1	Akutseng, somatik	0.6768
18	Reumatologi, us	0.4785	6	OP	0.4827
21	Ortopædkirugi, seng	0.4919	17	Endokrinologi, us	0.4961
22	Ortopædkirurgi, us	0.8703	19	Intern medicin, seng	0.8237
23	Arbejdsmedicin, us	0.7453	28	Urologi, us	0.6987
34	Gynækologi, us	0.7587	32	Nefrologi, us	0.7121
37	Admin, kirurgi, urologi,		33	Gynækologi, seng	
	gastro, Nefro, gyn, otologi		39	Onkologi, us	
49	Psykiatri, v, us		40	Hæmatologi, seng	
53	Psykiatri, admin		45	Oftalmologi, seng	
56	Fødestue		46	Neuro, us	
57	Obstetrik, seng		55	Pædiatri, us	
60	Administration og		58	Obstetrik, us/føde	
	forskning		59	Obstetrik/Pædiatri, admin	
63	Ergoterapi og fysioterapi		66	Apotek	

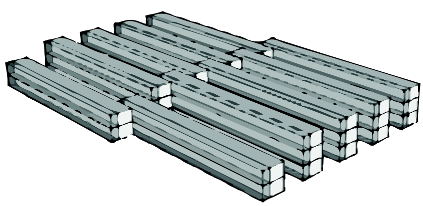
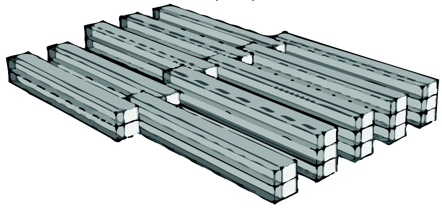
Number 3, 19,790 m^2			Number 4, 19,760 m^2		
					
	Functionalities in unit	Costs		Functionalities in unit	Costs
2	Akutseng, psyakiatri	0.7261	3	Akut, us, diag, skadest	0.7257
5	Intensiv, seng	0.5034	4	Akut, admin, vagtvær	0.4941
7	Opvågning	0.5167	8	Intensiv, admin	0.5074
11	Diagnostik, admin	0.9117	9	Diagnostik	0.9028
13	Lungemed, us	0.7867	15	Kardiologi, us	0.7778
20	Intern medicin, us	0.8000	16	Endokrinologi, seng	0.7911
25	Kirurgi, seng		24	Admin, lung, kar, endo,	
29	Gastroenhed, seng			reuma, intern, orto, arbejds	
31	Nefrologi, seng		26	Kirurgi, us	
43	Neurologi, seng		27	Urologi, seng	
44	Neuroreha/fysiol, seng		30	Gastroenhed, us	
47	neuro, admin		38	Onkologi, seng	
48	Psykiatri, seng		41	Hæmatologi, us	
50	Psykiatri, b/u, seng		51	Psykiatri, b/u, us	
52	Psykiatri, us		65	Køkken og kantine	
54	Pædiatri, seng				
62	Ernæringsenheden				
64	Kirkerum og kapel				

Number 5, 13,098 m^2			Costs in units, respectively
			
	Functionalities in unit	Costs	
10	Laboratorium	0.6425	
12	Lungemed, seng	0.3432	
35	Otologi, seng	0.3565	
36	Otologi, us	0.6300	
42	Admin, onkologi,	0.5050	
	hæmatologi	0.5184	
61	Patienthotel		

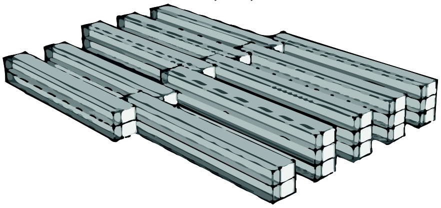
The table visualizes the design concept of geometric units as several combined layout entities. With the visualization of the units follows a list of inherent functionalities and the respective costs. Finally the overall cost function illustrates an evaluation of the design configuration.

Table 8-2 Example of design concept generated by B_T=2 (Urban). B_T=2 (Urban), L_T=1 (Rectangular with exterior corridor), O_T=1 (Functionally split)



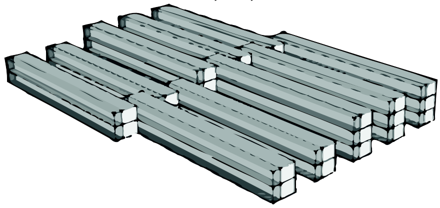
	Number 1, 18,723 m^2			Number 2, 18,597 m^2	
					
	Functionalities in unit	Costs		Functionalities in unit	Costs
8	Intensiv, admin	0.7160	3	Akut, us, diag, skadest	0.7091
18	Reumatologi, us	0.3867	6	OP	0.5572
21	Ortopædkirugi, seng	0.4001	16	Endokrinologi, seng	0.5705
43	Neurologi, seng	0.7393	17	Endokrinologi, us	0.8928
49	Psykiatri, v, us	0.6943	19	Intern medicin, seng	0.8478
52	Psykiatri, us	0.7077	26	Kirurgi, us	0.8611
53	Psykiatri, admin		30	Gastroenhed, us	
57	Obstetrik, seng		31	Nefrologi, seng	
61	Patienthotel		32	Nefrologi, us	
			34	Gynækologi, us	
			37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	
			54	Pædiatri, seng	
			55	Pædiatri, us	
			65	Køkken og kantine	

Number 3, 18,050 m^2



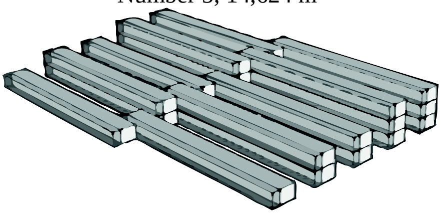
	Functionalities in unit	Costs
7	Opvågning	0.7063
9	Diagnostik	0.5312
13	Lungemed, us	0.5445
15	Kardiologi, us	0.8696
25	Kirurgi, seng	0.8246
33	Gynækologi, seng	0.8379
36	Otologi, us	
41	Hæmatologi, us	
46	Neuro, us	
47	neuro, admin	
51	Psykiatri, b/u, us	
56	Fødestue	
58	Obstetrik, us/føde	
60	Administration og forskning	
63	Ergoterapi og fysioterapi	

Number 4, 18,012 m^2



	Functionalities in unit	Costs
20	Intern medicin, us	0.7008
22	Ortopædkirurgi, us	0.5539
24	Admin, lung, kar, endo,	0.5673
	reuma, intern, orto, arbejds	0.8742
27	Urologi, seng	0.8292
28	Urologi, us	0.8426
29	Gastroenhed, seng	
35	Otologi, seng	
38	Onkologi, seng	
39	Onkologi, us	
40	Hæmatologi, seng	
42	Admin, onkologi,	
44	hæmatologi	
	Neuroreha/fysiol, seng	
45	Oftalmologi, seng	
48	Psykiatri, seng	
59	Obstetrik/Pædiatri, admin	
62	Ernæringsenheden	
66	Apotek	

Number 5, 14,624 m^2



	Functionalities in unit	Costs
11	Diagnostik, admin	0.6591
12	Lungemed, seng	0.3545
14	Kardiologi, seng	0.3679
23	Arbejdsmedicin, us	0.6249
50	Psykiatri, b/u, seng	0.5799
64	Kirkerum og kapel	0.5933

Costs in units, respectively

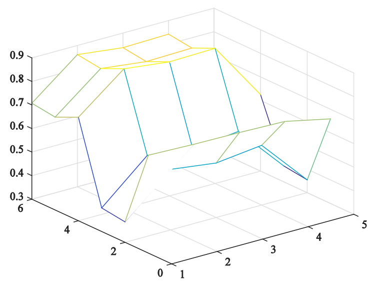
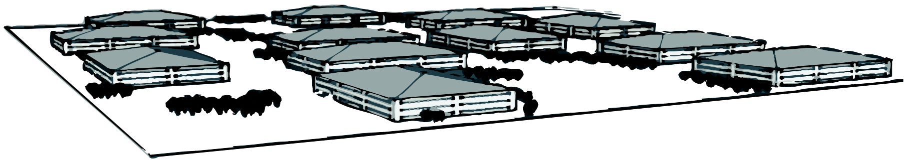
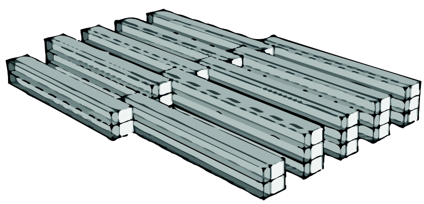


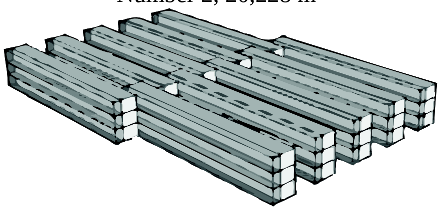
Table 8-3 Example of design concept generated by B_T=3. B_T=3 (Campus), L_T=1 (Rectangular with exterior corridor), O_T=1 (Functionally split)



Number 1, 18,412 m^2

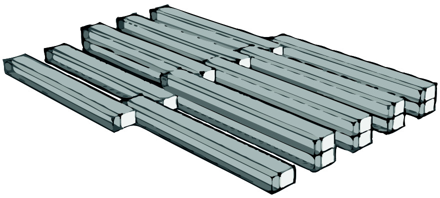


Number 2, 20,228 m^2



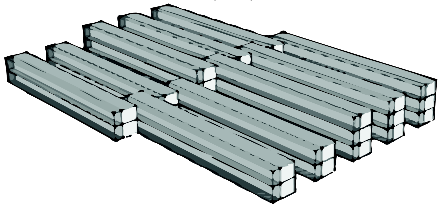
	Functionalities in unit	Costs		Functionalities in unit	Costs
12	Lungemed, seng	0.7204	10	Laboratorium	0.7329
15	Kardiologi, us	0.5256	13	Lungemed, us	0.4564
16	Endokrinologi, seng	0.5389	22	Ortopædkirurgi, us	0.4697
19	Intern medicin, seng	0.8114	27	Urologi, seng	0.7770
21	Ortopædkirugi, seng	0.9364	31	Nefrologi, seng	0.9020
23	Arbejdsmedicin, us	0.9497	32	Nefrologi, us	0.9154
25	Kirurgi, seng		33	Gynækologi, seng	
26	Kirurgi, us		36	Otologi, us	
39	Onkologi, us		42	Admin, onkologi, hæmatologi	
43	Neurologi, seng				
48	Psykiatri, seng		49	Psykiatri, v, us	
51	Psykiatri, b/u, us				
52	Psykiatri, us				
56	Fødestue				
58	Obstetrik, us/føde				
65	Køkken og kantine				

Number 3, 11,417 m^2



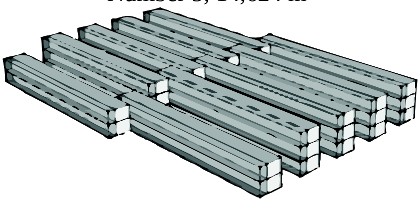
	Functionalities in unit	Costs
17	Endokrinologi, us	0.5713
18	Reumatologi, us	0.3313
30	Gastroenhed, us	0.3446
	neuro, admin	0.4865
47	Obstetrik, seng	0.6115
57	Obstetrik/Pædiatri, admin	0.6248
59	Administration og	
60	forskning	
61	Patienthotel	
62	Ernæringsenheden	
64	Kirkerum og kapel	
66	Apotek	

Number 4, 18,119 m^2



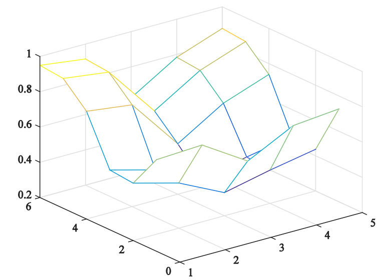
	Functionalities in unit	Costs
11	Diagnostik, admin	0.7024
24	Admin, lung, kar, endo,	0.3889
	reuma, intern, orto, arbejds	0.4022
28	Urologi, us	0.6462
29	Gastroenhed, seng	0.7712
35	Otologi, seng	0.7845
40	Hæmatologi, seng	
44	Neuroreha/fysiol, seng	
45	Oftalmologi, seng	
50	Psykiatri, b/u, seng	
53	Psykiatri, admin	
54	Pædiatri, seng	
55	Pædiatri, us	

Number 5, 14,624 m^2



	Functionalities in unit	Costs
3	Akut, us, diag, skadest	0.7267
7	Opvågning	0.4362
8	Intensiv, admin	0.4496
9	Diagnostik	0.7393
14	Kardiologi, seng	0.8643
20	Intern medicin, us	0.8777
34	Gynækologi, us	
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	
38	Onkologi, seng	
41	Hæmatologi, us	
46	Neuro, us	
63	Ergoterapi og fysioterapi	

Costs in units, respectively



The three examples outline and exemplify the design configuration with different building typologies, and the same layout and organization typologies. The illustration of the building typology visualizes the different frameworks for the following architectural exploration to set the framework of the different design configurations.

The tables outline the design concepts with typologies for the overall design configuration. The building typology defines the overall hospital concept, and a variable number of layout units define the framework for the geometric units. The design configuration is one alternate out of several.

In the three examples, the differentiation in cost functions at the bottom of the tables show a relative consistency in costs across the units within each configuration. The examples demonstrate how the random number generator influences the size of the geometric units. The unit size varies from 17 layout units responding an area of 11,417 m^2 to 30 layout typologies giving 20,228 m^2. With the same input in terms of the correlation matrix, the cost functions are comparable, because the normalization of the cost functions is on the overall level. This is also seen by the lowest cost on 0.3313 and the highest on 0.9497, even though the range is [0-1].

Parallels in the functional distributions appear; especially the functionalities with few correlation constraints correlate similarly, e.g. psychiatrics and obstetrics/delivery rooms. The remaining functionalities are distributed differently in each configuration, and there is no clear consistency in the distributions.

The distributions possess a high degree of randomness, which makes the design model detrimental to design generation in practice. The degree of randomness is too high. There is a need for adjusting and improving the design model, which the following subsection will describe.

8.3. Design configuration improvements

This study maintains the overall construction of the design model, as defined in Chapter 7, with the definition of the principal drivers, the correlation matrix as input and weighted summarized optimization objective. The following explores adjustments and evaluation of the model, with the aim of improving the design model in terms of its application and usability.

Firstly, there will be an analysis of the convergence in the functional distributions in terms of the correlation factor. The correlation factor is decisive for the objective function of costs because it defines the link between input and output in terms of the correlation of functionalities. The objective function (and thus the optimized design concept derived from the design model) uses the correlation factor as an evident term.

8.3.1. Convergence in correlation factor

The correlation factor is normalized in terms of operating with cost functions ranging from 0 to 1. The maximum correlation normalizes the correlation factor. The maximum correlation factor derives from several iterations of each configuration. The maximum correlation factor of 360.0 defines the upper boundary. The evaluation of design configuration by cost functions will include the normalized correlation factor.

Variation in the correlation factor is present because of the random distribution of functionalities. The distribution of functionalities is subject to the genetic algorithm that configures a design vector of variables. The design vector defines the content of the varying geometric units and contributes to the final definition of the geometric unit. Moreover, a random number generator initially defines the varying framework for the geometric units. With two initial random processes (a random number generator and a GA searching the design space), variations in the correlation factor are expected.

The variation in the correlation factor is analyzed to evaluate the convergence of the objective function and thereby the functional distributions. 380 simulations perform the foundation for the analysis, and the following statistics can be applied to the resulting correlation factor. The simulations have a fixed configuration of principal drivers: building typology, layout typology and organizational typology as well as number of geometric units.

Table 8-4 Correlation factor for 10, 20, 50, 100 and 200 simulations, respectively for $B_T = 1$ (High-rise), $L_T = 2$ (Rectangular, interior), $O_T = 1$ (Functionally split), $N_{GU} = 5$ units.

Number of simulations	10	20	50	100	200
Min	166.5	159.8	166.0	145.3	152.8
Max	308.0	337.6	353.9	359.3	356.7
Average	213.8	223.4	234.9	227.5	236.3
Median	179.7	193.6	199.4	189.0	199.8
Variance	2,930	3,136	4,009	3,765	4,543
Coefficient of variation	25 %	25 %	27 %	27 %	29 %

With a coefficient of variation approx. 25-30%, as outlined in the last row of Table 8-4, the correlation factor varies more than preferred for the simulations in order to achieve consistency in the model. However, the analysis shows how the correlation factor has a relatively constant coefficient of variation of 30 % for all simulations (10, 20, 50, 100 and 200).

As a reflection of the input data in terms of the correlation matrix, the correlation factor quite directly describes the functionality distribution. However, the weighted sum of performances defines the objective function. Therefore, this study performs a similar analysis of the consistency of the objective function, because the correlation factor is merely a term in that function, which also reflects the geometric behavior of the configuration. The following outlines the parallel analysis on the objective function.

Table 8-5 Optimization objective for 10, 20, 50, 100 and 200 simulations, respectively for B_T = 1 (High-rise), L_T = 2 (Rectangular, interior), O_T = 1 (Functionally split), N_{GU} = 5 units.

Number of simulations	10	20	50	100	200
Min	16.1	16.0	16.2	15.9	15.9
Max	22.5	22.3	21.5	23.0	23.0
Average	18.0	17.6	17.9	18.2	18.2
Median	16.6	16.7	16.8	16.8	16.8
Variance	5.96	3.31	2.79	6.18	6.18
Coefficient of variation	14 %	10 %	9 %	14 %	14 %

The objective function is clearly more converged than the correlation factor. As outlined in Table 8-5, the coefficient of variation of the objective function is approx. 10-15 %. A coefficient of variation of 10-15 % means that there is a minor variation in the model, which is satisfying in terms of consistency of the distributions. Compared to design configurations in practice, there is a high variation across proposals e.g. in construction projects of hospitals where high variation characterizes the different proposals defined on the same basis. Therefore, a variation in the objective function of 10-15 % is acceptable, and the model is considered to produce converged simulation.

In the optimization procedures, the correlation factor and objective functions are maximized, and so it is interesting to compare the maximum correlation factor and the maximum objective function. The following comparisons on the maximum correlation factor and the max objective function define the benchmarks for the converged max correlation factor and the converged max objective function. Because the optimization procedure is a minimization, the integers of the model are negative ($\in Z$), which in these tables are natural numbers ($\in N$). This makes the maximum smaller than the minimum.

Table 8-6 Analysis of maximum correlation factor, *cf* for 10, 20, 50, 100 and 200 simulations

Simulations	Max cf		
10	308.00	Max	308.0
20	337.60	Min	359.3
50	353.90	Average	343.1
100	359.30	Median	353.9
200	356.70	Variance	365.3
		Coefficient of variation	5.6%

The maximum correlation factors across the simulations, as outlined in Table 8-6, are clearly more converged with a 5.8 % coefficient of variation. Consequently, the analysis of the design model can use the maximum correlation factor for 10 simulations. Similar to the correlation factor, there is an analysis of the objective function.

Table 8-7 Analysis of objective function *f(**X**)* for 10, 20, 50, 100 and 200 simulations

Simulations	Max *f(**X**)*		
10	22.58	Max	20.75
20	22.31	Min	23.01
50	21.49	Average	22.03
100	23.01	Median	22.31
200	20.75	Variance	0.654
		Coefficient of variation	3.7%

For the analyzed simulations, the maximum objective function has a 2.5 % coefficient of variation. This describes a converged objective function.

The coefficient of variation is similar for 10, 20, 50, 100 and 200 simulations, respectively. Consequently, the following will take point of departure in 10 simulations as sufficient for generating a converged design configuration.

Throughout the simulations, the correlation factor varies more than the objective function. This is a consequence of the random distribution of functionalities according to the use of GAs and the varying sizes. With a converged objective function, the varying correlation factor must reflect varying geometric definitions in opposition to the correlation factor in order to achieve converged objective functions.

8.3.2. Addition of constraint functions reflecting perspectives from practice

With the converged objective function, the varying correlation factor reflects variations in the functionality distribution. However, the design configurations represent a too high degree of randomness. There is an absence of systematics in the distributions. The inexplicit perspectives from practice especially lack in the design model. For instance, the technically demanding functionalities and technically less-demanding functionalities mix. This parameter is evident in the costs of the construction, as reflected by the functional typological costs in Equation 21. Moreover, the distinction of technically demanding and less-demanding functionalities is a parameter practice values highly, pays much attention to and uses actively in the design process. According to Equation 22, the functional typological cost of each unit reflects the maximum functional typology within the unit. It is preferred to minimize the difference between the minimum and maximum functional typology, to have similar technical requirements in each unit.

8.3.2.1 Functional typology constraint

For several distributions, the functional typological costs consequently reflect 0.35 with sporadic exceptions of 0.46. There is no significant diversifying in the construction costs of the different units. The technically demanding functionalities and the less technically demanding functionalities are mixed, and this mix causes high construction costs.

In order to minimize the mix of functionalities, another constraint function is applied to the optimization problem in Equation 8. The constraint, $g_i(\boldsymbol{X})$, reflects the gross/net factor of the optimization by maximizing the effective area of each unit. By applying another constraint function relating the technically demanding functionalities, $h_i(\boldsymbol{X})$, the optimization is moreover subject to converging the functional typological costs in each unit. The following equation defines the constraint function that must be applied:

$$\text{subject to} \quad h_i(\boldsymbol{X}) = 0 \quad i=1,2,\ldots,N_{GU} \qquad \text{Equation 23}$$

where X is the vector of design variables, N_{GU} is the number of geometric units, and $h_i(X)$ are vectors of equality constraints.

The constraints $h_i(\boldsymbol{X})$ define the difference of functional typology within the units, given as:

$$h_i(\boldsymbol{X}) = \max FT(\boldsymbol{X})_i - \min FT(\boldsymbol{X})_i - tol \qquad \text{Equation 24}$$

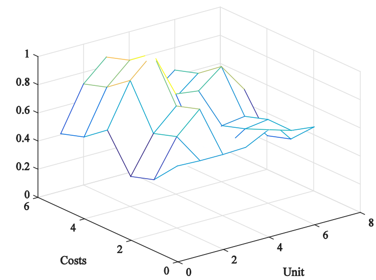
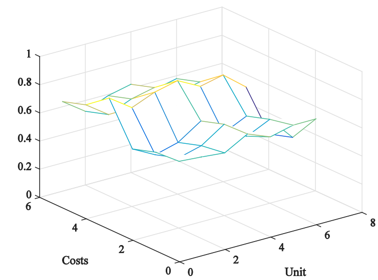
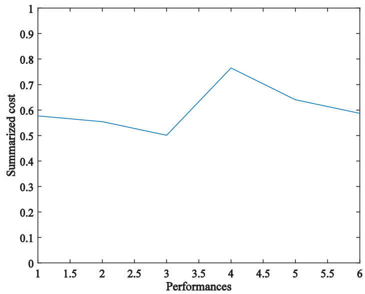
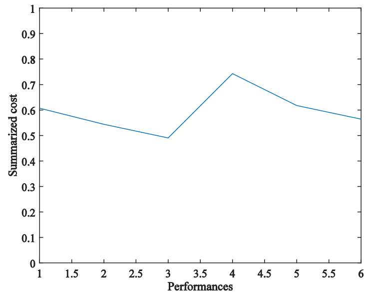
where *tol* is the allowed tolerance.

This constraint function is applied to the program of the intermediate construction in the constraint function. Thus, the constraint function consists of a vector of two inequality constraints that have to be satisfied. Hence, the design space for the objective function is within the constraints given by the inequality vector.

While applying the second constraint function, an immediate differentiation in the results emerges. Instantly, the construction costs are minimized and the functional typological cost for each unit are differentiated. Table 8-8 shows a clear differentiation in the functional distributions. The implication by the functional typological cost differentiates the construction costs as outlined along with the costs.

The first column in Table 8-8 outlines the original function of one constraint function, $g_i(\boldsymbol{X})$. The second column outlines the constrained function of $g_i(\boldsymbol{X})$ and $h_i(\boldsymbol{X})$. The first row outlines $FT(\boldsymbol{X})_i$ followed by diagrams of the cost functions and diagrams of the summarized costs. The surface plot of cost functions illustrates the costs as a function of the six performance evaluators and the geometric units. The summarized cost diagrams visualize the costs as a function of the six performance evaluators.

Table 8-8 Cost function for B_T = 1 (High-rise), L_T = 2 (Rectangular, interior), O_T = 1 (Functionally split), N_{GU} = 7 units.

minimize $f(\boldsymbol{X})$ subject to $g_i(\boldsymbol{X}) = 0$ i =1,2, … , N_{GU}	minimize $f(\boldsymbol{X})$ subject to $g_i(\boldsymbol{X}) = 0$ $h_i(\boldsymbol{X}) = 0$ i =1,2, … , N_{GU}
$FT(\boldsymbol{X})_i$=[0.35 0.35 0.35 0.35 0.35 0.46 0.35]	$FT(\boldsymbol{X})_i$=[0.35 0.35 0.35 0.46 0.46 0.46 0.64]
	
	

The table shows how the simulations possess a differentiation in *FT(**X**)$_i$* in the constrained optimization compared to the original. In the original optimization, *FT(**X**)* returns 0.35 for all units with the exception of one on 0.46. In the constrained optimization, *FT(**X**)* returns 0.35 for three units and 0.64 for one unit, meaning the last unit only encompasses of non-clinical facilities, whereby the requirements to the technical installations are low.

There is a clear differentiation in $FT(\boldsymbol{X})_i$. In the unconstrained simulation, the functional typological costs must reflect special clinical areas in all units, except one. This is a perspective practice pays extra attention to, as minimizing the special clinical areas is evident in minimizing the construction costs.

The costs functions visualize the differentiation by higher costs in the surface plot, where the construction costs for the last units (4-7) are higher (and thereby lower). The diagram of the summarized costs below visualizes the differentiation in construction costs more clearly. For the original optimization, the construction costs are 0.57 and for the constrained optimization, the construction costs are 0.62.

8.3.2.2 Achieved correlation and potential constraint

It is possible to achieve ‘good’ solutions by the objective function, where some perspectives from practice are not inherent, and so practice will consider the solutions ‘bad’. This follows the fact that practice’s design process is weakly defined with several implicit and informal parameters, and the evaluations do not follow predefined objective functions, but they are implied and informal. It is evident to implement the implicit architectural understanding in the constraints, so that the model formally implements the architectural understanding of the design problem e.g. by constraints.

Another perspective to evaluate and distinguish is the quality of the correlations. Currently, the correlation factor refers to the summarized correlations in the geometric units. This perspective stands firm. However, a constraint function is defined on the efficiency of the correlations within the units related to the potential correlation.

This second constraint function is applied to the optimization problem in Equation 8, which now is subject to the constraints of $g_i(\boldsymbol{X})$ reflecting the gross/net factor, $h_i(\boldsymbol{X})$, reflecting the technical-demanding/less-demanding functionalities, and lastly subject to $l_i(\boldsymbol{X})$, reflecting the potential correlations and the actual correlations.

The following equation defines the constraint function to apply to Equation 8:

$$\text{subject to} \quad l_i(\boldsymbol{X}) = 0, \quad i = 1, 2, \dots, N_{GU} \qquad \text{Equation 25}$$

where X is the vector of design variables, N_{GU} is the number of geometric units, and $l_i(X)$ are vectors of equality constraints.

The constraints $l_i(\boldsymbol{X})$ define the difference in the potential correlation and the actual correlation in the geometric units, respectively, given as:

$$li_i(\boldsymbol{X}) = \sum_{j=1}^{N} \sum_{k=j+1}^{N} r_{jk} - 2 \sum_{j=1}^{N} \sum_{k=j+1}^{N} r_{jk} z_{ik} - tol \qquad \text{Equation 26}$$

r_{jk} is the correlation values given in the correlation matrix for *N* functionalities and z_{ik} is a decision variable equals 1 if functionality *k* is in unit *j*, and 0 otherwise. *tol* is the allowed tolerance.

This constraint function adds to the program of the intermediate construction. This narrows the design space further by the additional constraint in the inequality vector. While applying constraints to the program and narrowing the design space, it is evident to assure the program's continuous ability to operate. While the number of constraints increases, the design space for the objective function decreases. Application of tolerances for the respective constraints assures the operational ability. Table 8-9 outlines a simulation of 10 generations with satisfied constraints with tolerances.

Table 8-9 Constraints outlined for optimized configuration of $B_T = 3$ (Campus), $L_T = 3$ (Rectangular, double), $O_T = 1$ (Functionally split), $N_{GU} = 10$ units.

$EAgu$	$\max FT(\boldsymbol{X})_i - \min FT(\boldsymbol{X})_i$	FT	$\sum_{j=1}^{N} \sum_{k=j+1}^{N} r_{jk}$	$2\sum_{j=1}^{N} \sum_{k=j+1}^{N} r_{jk} z_{ik}$
0.8063	1	0.4600	40.0	11.00
0.8343	1	0.3500	40.2	11.20
0.8269	1	0.3500	32.3	8.20
0.7451	1	0.3500	159.6	52.20
0.7110	1	0.3500	100.7	29.20
0.7174	0	0.3500	264.6	112.60
0.7018	0	0.4600	107.4	30.80
0.7809	2	0.4600	55.0	14.20
0.8683	2	0.3500	52.1	13.20
0.8071	2	0.4600	107.3	29.00

Table 8-9 illustrates the variables with regard to the constraint functions. The simulation of Table 8-9 with N_{GU} = 10 takes 25 generations to achieve 10 generations with satisfied constraints. From the results, the required tolerances can be read. The effective area ranges from 70–85 %. Consequently, it requires a tolerance of 30 for $g_i(\boldsymbol{X})$.

$\max FT(\boldsymbol{X})_i - \min FT(\boldsymbol{X})_i$ shows a difference of up to 2. Accordingly, the tolerance is set to 2 for $h_i(\boldsymbol{X})$.

The two last columns illustrate the relation between the achieved correlation and the potential correlation. The constraint of the relativity of the potential correlations and the achieved correlations are set to be 0.5. This means that the non-achieved correlation must be less than or equal to 0.5 times the potential correlation.

A similar simulation is performed for N_{GU} = 5 to analyze the ability to operate with the constraints for different configurations.

Table 8-10 Constraints outlined for optimized configuration of B_T = 3 (Campus), L_T = 3 (Rectangular, double), O_T = 1 (Functionally split), N_{GU} = 5.

$EAgu$	$\max FT(\boldsymbol{X})_i - \min FT(\boldsymbol{X})_i$	FT	$\sum_{j=1}^{N}\sum_{k=j+1}^{N} r_{jk}$	$2\sum_{j=1}^{N}\sum_{k=j+1}^{N} r_{jk}z_{ik}$
0.8027	0	0.3500	103.1000	26.4000
0.9620	0	0.4600	120.9000	31.6000
0.8351	0	0.3500	166.2000	43.0000
0.8748	0	0.3500	228.6000	76.0000
0.7001	2	0.4600	340.4000	159.2000

The returned constraint satisfaction vector shows that all simulations satisfy the constraints, which means that it takes 10 generations to make 10 generations of satisfied constraints. Consequently, the ability of operate is increased in comparison to N_{GU} = 10, where it took 25 generations. Table 8-10 illustrates the variables with regard to the constraint functions. The effective area increases to 70-96 % and only one unit is below 80 %.

Moreover, the differentiation for maximum and minimum FT returns several zeros, whereby all functionalities in each unit are within the same category.

The relation between the achieved correlation and the potential correlation obtain a parallel relativity as for N_{GU} = 10. The tolerance of 0.5 times the potential correlations equals the achieved correlations.

The simulations of N_{GU} = 5 uphold the tolerances of N_{GU} = 10, and they even show less use of the tolerances. Therefore, the tolerances, as elaborated above, for N_{GU} = 10 are applied the constraints. Decreasing the tolerances will require too many generations for returning 10 generations of satisfied constraints.

The distribution of functionalities after applying additional constraint functions is clearly more qualified than the examples of subsection 8.2, where there is a lack of systematics. However, some functionalities within the constrained distributions remain to appear randomly placed. Due to the construction of the design model based on a random number generator and GAs, randomness is expected. It is applied to facilitate the search for new organizations of work and new definition of the geometric units. Randomness is an evident parameter in the construction of this design model. Randomness is a prerequisite in the search for optimized configurations by rules and formally described parameters. Dictation according to the formally described parameter will maintain the traditional patterns, and the new ways of organizing the work will not appear.

However, a certain degree of pattern generation is expected to assure repetitions of qualified arrangements. The following subsection searches for patterns in the distributions.

8.3.3. Distributional patterns

To analyze the quality and consistency in the functional distribution by input of correlation matrices, the following subsection analyzes the pattern configuration by the functionality distribution. In terms of consistency and pattern generation, it is evident that parallel patterns emerge for the same configuration.

The following analysis consists of two simulations of the same configurations. Diagrams analyze consistency in the simulations by pattern configurations. Two types of diagrams form the analysis: a bar plot and a contour plot.

The bar plot illustrates the correlation as a function of the functionalities along the x-axis and y-axis. The bar height represents the number of correlations of two functionalities in a given intersection. The bar visualizes the degree of repetition, and the tendency of repetition. However, it is difficult to identify the recurrent correlations, and the pattern of correlations. The contour plot illustrates this perspective. The contour plot is a two dimensional visualization of the three dimensional bar plot. It illustrates the repetitive function of correlations by color codes as a function of the functionalities along the x-axis and y-axis. Reflecting the increase in bar height, the color brightens. The yellow areas illustrate the repetitive correlation tendencies. The lighter the color of the contour plot is the more consistency exists in correlations throughout several simulations.

The contour plot is illustrative in showing between which functionalities correlation tendencies exists. Moreover, the contour plot illustratively shows different pattern configurations for different configurations of principal drivers.

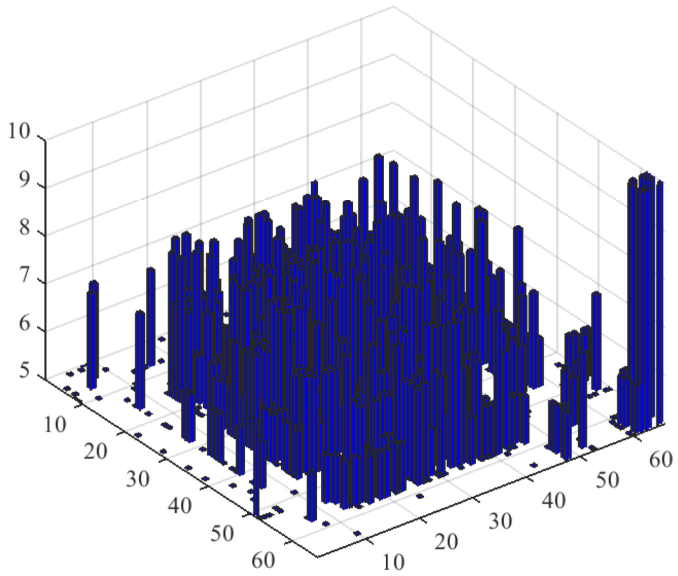
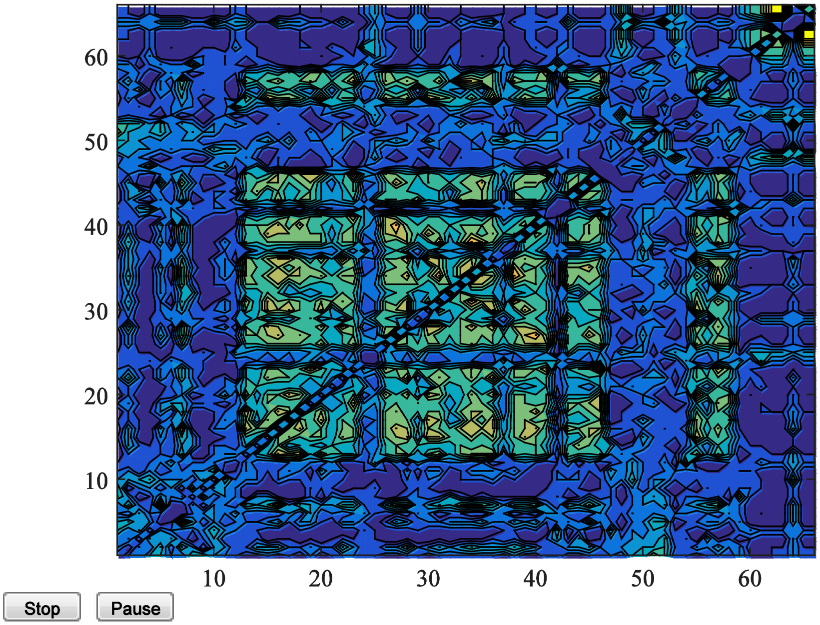


Figure 8-5 Pattern by bars in functional distributions after 10 simulations, B_T = 3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally split), N_{GU} = 5.

The bar plot shows how r_{jk}, increases while the correlation of two functionalities repeats in the simulations. As the correlation of two functionalities repeats, the bar plot illustrates the functional value of the increase given by the repetitions.

The bar heights illustrate the tendency of repetition in correlations. Increased function value (bar heights) refers to increased repetition in correlation for the respective functionalities. The functionalities are listed along the x- and y-axis and the correlation appears in the intersection of two functionalities. The yellow areas in the contour plot of Figure 8-6 illustrate the repetitive correlation tendencies. The pattern of yellow areas corresponds in the two diagrams in Figure 8-6. Differences in the diagrams appear, while similarities characterize the diagrams, and a clear pattern emerge in the configuration of B_T = 3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally split), N_{GU} = 5.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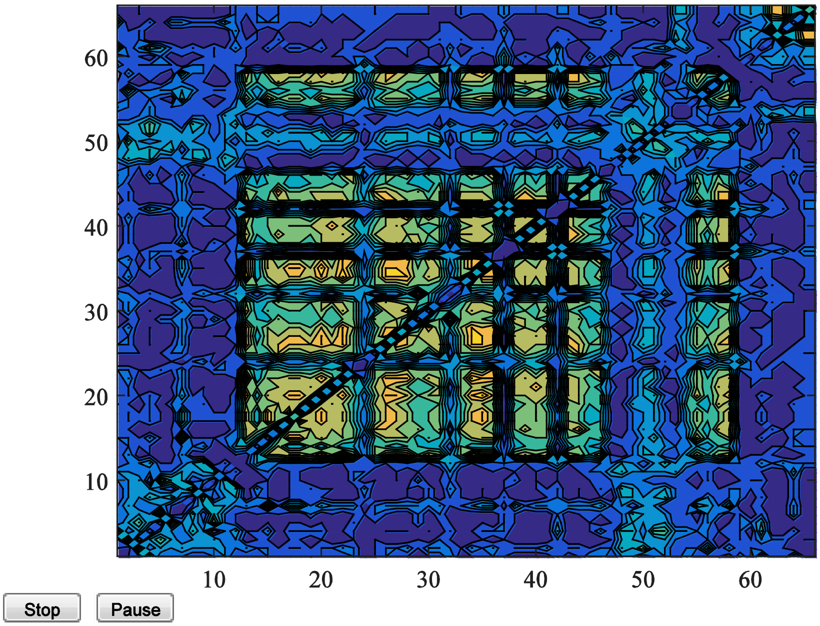
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Figure 8-6 Pattern by contour in two functional distributions after 10 simulations, BT = 3 (Campus), LT = 3 (Double corridor), OT = 1 (Functionally split), NGU = 5.

The plot in Figure 8-6 shows how a pattern configuration is present in the design model. There are clear tendencies for correlations in the two similar plots. The plot in Figure 8-6 refers, by colors, to the functional value of Figure 8-5 as bar heights.

In the analysis of pattern configuration, it is evident that similarities emerge while the configuration of design input and principal drivers are the same, as illustrated in Figure 8-6. Meanwhile, differences in other configurations assure that the different input of principal drivers has an actual impact in the design generation. If all configurations make similar patterns, the design generations are performed purely by the intermediate construction, and the initial choices by principal drivers do not influence the design. Therefore, the following shows different configurations of principal drivers for analyzing the pattern configurations.

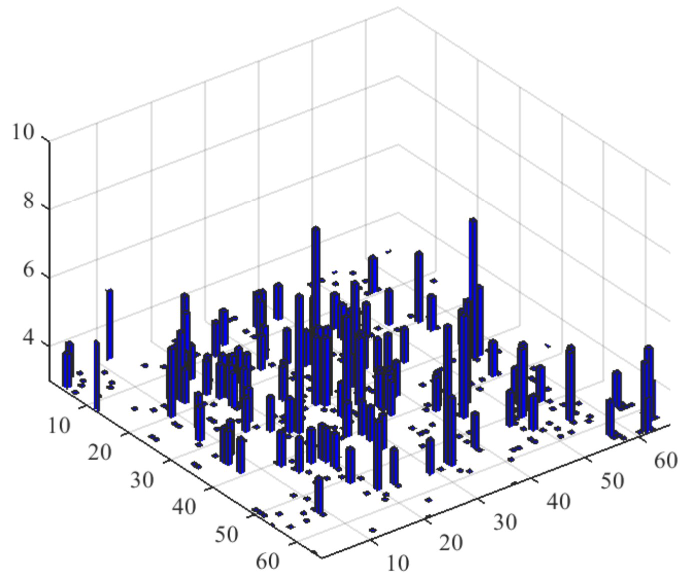


Figure 8-7 Pattern by bars in functional distributions after 10 simulations, 10 simulations, B_T = 1 (Campus), L_T = 1 (Double corridor), O_T = 2 (Sectorized), N_{GU} = 10.

Figure 8-7 shows a different pattern configuration from Figure 8-5. There is a clear differentiation between in the bar heights, which are remarkable lower in Figure 8-7.

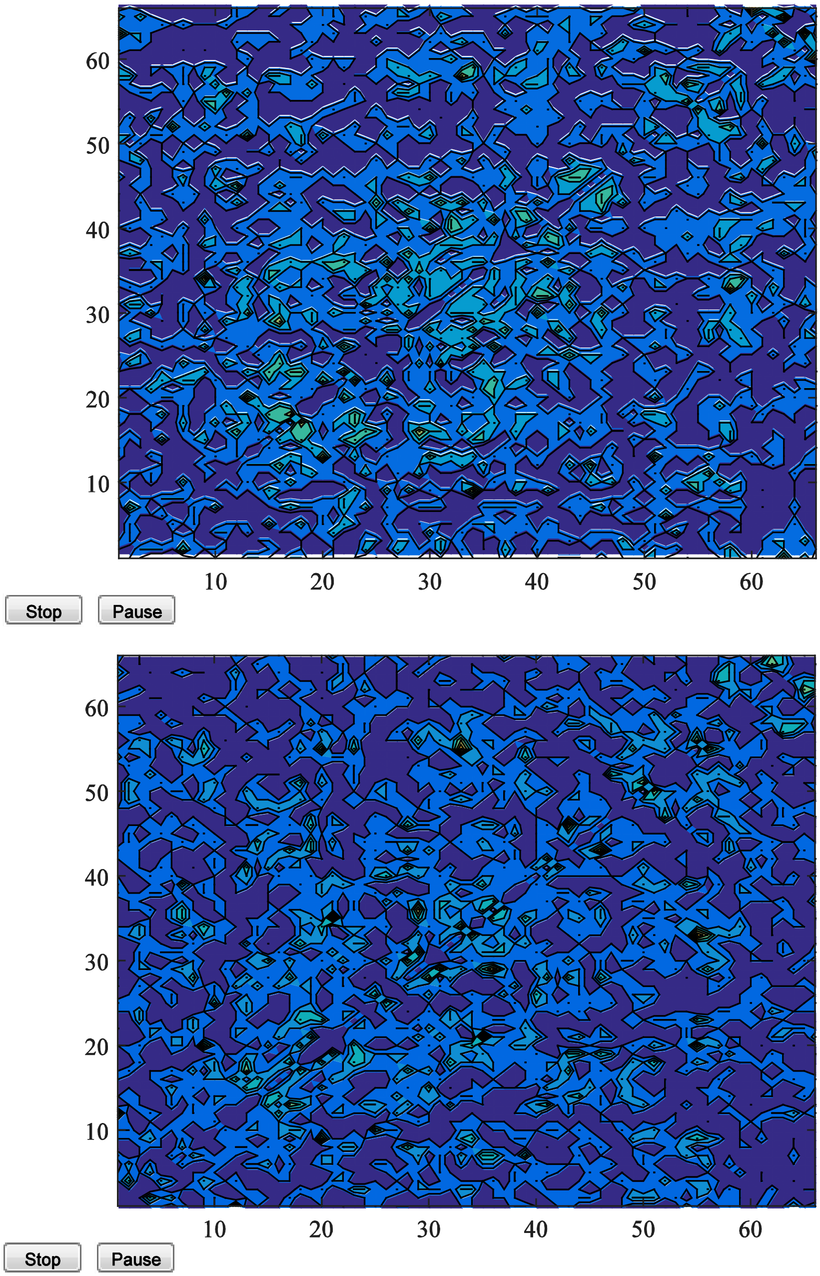


Figure 8-8 Pattern by contour in two functional distributions after 10 simulations, $B_T = 1$ (Campus), $L_T = 1$ (Double corridor), $O_T = 2$ (Sectorized), $N_{GU} = 10$.

Parallel to the lower bar height in Figure 8-7 compared to Figure 8-5, the contour of Figure 8-8 is remarkably less articulated than in Figure 8-6.

Figure 8-8 shows an increase in geometric units, but also another organization typology, which includes different input data by another correlation matrix, because of the different correlation strategies. With this less articulated pattern configuration, it is interesting to analyze if the pattern by $O_T = 2$ in Figure 8-8 can be more articulated and if the clear different pattern from Figure 8-6 could emerge by $O_T = 2$.

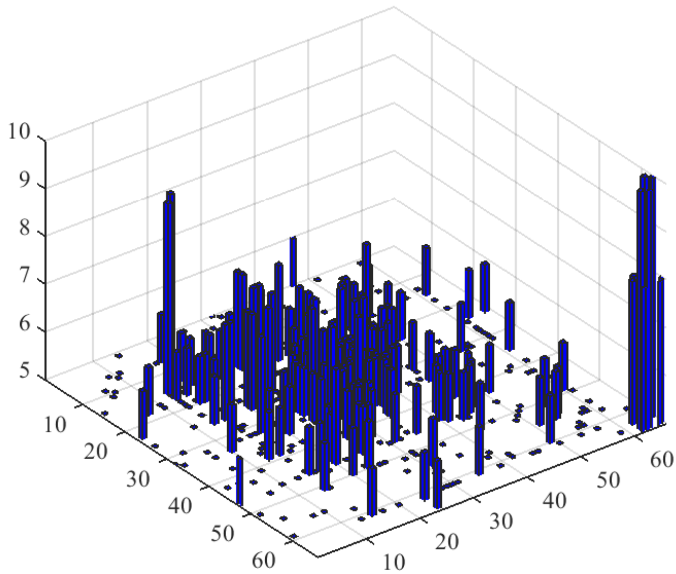
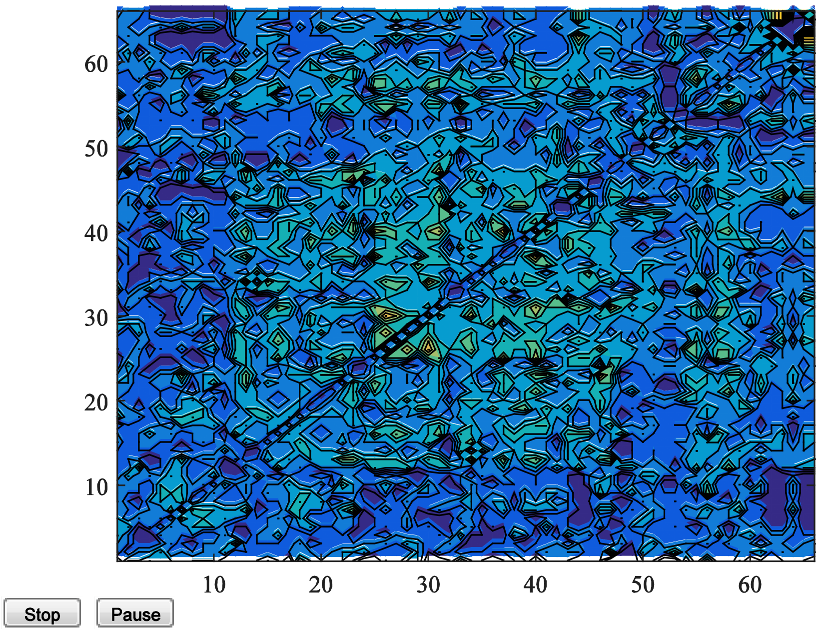


Figure 8-9 Pattern by bars in functional distributions after 10 simulations, $B_T = 2$ (Urban), $L_T = 1$ (Single corridor, exterior), $O_T = 2$ (Sectorized), $N_{GU} = 5$.

The bar plot of Figure 8-9 shows an increase in the height and thereby in repetition of the correlations and in r_{jk} in general. This follows the anticipation of decreased bar heights follows the increase in N_{GU}. The contour of Figure 8-10 shows a different pattern configuration than in Figure 8-6. The articulation increases in comparison to Figure 8-8, responding to the increased bar height in Figure 8-9, and the pattern by $O_T = 2$ is clearly different from $O_T = 1$ in Figure 8-6, which satisfies that the principal drivers imply the design configuration.



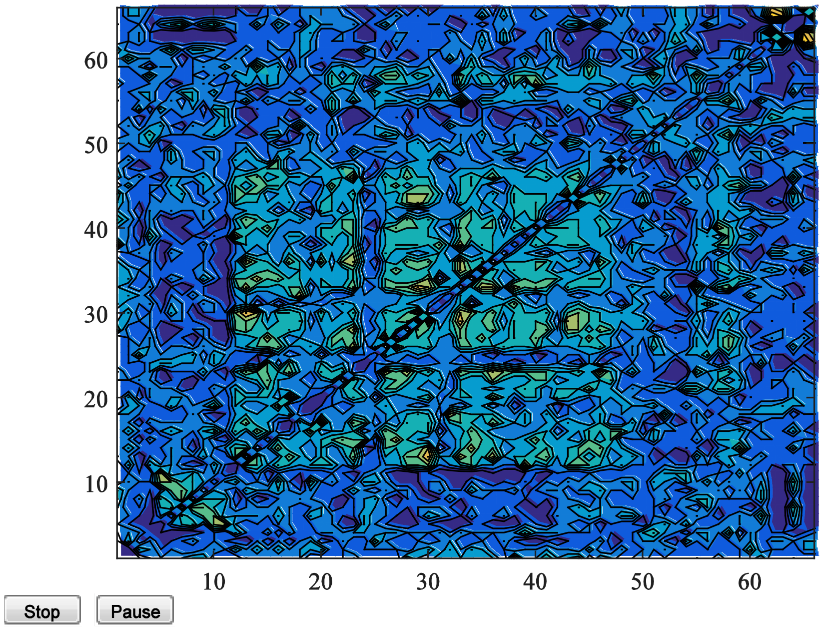


Figure 8-10 Pattern by contour in two functional distributions after 10 simulations, $B_T = 2$ (Urban), $L_T = 1$ (Single corridor, exterior), $O_T = 2$ (Sectorized), $N_{GU} = 5$.

While having more units, e.g. N_{GU} = 10, the pattern configuration becomes less expressed. The bar height is lower in Figure 8-7 compared to Figure 8-5 and Figure 8-9. This follows the configuration of N_{GU} = 10 in comparison to N_{GU} = 5. An increase in N_{GU} is an increase in number of units, whereby the functionalities must be distributed in more units. Consequently, the average number of functionalities in one unit, and thereby correlated functionalities, decreases from 13-14 correlated functionalities per unit for N_{GU} = 5 to 6-7 correlated functionalities for N_{GU} = 10.

The layout typologies possess different qualities and varying sizes. By the largest layout typology there is a potential to emphasize the weak pattern configuration of Figure 8-7 and Figure 8-8, because of the size of the unit. The typological choice of L_T = 5 will cause larger geometric units and, thereby more functionalities within the units. The following subsection will analyze this aspect with respect to pattern configuration.

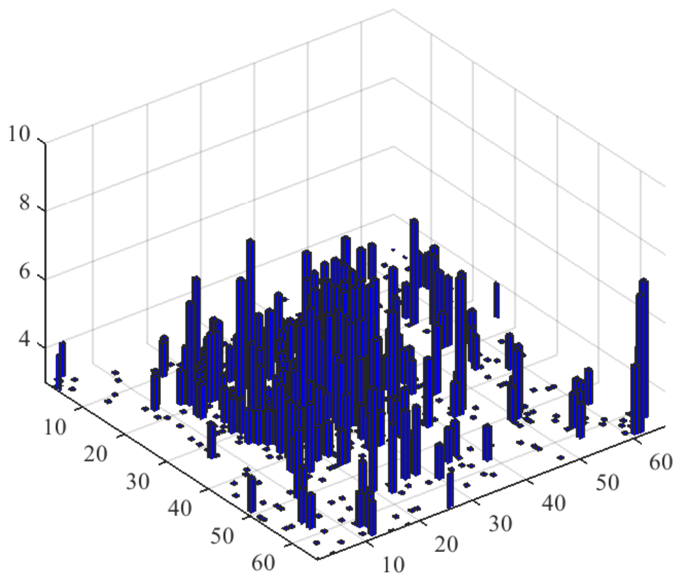


Figure 8-11 Pattern by bars in functional distributions after 10 simulations, B_T =1 (High-rise), L_T = 5 (Courtyard, interior), O_T = 1 (Functionally split), N_{GU} = 10.

The bar plot of Figure 8-11 appears more dense than Figure 8-7. Figure 8-12 shows an emphasized pattern configuration, where yellow spots appear in comparison to Figure 8-8.

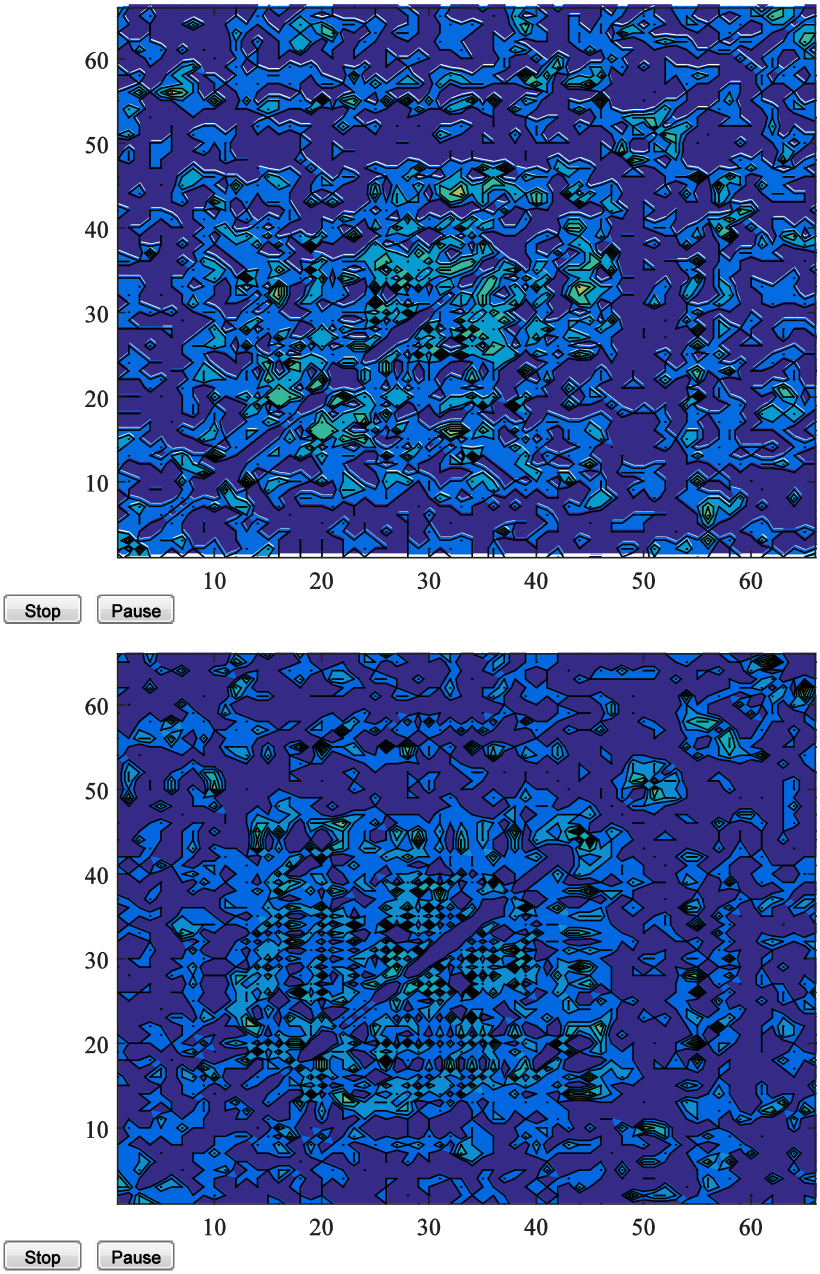


Figure 8-12 Pattern by contour in two functional distributions after 10 simulations, B_T =1 (High-rise), L_T = 5 (Courtyard, interior), O_T = 1 (Functionally split), N_{GU} = 10.

The pattern configuration shows that the design model reflects the different principal drivers. The design model clearly distributes the functionalities as a function of the principal drivers as intended by the parametric construction of the design model. Table 8-11 outlines the repetition in correlations representing the required and preferred correlations by the correlation matrix.

Table 8-11 Degree of repetition for 10 simulations, with preference of 586 correlations (varying in degree from 0.3-1.0]. The design configuration ,

Correlation repetition [%]	10	20	30	40	50	60	70	80	90	100
$B_T = 1, L_T = 5, O_T = 1, N_{GU} = 10$										
Number of repetitions	2698	1206	504	146	50	18	4	2	0	0
Correlation repetition [%]	460	206	86	25	9	3	1	0	0	0
$B_T = 1, L_T = 5, O_T = 1, N_{GU} = 8$										
Number of repetitions	3072	1708	830	392	182	82	40	10	0	0
Correlation repetition [%]	524	291	142	67	31	14	7	2	0	0
$B_T = 1, L_T = 5, O_T = 1, N_{GU} = 5$										
Number of repetitions	3600	2710	1952	1508	1222	918	524	184	48	4
Correlation repetition [%]	614	462	333	257	209	157	89	31	8	1
$B_T = 2, L_T = 1, O_T = 1, N_{GU} = 5$										
Number of repetitions	3802	2816	1918	1300	848	556	274	74	24	6
Correlation repetition [%]	649	481	327	222	145	95	47	13	4	1
$B_T = 2, L_T = 3, O_T = 1, N_{GU} = 5$										
Number of repetitions	3694	2860	2008	1408	1043	660	316	118	36	2
Correlation repetition [%]	630	488	343	240	178	113	54	20	6	0
$B_T = 3, L_T = 3, O_T = 1, N_{GU} = 5$										
Number of repetitions	3772	2888	1846	1002	508	190	68	24	12	2
Correlation repetition [%]	644	493	315	171	87	32	12	4	2	0
$B_T = 3, L_T = 3, O_T = 2, N_{GU} = 5$										
Number of repetitions	3894	2980	1870	890	340	116	22	14	8	2
Correlation repetition [%]	665	509	319	152	58	20	4	2	1	0

Table 8-11 and the contour figures show how the model distributes functionalities more easily and with a higher degree of repetition with fewer units and as a function of the layout typologies. With five units, N_{GU} = 5, the design model distributes the functionalities more easily and more systematically than with 10 units. The eased distributions respond with increased repetition. While having more units (N_{GU} is increased), fewer functionalities are present in each unit and the repetition is lower. In the first row, where N_{GU} = 10, 50 % repetition in correlation appear for 9 % of the required correlations. The third row presents a configuration, where the 50 % repetition is above 200 % of the required correlations. This configuration of B_T = 1, L_T = 5, O_T = 1, N_{GU} = 5 appears to be one of the less constrained configurations, whereby the optimization is eased and the consistency in the distributions is high.

It is seen how the problem becomes more constrained with increased N_{GU}. Subsection 8.3.2 illustrates this increase of constraint in the model operation, where one simulation of 10 generations with satisfied constraints require 25 generations for N_{GU} = 10 and only 10 for N_{GU} = 5.

Moreover, Table 8-11 illustrates how a decrease in repetition for organization typology 2 in the last row reflects the different input data of the other correlation matrix.

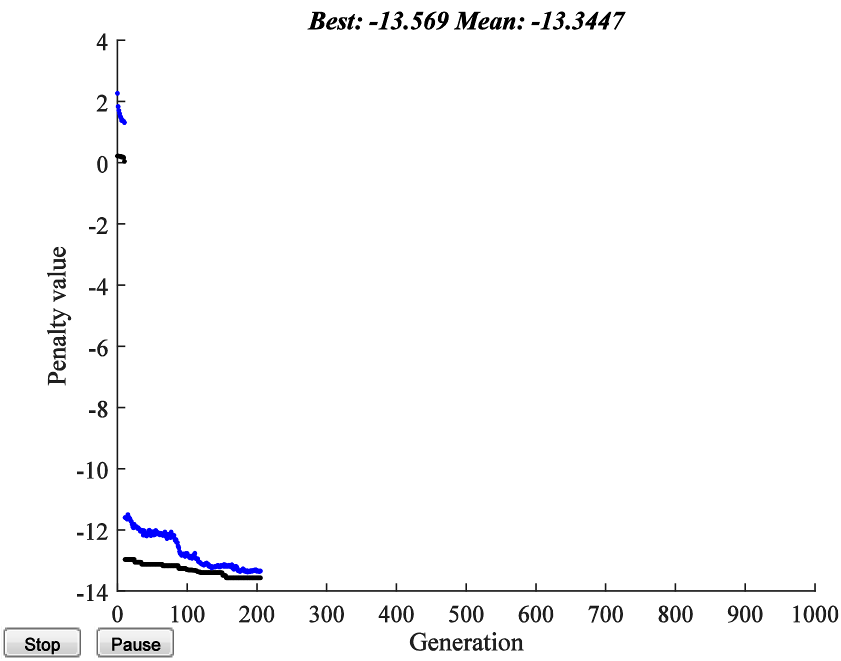


Figure 8-13 Curve, B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 2 (Sectorized), N_{GU} = 5.

Figure 8-13 presents the typical development of the objective function value as the solution iteratively is improved. The graph illustrates how the first 10 generations in the optimization procedure yield a penalty value from 4 to 0 concerning the constraints. After approx. 10 generations, the penalty functions illustrate the objective function of costs from -11 to -15. This typical development of the optimization concerns the solutions of N_{GU} = 5, which is the less constrained configuration. For N_{GU} = 10, the typical development is different as the configuration is more constrained. Several simulations terminate the optimization prematurely due to an average change in the penalty fitness value less than desired and so the constraints are not satisfied. For the simulations where the constraints are satisfied, the mean number of generations before the penalty value jumps is approximately 200-300 in comparison to 10 generations for N_{GU} = 5 as illustrated in Figure 8-13.

8.4. Summary

This chapter elaborated on the definition of the design model as defined in Chapter 7. The elaboration involves an analysis of the consistency and sensitivity of the model, resulting in additional constraints reflecting the informal perspectives from practice. Moreover, the construction of the inherent optimization is modified to secure the operational ability of the model. The design space for the objective function became too narrow with the additional constraints, especially for design configurations of N_{GU} = 10. The consequence of the narrow design space is that the GA does not find solutions, where the constraints are satisfied, and so it searches for results, where the constraints are satisfied. Consequently, it uses all its iterations to find solutions with satisfied constraints, and thereby it does not start finding results that are better and better for each iteration. Table 8-10 reflects this, where it takes 2.5 times the required generations to achieve the required number of generations where constraints are satisfied.

An analysis of the pattern configuration by principal drivers outlines the effect on the various design generations. Table 8-11 visualizes the different principal drivers' influence on the design generation. The configuration of the principal drivers constrains the problem differently, and so the design space for the objective function became more or less constrained. N_{GU} is decisive in constraining the problem, and the layout typologies in terms of size constrain the problem as well. The design space narrows according to the decrease in the size of the layout typology.

These perspectives on the design space reflect the problem solving from practice. While the numbers of unit increased, the problem become more complex to solve as the constraints increased.

Chapter 9. Usability of the Hospital Design Model

The design model is implemented in MATLAB ® and uses the global optimization toolbox for Mixed Integer Optimization Problems by GA. The design input is data from a project competition for a regional hospital in Denmark, combined with state-of-the-art knowledge of hospital design and data from hospital operation, in a correlation matrix as elaborated on in Chapter 4.

The design model produces a design concept for a chosen design configuration. Each design concept is an exemplification of the simulations based on the initial configurations. The design concept provides a framework for further architectural exploration. Along with production of design concepts for further exploration, the design model produces evaluations in terms of the six performance evaluators. The evaluations drive the design as the objective cost functions; meanwhile, they provide information of qualities and consequences of the design choices.

This chapter investigates the quality and usability of the design concepts produced by the design model and deals with the second research *question of what is the usability of systemized design models when applied to hospital functionality.*

How to distribute the several functionalities of a hospital is a time consuming process in practice. Distribution of functionalities is one of the main contributions of the model. Therefore, it is evident to evaluate the distribution of functionalities while evaluating the usability of the design model. The design model's other main contribution to practice is the ongoing evaluations of the design by the performance evaluators and the correlations. While analyzing the performance evaluators and correlations, it is essential to analyze the implication of the principal drivers by the sensitivity. This perspective follows the analysis of pattern configuration in Chapter 8.

This chapter analyses the usability of the design model in practice by this approach. The first subsection processes the building typologies and their influence on the design configuration, and thereby the sensitivity of the building typologies. The following subsections analyze the organization typologies and layout typologies, respectively. The last of the principal drivers and initial choices are the number of geometric units. Subsection 9.4 analyzes the influence of number of geometric units.

Subsequently, subsection 9.5 will discuss the usability in terms of the distribution of functionalities, by analyzing the 'best' simulations. This defines the foundation for discussing the usability and applicability of the model in practice in subsection 9.6.

All analyses take their point of departure in the output of the design model, as illustrated in the previous chapter. The output is a table illustrating the building typology, a definition of the geometric units with the respective functionality distribution and the evaluations of the performances.

The design model frames a design approach that explores the consequences of the initial choices for informed decision-making. The initial choices are the principal drivers that easily can be changed so new simulations are made. The initial choices are essential in the design configuration, and the hierarchical structure emphasizes this perspective. The initial choices or the principal drivers define the framework for the design configuration. They inform the design configuration defined by the mathematically formulated rules and parameters in the intermediate construction. The following subsections analyze the impact of the principal drivers on the design configuration as part of analyzing the usability of the model.

In the analysis of the design model there will be comparisons of design output for different configurations. Firstly, the influence and thereby the sensitivity of the building typologies is compared. Presumably, the building typologies do not influence the functional distribution because the building typology sets the framework for the configuration of the geometric units, which is part of the architectural exploration following the conceptual design by the design model. The functionality distribution does not depend on the building typologies directly. However, the building typologies influence the objective function differently, which may influence the functionality distribution.

9.1. Influence of building typologies on design configuration

The first comparison is made on the costs functions, because this is where the building typologies most directly influence according to the construction of the design model. According to Equation 13 the building typologies influence the cost index by principal drivers. This perspective represents the typological qualities from practice, as elaborated in Chapter 5. The building typologies indirectly influence the cost index by the function of the functional distribution in terms of the typological qualities, which potentially drive the objective function of summarized costs.

The simulations of building typologies follow the numeration of the typologies: Firstly, the high-rise typology, then the urban typology and finally the campus typology. The following pages will outline the cost functions as functions of the principal drivers and the intermediate construction defining the functional distributions. The upper diagram illustrates by a surface the cost functions as a function of the unit and the respective performance. The surface illustrates the performance cost along the z-axis, as a function of the unit along the x-axis and the six performance evaluators along the y-axis. The surface represents the three-dimensional function of the individual functional responses.

The lower diagram shows the summarized for each units. The function of summarized costs is along the y-axis and the the individual performance evaluators along the x-axis. Both costs functions are normalized according to the definition in Chapter 7.

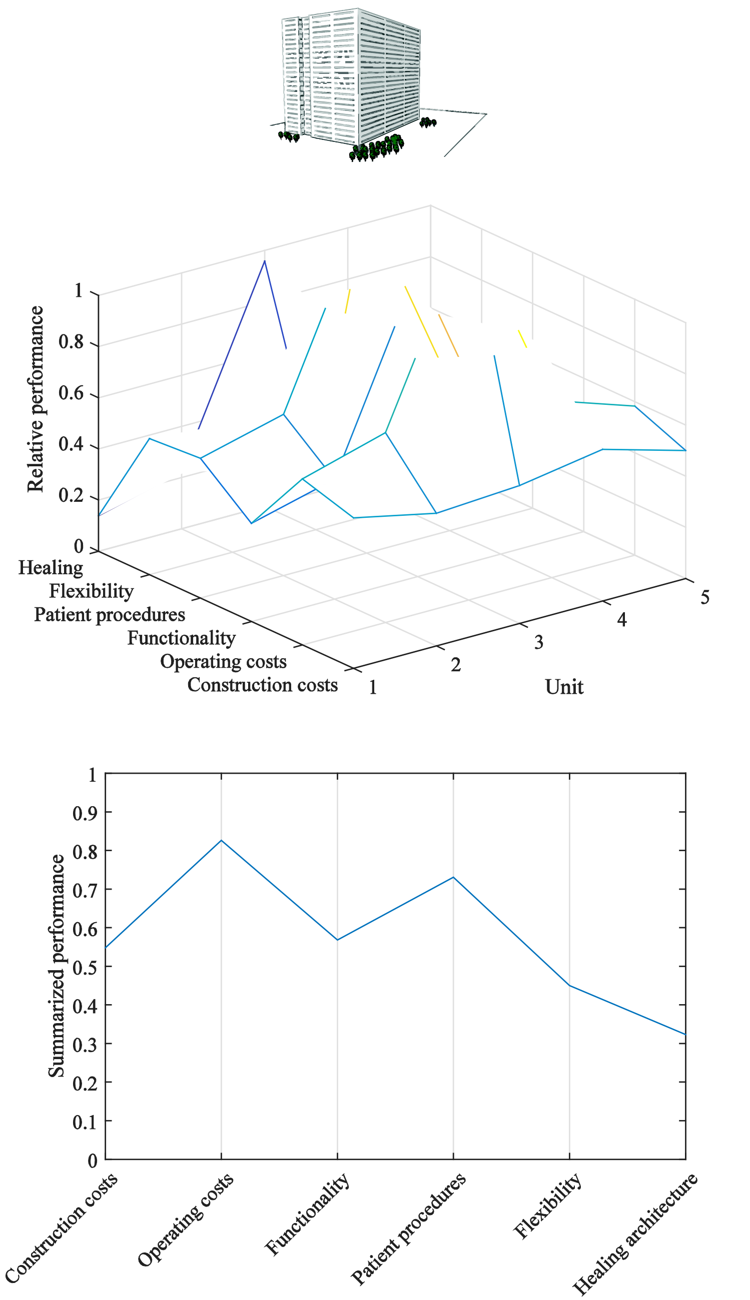


Figure 9-1 Mean costs of functional distributions after 10 simulations, $B_T = 1$ (High-rise), $L_T = 3$ (Double corridor), $O_T = 1$ (Functionally split), $N_{GU} = 5$ units.

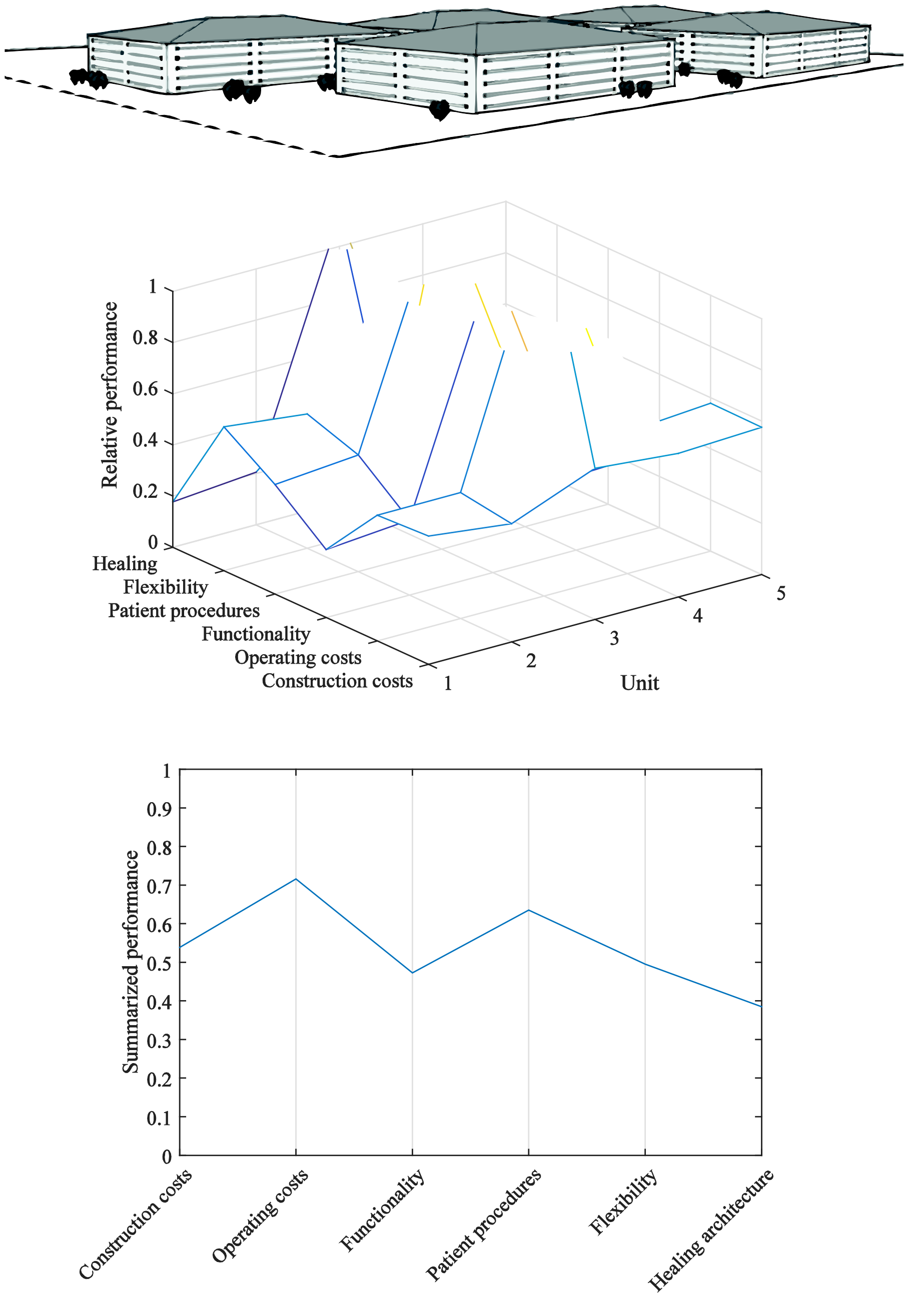


Figure 9-2 Mean costs of functional distributions after 10 simulations, B_T =2 (Urban), L_T = 3 (Double corridor), O_T = 1 (Functionally split), N_{GU} = 5 units.

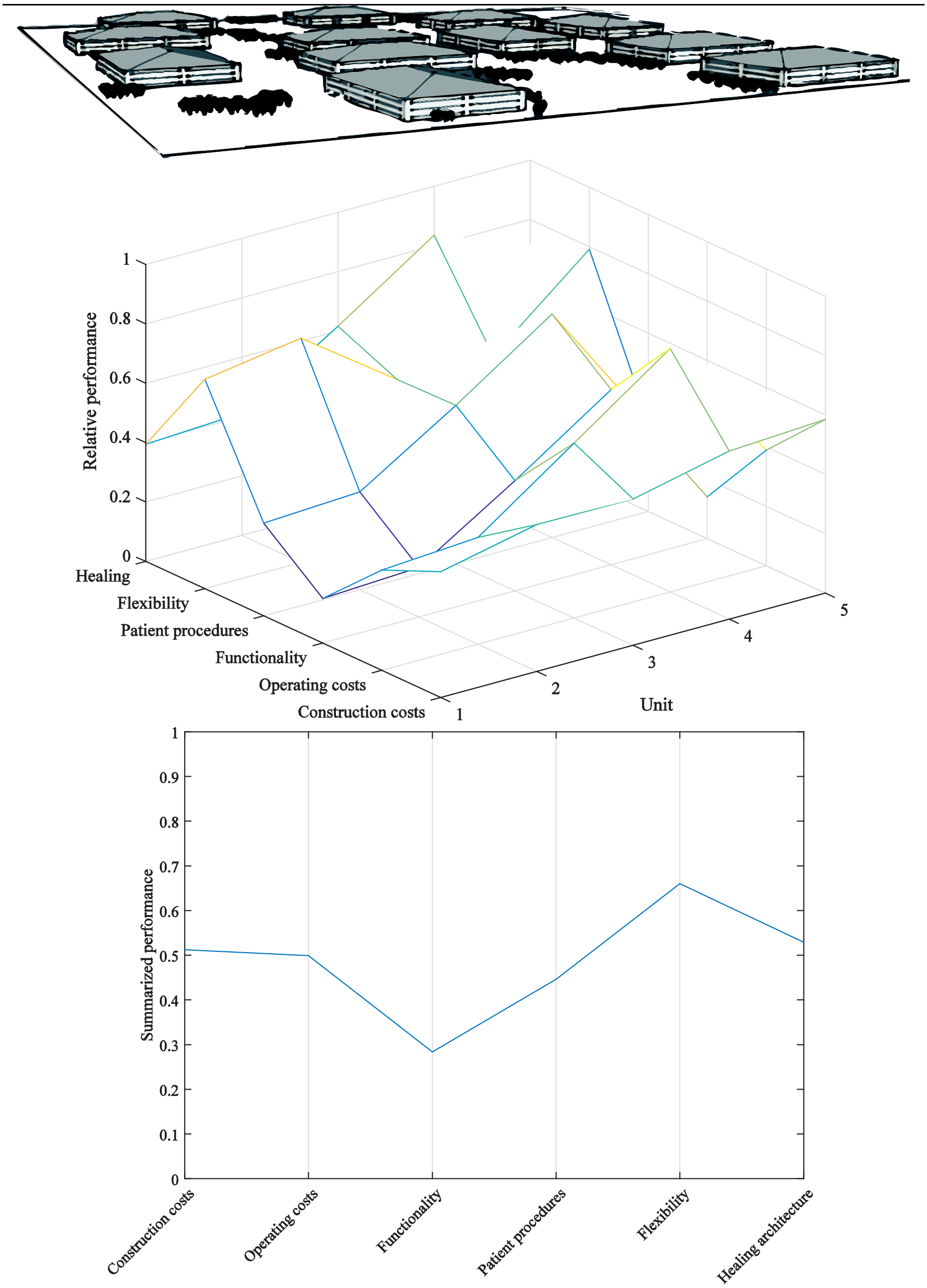


Figure 9-3 Mean costs of functional distributions after 10 simulations, B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally split), N_{GU} = 5.

The simulations show clear differences in the cost functions. The costs across the units vary remarkably, and some unit costs reach the upper boundary, as seen in Figure 9-1 and Figure 9-2 for unit number 3. This is expected to be a consequence of either a large unit 3 in size or in number of functionalities. A large unit in size or functionalities will cause a high correlation factor of the unit, which is decisive in the cost functions of all performance evaluators, except the first: construction costs, as observable in Figure 9-1 and Figure 9-2.

The summarized costs ease the comparison across the configurations, because the individual varying unit costs hamper the transparency of the total performance of the hospital configuration. There is a clear tendency for the operational costs to decrease when the plot area increases (the building typologies go from high-rise to urban to campus). Figure 9-1 shows a summarized operational cost at 0.8, which decreases to 0.7 in Figure 9-2 and further to 0.5 in Figure 9-3. This has a clear reference to the tables of Chapter 5, where the size of the plot affects the operational costs by increased transportations etc. across the hospital when the size increases. Flexibility and healing architecture oppose this tendency of decrease. Their cost functions increase across the configurations from lowest in high-rise to highest in the campus configuration. However, the building typology and plot size affect the flexibility more than it affects healing architecture, as seen in the diagrams.

The cost function of the general functionality of the hospital drops in the campus configuration in Figure 9-3. There is no direct connection between the drop and the sizes of the plot following the building typologies. The drop in functionality can be a consequence of the functionality distribution, which was already indicated by the high costs in unit 3 in Figure 9-1 and Figure 9-2. The functionality distributions of the respective simulations, outlined in Appendix C verify this indication. The high-rise and the urban configuration both consist of a unit 3 with several wards and examination rooms causing a very high correlation factor in this unit.

The high degree of correlation between wards and examination rooms was expected after reading the cost functions for the respective units, where unit 3 reached the upper boundary for both the high-rise and the urban configuration. However, it was not expected that the examination rooms and wards correlated this much, because the organization typology is the functionally split typology emphasizing a differentiation between wards and examination rooms. The organization typology is defined to correlate one type of ward with another..

The correlation requirements between wards are high, and equally the correlation between examination rooms is high. However, the correlation between wards and examination rooms is only a preference for the directly related functionalities, e.g. cardiology wards and examination rooms. A professional cluster of several wards and examination rooms is not encouraged, which is why the extensive correlated unit is unexpected.

The functionality distributions as outlined in Appendix C possess several parallels, which is emphasized by the clear pattern configuration. This corresponds to Chapter 8, where configurations of L_T = 3 (Double corridor), O_T = 1 (Functionally split), N_{GU} = 5 showed consistency in the configurations of 8.3.3

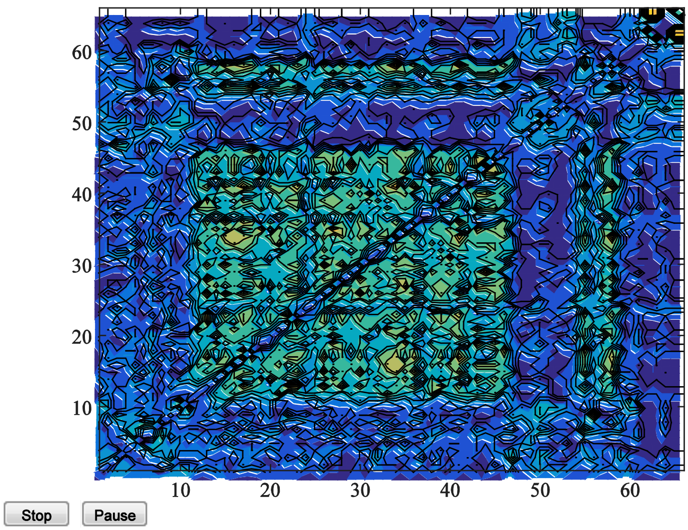


Figure 9-4 Pattern of functional distributions after 10 simulations, B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally split), N_{GU} = 5.

The pattern configuration in Figure 9-4, follows the less constrained optimization problem of N_{GU} = 5. It verifies the consistency in the functional distributions, as outlined in Appendix C, where several parallels exist. The similarities in the functional distributions follow the definition of the design model and the intermediate construction, where the building typologies only indirectly influence the functional distributions. It is the layout typologies and the organization typologies that define the parameters of the intermediate construction.

The configurations by different building typologies, as this subsection analyzes, show an interesting perspective in terms of the functionality distribution. The chosen principal drivers of this subsection, L_T = 3 (Double corridor), O_T = 1 (Functionally split), N_{GU} = 5 units, appear to provide a framework for design configuration, where optimization is eased by a less constrained configuration. The objective function performs design configurations that are more optimized than expected, as the wards and examination rooms correlate, respectively. This eased and extended optimization influenced the pattern configuration to be high and parallel across the building typologies.

The building typologies do not affect the functional distributions, and the sensitivity of the building typologies is low if not non-existing. It corresponds to the definition of the intermediate construction, where the layout typologies and the organization typologies define the variables.

However, the cost functions show a high variation as a function of the configurations, and thus a high sensitivity of the building typologies shows in the cost functions. This corresponds with the definition of the model, where the building typologies define the variables of the objective function equally with the layout typologies.

9.2. Comparison of organization typology

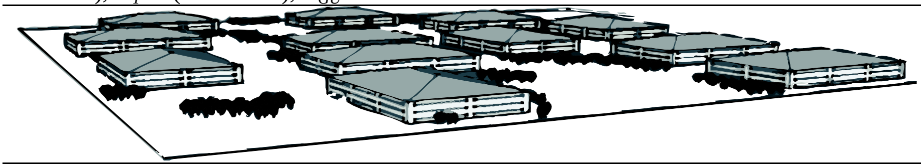
This subsection analyzes the sensitivity of the organization typologies in the functional distribution and in the cost functions. Firstly, the subsection will outline the functional distribution as a mean example of one simulation consisting of 10 generations.

The configurations of 9.1 showed an eased optimization with extended optimization Even the weakly defined correlations of wards and examination rooms were achieved. The organization typology of 9.1 was the functionally split organization typology, and it was expected that the extended correlation between wards and examination rooms were reserved for the sectorized typology. A curiosity of the design model's handling of the sectorized typology drives the following analysis, along with a questioning of the sensitivity of the organization typology.

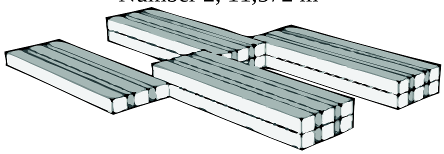
The organization typology influences the hospital construction in Denmark in waves. The Danish hospital constructions initiated in 2005 followed the sectorized organization typology, and the projects initiated from 2010 started taking the functionally split-approach (1). The arguments for and against one approach or another are the same, and evidence in research for the typologies is very limited.

This subsection attempts to outline the differences by the typologies within the design model. Firstly, there will be an analysis of the functional distribution. The functional distribution of the former simulations takes part of the comparison. They are enclosed in Appendix C.

Table 9-1 Example of functional distribution generated by B_T=3 (Campus), L_T=3 (Double corridor), O_T=2 (Sectorized), N_{GU} = 5 units.

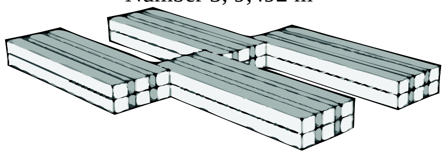


Number 2, 11,572 m²



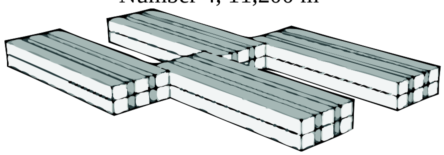
	Functionalities in unit
6	OP
15	Kardiologi, us
18	Reumatologi, us
27	Urologi, seng
32	Nefrologi, us
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi

Number 3, 9,492 m²



	Functionalities in unit
5	Intensiv, seng
7	Opvågning
11	Diagnostik, admin
16	Endokrinologi, seng
59	Obstetrik/Pædiatri, admin

Number 4, 11,200 m²



	Functionalities in unit	Costs
20	Intern medicin, us	
43	Neurologi, seng	
48	Psykiatri, seng	
50	Psykiatri, b/u, seng	
53	Psykiatri, admin	
58	Obstetrik, us/føde	

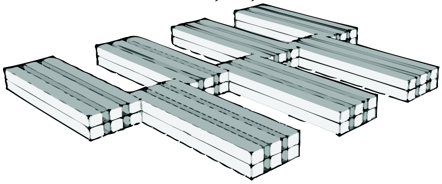
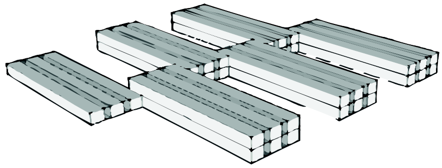
	Number 5, 30,888 m^2		Number 1, 24,849 m^2
			
	Functionalities in unit		Functionalities in unit
3	Akut, us, diag, skadest	1	Akutseng, somatik
8	Intensiv, admin	2	Akutseng, psyakiatri
9	Diagnostik	4	Akut, admin, vagtvær
10	Laboratorium	19	Intern medicin, seng
12	Lungemed, seng	25	Kirurgi, seng
13	Lungemed, us	29	Gastroenhed, seng
14	Kardiologi, seng	31	Nefrologi, seng
17	Endokrinologi, us	33	Gynækologi, seng
21	Ortopædkirugi, seng	34	Gynækologi, us
22	Ortopædkirurgi, us	36	Otologi, us
23	Arbejdsmedicin, us	38	Onkologi, seng
24	Admin, lung, kar, endo,	40	Hæmatologi, seng
26	reuma, intern, orto, arbejds	42	Admin, onkologi,
28	Kirurgi, us	44	hæmatologi
30	Urologi, us	45	Neuroreha/fysiol, seng
35	Gastroenhed, us	46	Oftalmologi, seng
39	Otologi, seng	47	Neuro, us
41	Onkologi, us	51	neuro, admin
49	Hæmatologi, us	52	Psykiatri, b/u, us
56	Psykiatri, v, us	54	Psykiatri, us
61	Fødestue	55	Pædiatri, seng
	Patienthotel	57	Pædiatri, us
		60	Obstetrik, seng
		62	Administration og
		63	forskning
		64	Ernæringsenheden
		65	Ergoterapi og fysioterapi
		66	Kirkerum og kapel
			Køkken og kantine
			Apotek

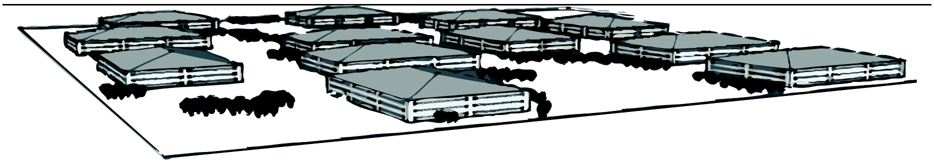
Table 9-1 proposes two units of wards and respective examination rooms. The sectorized distribution is more extensive than the functionally split configurations of 9.1. However, the distributions of 9.1, enclosed in Appendix C, had an unexpected high presence of correlations between wards and respective examination rooms. The example of Table 9-1 shows a different distribution of two parallel units (unit numbers 1 and 5) consisting of wards and examination rooms compared to the tables of Appendix C, where one single unit of correlated wards and examination rooms characterized the distributions. However, the similarities in the distributions are extensive, possibly caused by the less constrained configuration of principal drivers of subsection of 9.1. There is a tendency of similar distributions, despite the different organization typologies.

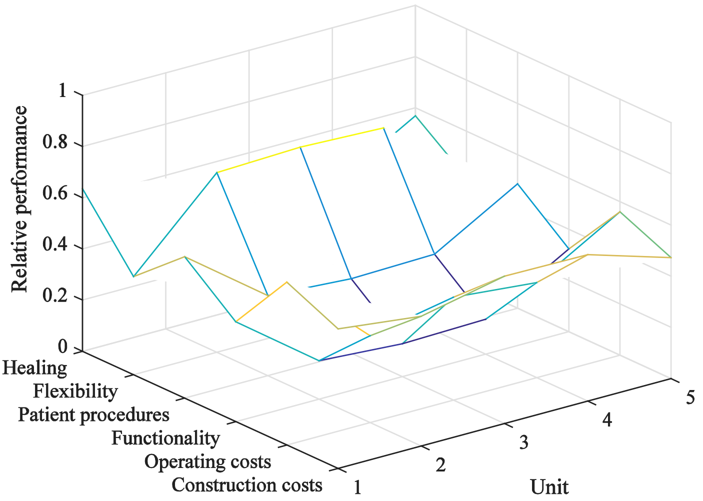
The organization typologies differ in the input data with different correlation matrices, Appendix A and Appendix B. The correlation matrices index the functionalities differently, as described in Chapter 4. The sensitivity of organization typologies is definitely less than expected, because of the weak but different distributions in Table 9-1 in comparison to the distributions of 9.1 in Appendix C.

However, the cost functions across the typologies are more differentiated, and so a sensitivity in terms of costs is present. As described in Chapter 5, the organization typologies imply the functionality distribution directly by the different indexation in the correlation matrix, and so a direct differentiation is present in the definition of costs, because the number of required correlated functionalities differs.

The directly influenced cost by indexation of principal drivers is limited to flexibility, as defined in Chapter 5. In the results, this direct indexation is present in Figure 9-5, where the costs of flexibility are 0.6 responding the costs in terms of the sectorized organization. These are 0.7 in Figure 9-3 for the functionally split organization. This corresponds to the philosophies of the organization typologies, where the functional split argues for higher flexibility in terms of sharing functionalities across specialties.

The functionality of the sectorized configuration with a cost of 0.2 is lower than in the functionally split configuration of 0.3. This confirms the anticipation of higher functionality within the specialties and patient treatments in the sectorized configuration, because there is a potential in sharing functionalities and distributing workloads across specialties.





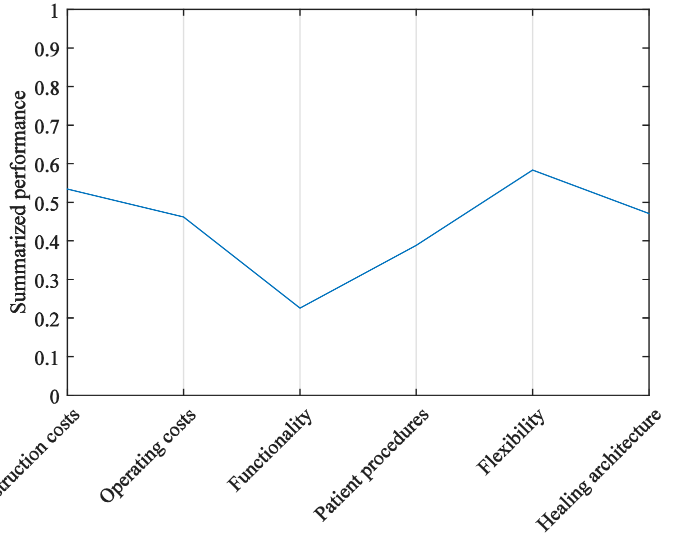


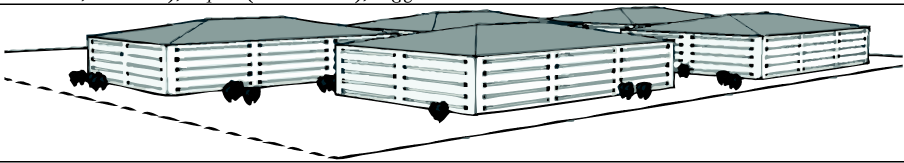
Figure 9-5 Mean costs of functional distributions after 10 simulations, B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 2 (Sectorized), N_{GU} = 5 units.

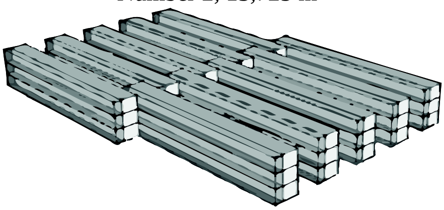
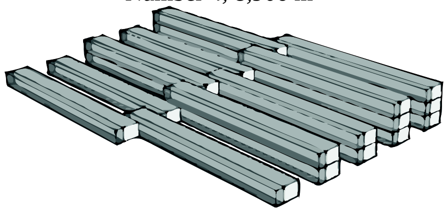
In general, the functionality distributions are examples of distribution of functionalities within the framework given by the principal drivers. The design concepts illustrated in tables and figures are geometric reflections for further architectural exploration by architects, hospital planners and engineers. One reason for the strong parallels between the two organization typologies could be the fact that the examples are derived from the mean generation of each simulation. Moreover, the less constrained configuration of 9.1 as mentioned earlier can facilitate the optimized functionality distribution for the functionally split configuration.

9.3. Comparison of design configuration by layout typologies

This subsection analyzes the impact of layout typologies. Similar to above, the examples are the mean distribution of each simulation. The following illustrates the functionality distributions of the single corridor typologies, succeeding the double corridor of the two previous subsections.

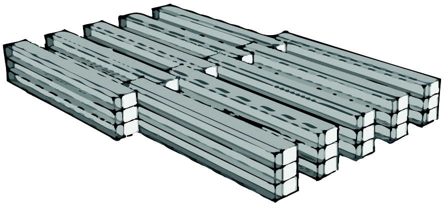
Table 9-2 Example of functional distribution generated by B_T=2 (Urban), L_T=1 (Single corridor, exterior), O_T=2 (Sectorized), N_{GU} = 5 units.



Number 2, 13,725 m^2		Number 4, 8,906 m^2	
			
Functionalities in unit		Functionalities in unit	
23	Arbejdsmedicin, us	21	Ortopædkirugi, seng
51	Psykiatri, b/u, us	25	Kirurgi, seng
53	Psykiatri, admin	29	Gastroenhed, seng
60	Administration og forskning	43	Neurologi, seng
62	Ernæringsenheden	52	Psykiatri, us
63	Ergoterapi og fysioterapi	54	Pædiatri, seng
65	Køkken og kantine	59	Obstetrik/Pædiatri, admin
66	Apotek	64	Kirkerum og kapel

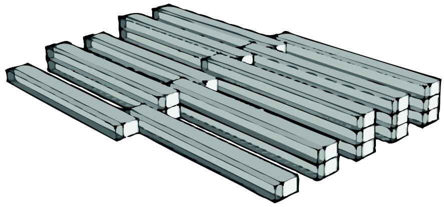
Number 1, 32,716 m^2

36



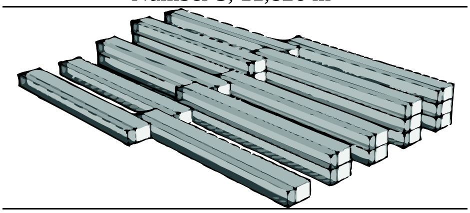
1	Akutseng, somatik
4	Akut, admin, vagtvær
5	Intensiv, seng
7	Opvågning
8	Intensiv, admin
9	Diagnostik
11	Diagnostik, admin
12	Lungemed, seng
14	Kardiologi, seng
20	Intern medicin, us
26	Kirurgi, us
31	Nefrologi, seng
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi
38	Onkologi, seng
40	Hæmatologi, seng
42	Admin, onkologi, hæmatologi
46	Neuro, us
48	Psykiatri, seng
49	Psykiatri, v, us
55	Pædiatri, us

Number 3, 20,833 m^2



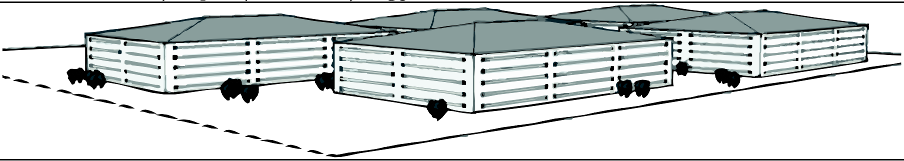
2	Akutseng, psyakiatri
3	Akut, us, diag, skadest
10	Laboratorium
13	Lungemed, us
15	Kardiologi, us
17	Endokrinologi, us
18	Reumatologi, us
22	Ortopædkirurgi, us
27	Urologi, seng
28	Urologi, us
30	Gastroenhed, us
32	Nefrologi, us
33	Gynækologi, seng
34	Gynækologi, us
35	Otologi, seng
36	Otologi, us
39	Onkologi, us
41	Hæmatologi, us
44	Neuroreha/fysiol, seng
45	Oftalmologi, seng
47	Neuro, admin
57	Obstetrik, seng
58	Obstetrik, us/føde

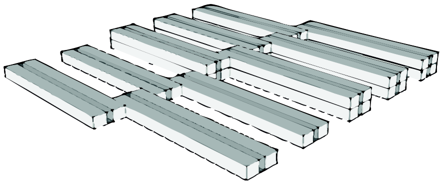
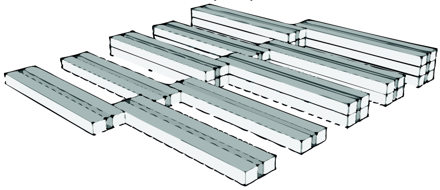
Number 5, 11,826 m^2

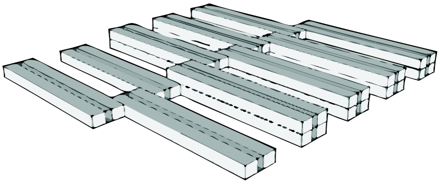
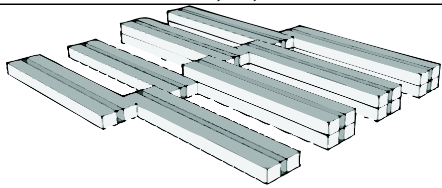
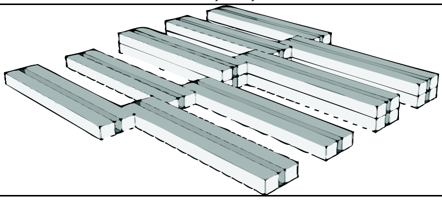


6	OP
16	Endokrinologi, seng
19	Intern medicin, seng
24	Admin, lung, kar, endo,
50	reuma, intern, orto, arbejds
56	Psykiatri, b/u, seng
61	Fødestue
	Patienthotel

Table 9-3 Example of functional distribution generated by B_T=2 (Urban), L_T=2 (Single corridor, interior), O_T=2 (Sectorized), N_{GU} = 5 units.



Number 2, 22,334 m^2		Number 3, 26,726 m^2	
			
Functionalities in unit		Functionalities in unit	
2	Akutseng, psyakiatri	1	Akutseng, somatik
9	Diagnostik	4	Akut, admin, vagtvær
11	Diagnostik, admin	5	Intensiv, seng
13	Lungemed, us	7	Opvågning
15	Kardiologi, us	8	Intensiv, admin
17	Endokrinologi, us	14	Kardiologi, seng
18	Reumatologi, us	16	Endokrinologi, seng
20	Intern medicin, us	19	Intern medicin, seng
28	Urologi, us	21	Ortopædkirugi, seng
30	Gastroenhed, us	22	Ortopædkirurgi, us
34	Gynækologi, us	23	Arbejdsmedicin, us
36	Otologi, us	25	Kirurgi, seng
42	Admin, onkologi, hæmatologi	27	Urologi, seng
46	Neuro, us	29	Gastroenhed, seng
47	neuro, admin	38	Onkologi, seng
48	Psykiatri, seng	43	Neurologi, seng
49	Psykiatri, v, us	44	Neuroreha/fysiol, seng
51	Psykiatri, b/u, us	45	Oftalmologi, seng
52	Psykiatri, us	50	Psykiatri, b/u, seng
54	Pædiatri, seng	57	Obstetrik, seng
55	Pædiatri, us	60	Administration og forskning
56	Fødestue		
59	Obstetrik/Pædiatri, admin		
61	Patienthotel		

Number 1, 12,487 m^2		Number 5, 15,414 m^2	
			
Functionalities in unit		Functionalities in unit	
3	Akut, us, diag, skadest	24	Admin, lung, kar, endo,
10	Laboratorium	37	reuma, intern, orto, arbejds
31	Nefrologi, seng	53	Admin, kirurgi, urologi,
33	Gynækologi, seng	62	gastro, Nefro, gyn, otologi
35	Otologi, seng	63	Psykiatri, admin
40	Hæmatologi, seng	65	Ernæringsenheden
41	Hæmatologi, us	66	Ergoterapi og fysioterapi
64	Kirkerum og kapel		Køkken og kantine
Number 4, 11,045 m^2			Apotek
			
Functionalities in unit			
6	OP		
12	Lungemed, seng		
26	Kirurgi, us		
32	Nefrologi, us		
39	Onkologi, us		
58	Obstetrik, us/føde		

The functional distributions by layout typologies do not differ significantly across the different configurations. There are several parallels in Table 9-1, Table 9-2 and Table 9-3, representing the double corridor, the single corridor-exterior and the single corridor-interior respectively. The tendency of correlating wards and examination rooms is exhaustive. Compared to the examples of 9.1 with one unit of combined ward and examination rooms, these examples possess consistently two units of correlated wards and examination rooms. This tendency emphasizes the stated tendency of subsection 9.2: a behavior of frequently correlating examination rooms and wards in two units for the sectorized organization typology. The functionality distributions across layout typologies support this statement.

In the definition of the design model in the intermediate construction, the layout typologies are decisive in defining design variables. The layout typologies provide a given area for the functionality distributions based on the typological dimensions and the random number generator. However, the functionality distributions show parallel distributions for the different typologies. For layout typology 1, in Table

9-2, the area of the geometric units ranges from 8,906 m^2 to 32,716 m^2, for layout typology 3, in Table 9-1, the range is 9,492 m^2 to 30,488 m^2, and for layout typology 4 the range is 8,930 m^2 to 34,665 m^2. Hence, there is no direct relation of the different typology dimensions and the area of the geometric units. The area adjusts according to the weighted summarized objective function, where the area is inherent in all performance objectives, and so, there are no preferences of similar sizes or different sizes of the units. It is the functionalities and their correlation that are decisive. The layout typologies provide the framework for the functionality distribution as a dimensioning constraint of the intermediate construction, as described and defined in 7.2. However, the decisive parameter in the definition of the geometric units is the correlation matrix and the dimensioning of the functionalities.

The functionality distributions across the layout typologies correspond, and this subsection confirms the tendency outlined in subsection 9.2. The correlations drive the functionality distribution, and the decisive principal driver of the functionality distribution is the organization typology.

The parallels in the distributions correspond with the pattern configurations. An elaborated pattern shows in the functionally split configuration indifferent of the layout typologies. The pattern for the sectorized is less articulated, which corresponds to the tendency of splitting the correlated wards and examination rooms in two units instead of one. Splitting the wards and examination rooms causes fewer repetitions in correlations, as the split is different from simulation to simulation, as outlined in Table 9-1, Table 9-2 and Table 9-3.

The layout typologies are, as mentioned, decisive in the definition of design variables in the intermediate construction. The layout typologies provide, along with the random number generator, the dimensions for the functionality distributions. Moreover, the layout typologies are directly inherent in the cost functions. The indexation by principal drivers represents contradicting costs by the layout typologies. The term of the cost function as a function of the functional distribution includes the dimensions and qualities of the layout typologies.

The layout typologies directly affect the cost functions in both terms. Subsection 7.2.3 outlines L_T, the first term of the indexation by principal drivers, with a matrix. The layout typologies also directly affect the second term, the function of the functional distribution as they define the framework of the functional distributions. Moreover, the layout typologies as construction of the dimensioning of the geometric units influence the geometry essentially. The qualities of the typologies imply the performance evaluators and thereby the cost functions. The following subsection outlines the cost functions for the different layout configurations in order to analyze the impact of layout typologies in terms of cost functions and the sensitivity of layout typologies within the model.

In the comparison across layout typologies, the below summarized cost function as a function of the costs of the six performance evaluators provide the immediate transparency. However, the upper surface diagram displays the variation across units in the given configurations. This is very valuable in illustrating the differentiation across the hospital configuration. It is apparent how the functional distributions give preference to two units of correlated wards and examination rooms. In the examples of the functionally split configuration in 9.1, the cost functions corresponded to the correlation of wards and examination rooms with one unit of costs reaching the upper boundary. The cost functions in the following are more equal across the units, and a correspondence of high costs in the units of correlated wards and examination rooms is not seen, unambiguously. Furthermore, a unit of several correlated psychiatric facilities reflects high costs (see Figure 9-7).

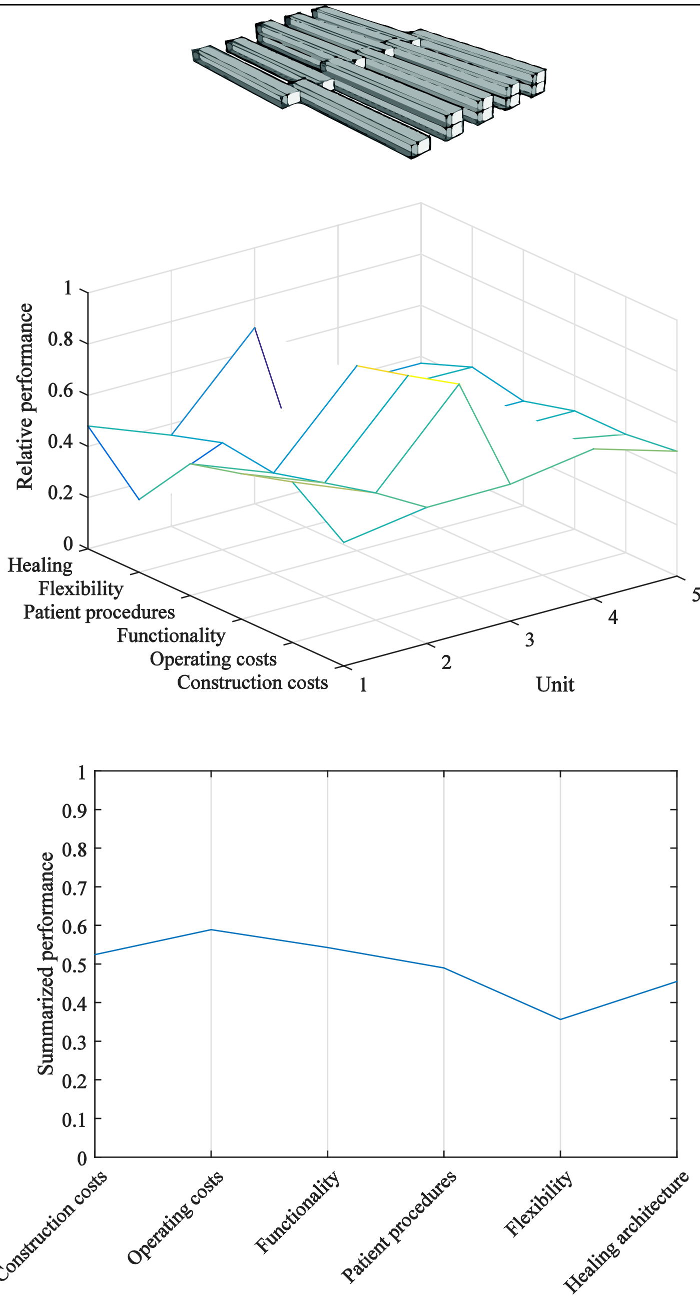


Figure 9-6 Mean costs of functional distributions after 10 simulations, B_T =2 (Urban), L_T = 1 (Single corridor, exterior), O_T = 2 (Sectorized), N_{GU} = 5.

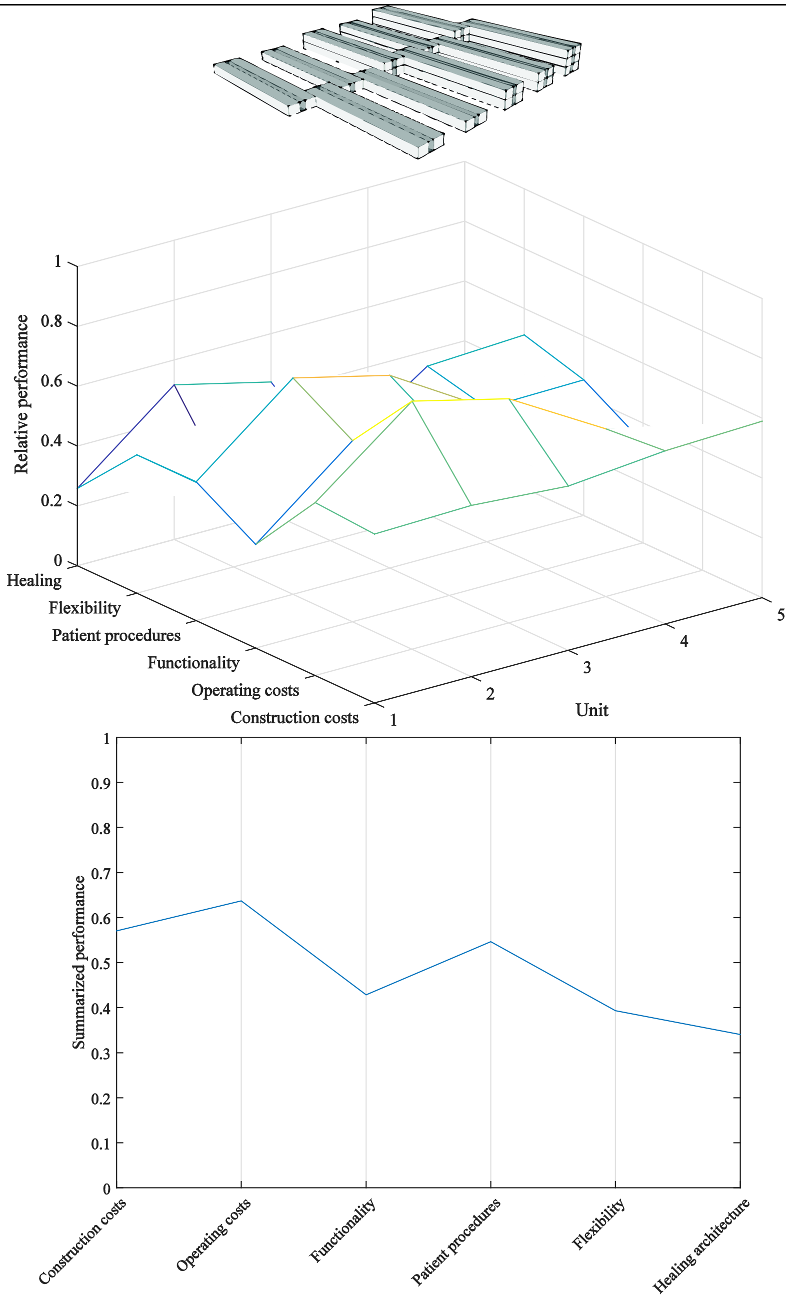


Figure 9-7 Mean costs of functional distributions after 10 simulations, B_T =2 (Urban), L_T = 2 (Single corridor, interior), O_T = 2 (Sectorized), N_{GU} = 5.

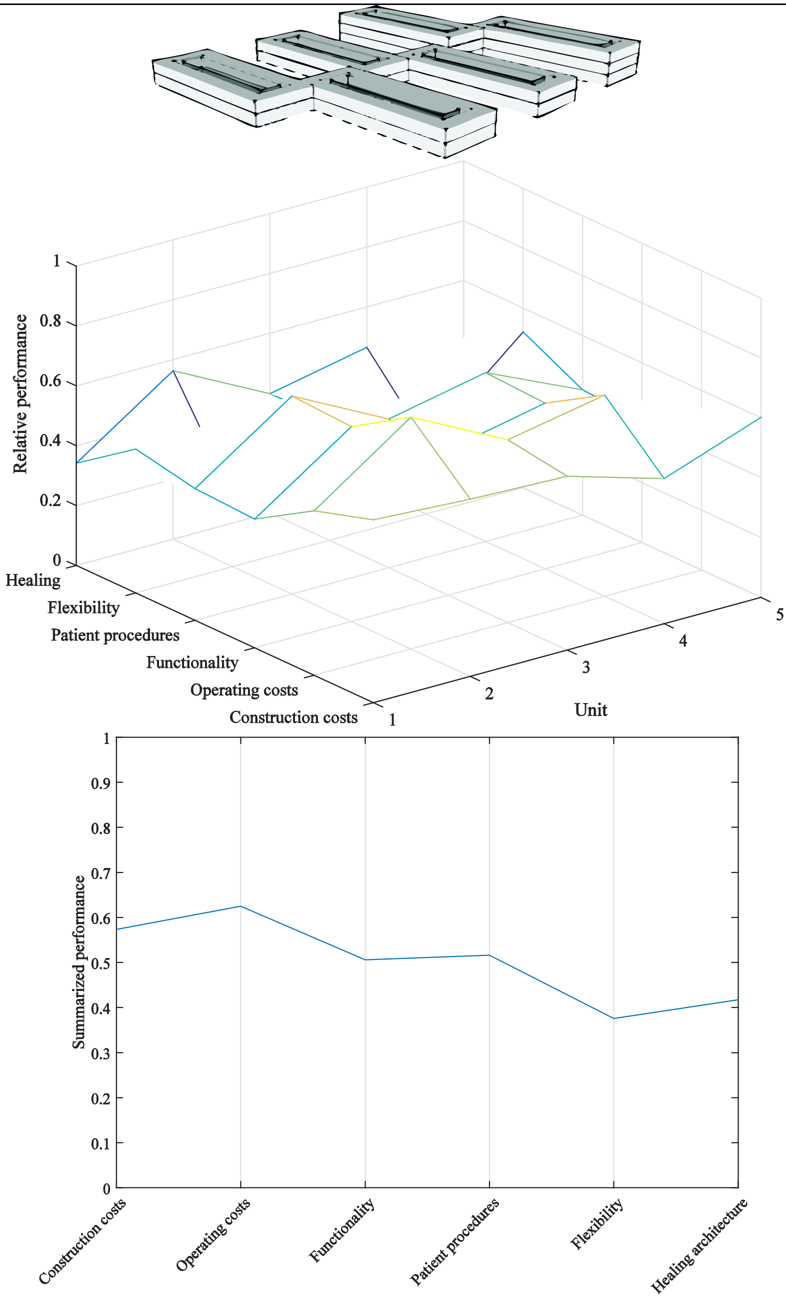


Figure 9-8 Mean costs of functional distributions after 10 simulations, B_T =2 (Urban), L_T = 4 (Courtyard, exterior), O_T = 2 (Sectorized), N_{GU} = 5.

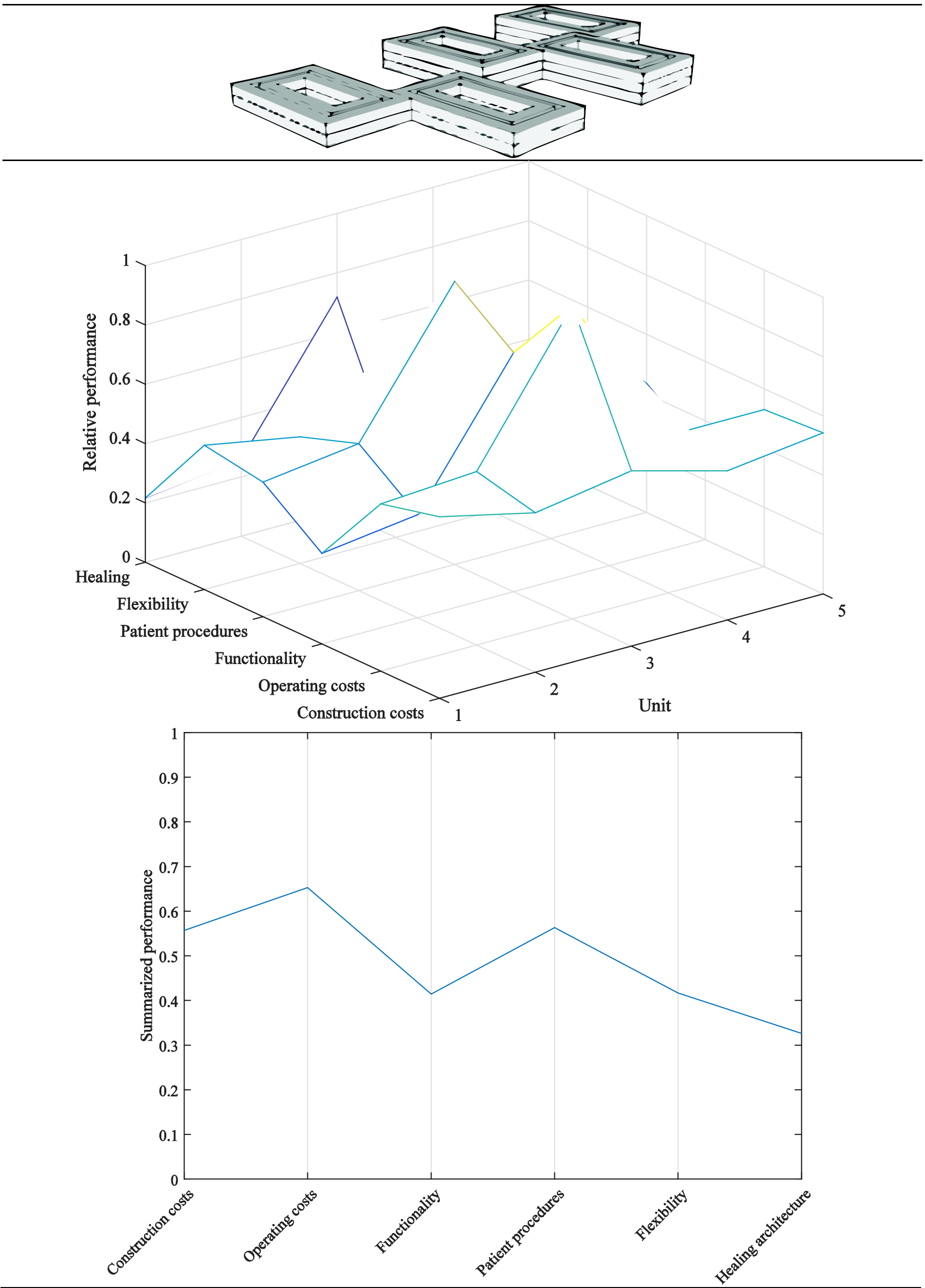


Figure 9-9 Mean costs of functional distributions after 10 simulations, B_T =2 (Urban), L_T = 5 (Courtyard, interior), O_T = 2 (Sectorized), N_{GU} = 5.

The summarized costs across the typologies differ remarkably. The single corridor in Figure 9-6 is quite average in all summarized cost evaluations, but also across the units. In Figure 9-7 the other single corridor has more similarities to the courtyard in Figure 9-8 and Figure 9-9, with varying costs. The operational costs increase when the layout typology size increases.

The functionality is highest in typologies one and four, where the unit size is delimited and professional unison encouraged. The costs of healing architecture follow the tendencies of functionality with increased cost function in smaller units.

It is remarkable and unexpected how the courtyard typology with interior corridor has a similar level of healing architecture as the single corridor. It was expected that the presence of a courtyard for integration of atmosphere, green areas and natural settings in the architectural configuration provided increased cost functions for healing architecture. The counter for healing architecture in the courtyard typology compared to the interior corridor appears to be the size, and thereby the relation of area and façade. Moreover, the typology is remarkably larger than other typologies, whereby proximity to the exterior and green areas apparently is not inherent and sufficient in comparison to the other smaller typologies. The potential of integrating green areas and natural settings in the smaller typologies is extensive in the subsequent architectural exploration. This perspective appears decisive in the low healing architecture cost of the courtyard typology with interior corridor.

The typologies provide obvious different costs for the performance evaluators, even with similar functionality distributions. The different performance evaluators evidently influence the cost functions, and the sensitivity of layout typologies is high. This corresponds to general practice, where the definition of the layout principle is decisive in the hospital. Moreover, it corresponds with the definition of the design model, where the layout typologies are decisive in defining the design variables and in the definition of the cost functions. The layout typologies imply both the term of indexation by the principal drivers and the function of the functionality distribution. The cost functions provide a clear understanding of the qualities and consequences by the different typologies, even with similar functionality distributions.

9.4. Comparison of impact by number of units, N_{GU}

The analysis of consistency and pattern configuration in 8.3.3 shows a high impact of number of geometric units, N_{GU}. The patterns show how the optimization problem becomes more constrained with the increased number of geometric units, N_{GU}.

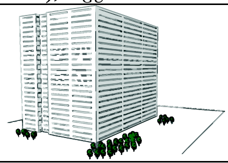
This subsection analyzes the impact of number and geometric units as a principal driver. The number of geometric units is a perspective directly implemented from practice. Practice focus much on professional unisons and definition of clusters, as their N_{GU}, which often is dertermined initially. By this design model, the number of clusters or N_{GU} can vary throughout the design processes in order to analyze the performances. It is evident that it is possible to evaluate the performances of design configurations with different number of geometric units to support the decision-making. Consequently, the following subsection analyzes the design configurations generated by a different number of geometric units in order to extract tendencies in distributions and costs.

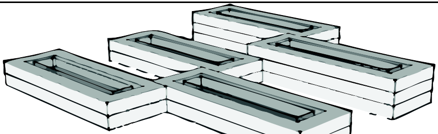
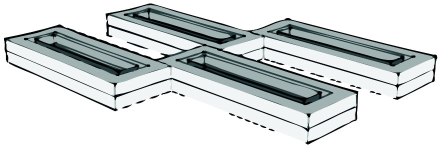
As already stated, an increase in the number of geometric units will constrain the optimization problem. This subsection also analyzes this perspective.

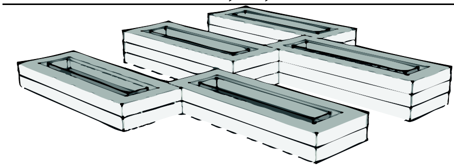
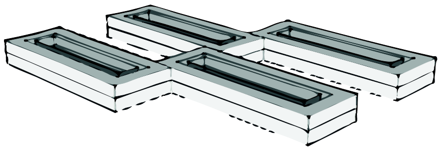
This section illustrates some of the functionality distributions by the different configurations of N_{GU}, the remaining are enclosed in Appendix D. N_{GU} = 5 is broadly illustrated in the previous sections, and so this analysis starts by illustrating the design configuration by N_{GU} = 6.

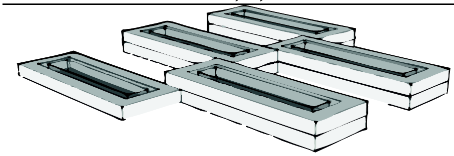
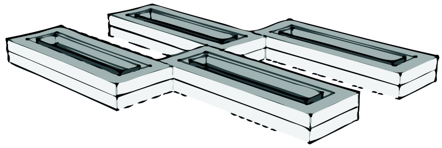
Firstly, the subsection analyzes the functional distributions followed by the cost functions. The illustrations of the cost functions are enclosed in Appendix D.

Table 9-4 Example of functional distribution generated by B_T=1 (High-rise), L_T=4 (Courtyard, exterior), O_T=2 (Sectorized), N_{GU} = 6 units.



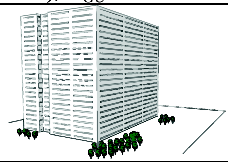
Number 1, 16,817 m^2		Number 2, 15,489 m^2	
			
Functionalities in unit		Functionalities in unit	
9	Diagnostik	5	Intensiv, seng
10	Laboratorium	24	Admin, lung, kar, endo, reuma, intern, orto, arbejds
11	Diagnostik, admin	27	Urologi, seng
13	Lungemed, us	49	Psykiatri, v, us
21	Ortopædkirugi, seng	53	Psykiatri, admin
		54	Pædiatri, seng

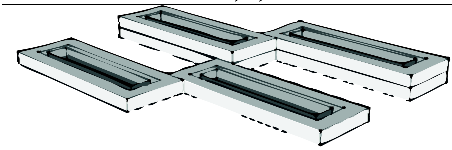
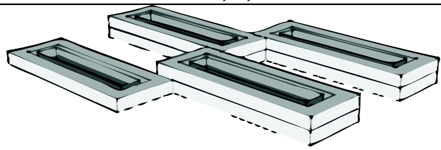
Number 3, 21,788 m^2		Number 4, 16,199 m^2	
			
Functionalities in unit		Functionalities in unit	
1	Akutseng, somatik	17	Endokrinologi, us
6	OP	23	Arbejdsmedicin, us
7	Opvågning	26	Kirurgi, us
8	Intensiv, admin	28	Urologi, us
14	Kardiologi, seng	29	Gastroenhed, seng
15	Kardiologi, us	30	Gastroenhed, us
22	Ortopædkirurgi, us	32	Nefrologi, us
31	Nefrologi, seng	34	Gynækologi, us
33	Gynækologi, seng	36	Otologi, us
43	Neurologi, seng	37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi
47	neuro, admin	38	Onkologi, seng
48	Psykiatri, seng	46	Neuro, us
50	Psykiatri, b/u, seng	57	Obstetrik, seng
52	Psykiatri, us	58	Obstetrik, us/føde
56	Fødestue	59	Obstetrik/Pædiatri, admin
64	Kirkerum og kapel	60	Administration og forskning
		61	Patienthotel

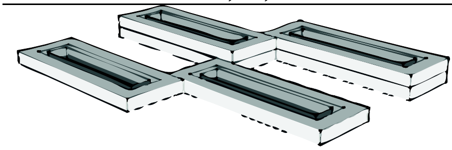
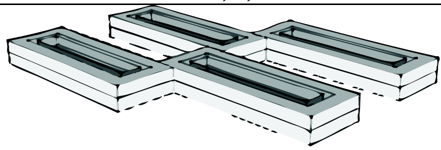
Number 5, 8,924 m^2		Number 6, 87,89 m^2	
			
Functionalities in unit		Functionalities in unit	
2	Akutseng, psyakiatri	3	Akut, us, diag, skadest
4	Akut, admin, vagtvær	12	Lungemed, seng
16	Endokrinologi, seng	18	Reumatologi, us
19	Intern medicin, seng	44	Neuroreha/fysiol, seng
20	Intern medicin, us	62	Ernæringsenheden
25	Kirurgi, seng	63	Ergoterapi og fysioterapi
35	Otologi, seng	65	Køkken og kantine
39	Onkologi, us	66	Apotek
40	Hæmatologi, seng		
41	Hæmatologi, us		
42	Admin, onkologi, hæmatologi		
45	Oftalmologi, seng		
51	Psykiatri, b/u, us		
55	Pædiatri, us		

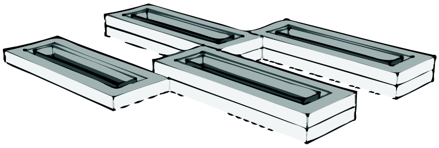
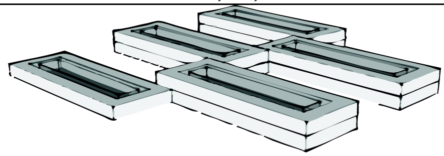
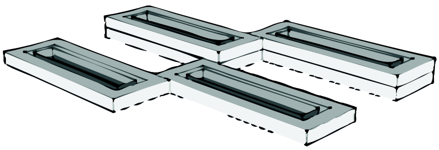
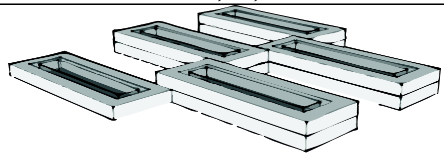
In the simulation of N_{GU} = 6, all units include some examination rooms and wards, mostly correlated. The simulation presents a design configuration with similarities to N_{GU} = 5, as in 9.1, 9.2 and 9.3. However, the pattern configuration becomes remarkably weaker, and the wards and examination rooms start splitting up against the required correlations in the input matrix.

Table 9-5 Example of functional distribution generated by B_T=1 (High-rise), L_T=4 (Courtyard, exterior), O_T=2 (Sectorized), N_{GU} = 8 units.



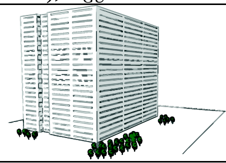
Number 1, 5,953 m^2		Number 2, 6,896 m^2	
			
Functionalities in unit		Functionalities in unit	
17	Endokrinologi, us	8	Intensiv, admin
21	Ortopædkirugi, seng	12	Lungemed, seng
32	Nefrologi, us	20	Intern medicin, us
62	Ernæringsenheden	38	Onkologi, seng
63	Ergoterapi og fysioterapi	40	Hæmatologi, seng
66	Apotek	44	Neuroreha/fysiol, seng
		45	Oftalmologi, seng
		46	Neuro, us

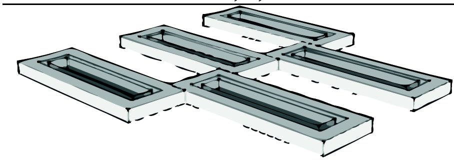
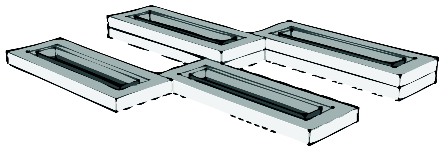
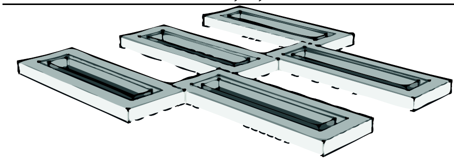
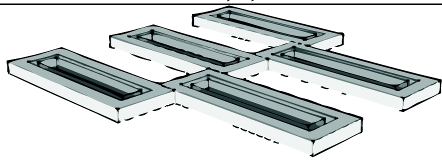
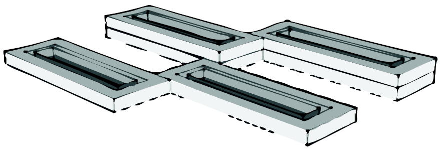
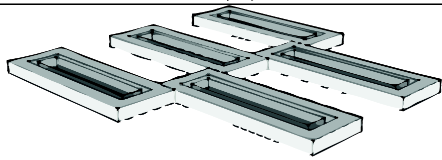
Number 3, 11,930 m^2		Number 4, 7,926 m^2	
			
Functionalities in unit		Functionalities in unit	
1	Akutseng, somatik	11	Diagnostik, admin
2	Akutseng, psyakiatri	26	Kirurgi, us
3	Akut, us, diag, skadest	41	Hæmatologi, us
4	Akut, admin, vagtvær	42	Admin, onkologi, hæmatologi
7	Opvågning	50	Psykiatri, b/u, seng
13	Lungemed, us	51	Psykiatri, b/u, us
19	Intern medicin, seng	52	Psykiatri, us
22	Ortopædkirurgi, us	54	Pædiatri, seng
36	Otologi, us	56	Fødestue
47	neuro, admin		

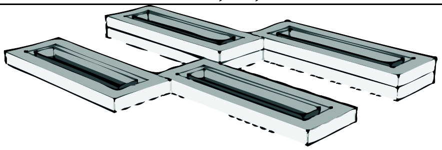
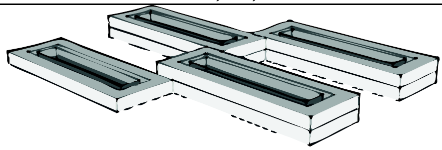
	Number 5, 14,234 m^2		Number 6, 11,869 m^2
			
	Functionalities in unit		Functionalities in unit
25	Kirurgi, seng	6	OP
31	Nefrologi, seng	9	Diagnostik
33	Gynækologi, seng	15	Kardiologi, us
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	18	Reumatologi, us
48	Psykiatri, seng	23	Arbejdsmedicin, us
55	Pædiatri, us	27	Urologi, seng
59	Obstetrik/Pædiatri, admin	35	Otologi, seng
60	Administration og forskning	43	Neurologi, seng
64	Kirkerum og kapel		
	Number 7, 10,862 m^2		Number 8, 18,336 m^2
			
	Functionalities in unit		Functionalities in unit
49	Psykiatri, v, us	5	Intensiv, seng
53	Psykiatri, admin	10	Laboratorium
57	Obstetrik, seng	14	Kardiologi, seng
61	Patienthotel	16	Endokrinologi, seng
65	Køkken og kantine	24	Admin, lung, kar, endo, reuma, intern, orto, arbejds
		28	Urologi, us
		29	Gastroenhed, seng
		30	Gastroenhed, us
		34	Gynækologi, us
		39	Onkologi, us
		58	Obstetrik, us/føde

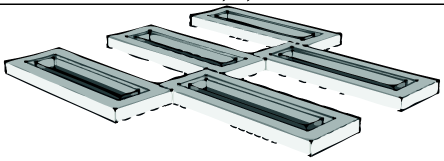
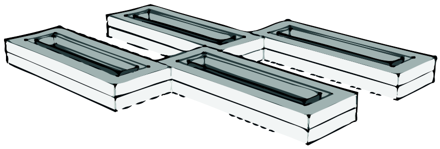
10 generations of satisfied constraints simulated the functionality distribution for N_{GU} = 8. The expected increase in the constrained problem by N_{GU} = 8 does not cause the optimization to terminate prematurely without having satisfied the constraints. The mixture of wards and examination rooms increases, and the correlation of the respective functionalities decreases. The increased constrained problem provides a visibly poorer optimized functionality distribution.

Table 9-6 Example of functional distribution generated by B_T=1 (High-rise), L_T=4 (Courtyard, exterior), O_T=2 (Sectorized), N_{GU} = 10 units.



Number 1, 9,346 m^2		Number 4, 10,431m^2	
			
Functionalities in unit		Functionalities in unit	
3	Akut, us, diag, skadest	1	Akutseng, somatik
11	Diagnostik, admin	7	Opvågning
22	Ortopædkirurgi, us	8	Intensiv, admin
23	Arbejdsmedicin, us	38	Onkologi, seng
30	Gastroenhed, us	44	Neuroreha/fysiol, seng
37	Admin, kirurgi, urologi, gastro, Nefro,	54	Pædiatri, seng
	gyn, otologi	61	Patienthotel
Number 2, 6,709 m^2		Number 3, 5,296m^2	
			
Functionalities in unit		Functionalities in unit	
6	OP	34	Gynækologi, us
13	Lungemed, us	46	Neuro, us
17	Endokrinologi, us	60	Administration og forskning
56	Fødestue	63	Ergoterapi og fysioterapi
64	Kirkerum og kapel		
Number 7, 6,943m^2		Number 8, 5,281m^2	
			
Functionalities in unit		Functionalities in unit	
18	Reumatologi, us	47	Neuro, admin
24	Admin, lung, kar, endo, reuma, intern,	48	Psykiatri, seng
31	orto, arbejds	51	Psykiatri, b/u, us
33	Nefrologi, seng	66	Apotek
42	Gynækologi, seng		
59	Admin, onkologi, hæmatologi		
	Obstetrik/Pædiatri, admin		

Number 5, 11,900m^2		Number 6, 13,846 m^2	
			
Functionalities in unit		Functionalities in unit	
5	Intensiv, seng	2	Akutseng, psyakiatri
16	Endokrinologi, seng	9	Diagnostik
19	Intern medicin, seng	10	Laboratorium
21	Ortopædkirugi, seng	20	Intern medicin, us
27	Urologi, seng	26	Kirurgi, us
28	Urologi, us	52	Psykiatri, us
29	Gastroenhed, seng	55	Pædiatri, us
32	Nefrologi, us		
36	Otologi, us		
40	Hæmatologi, seng		
57	Obstetrik, seng		
58	Obstetrik, us/føde		

Number 9, 9,177 m^2		Number 10, 9,077 m^2	
			
Functionalities in unit		Functionalities in unit	
4	Akut, admin, vagtvær	45	Oftalmologi, seng
12	Lungemed, seng	49	Psykiatri, v, us
14	Kardiologi, seng	50	Psykiatri, b/u, seng
15	Kardiologi, us	53	Psykiatri, admin
25	Kirurgi, seng	62	Ernæringsenheden
35	Otologi, seng	65	Køkken og kantine
39	Onkologi, us		
41	Hæmatologi, us		
43	Neurologi, seng		

15 generations simulated the functionality distribution for N_{GU} = 10 before achieving 10 generations of satisfied constraints.

The functionality distributions become less systematic along with an increase in units. This perspective corresponds with the pattern configuration of 8.3.3, where there was a clear distributional pattern for N_{GU} = 5, which vanished along with an increase in N_{GU}. The studies of Chapter 8 argue for a more constrained problem while N_{GU} increases. The analysis of this subsection recognizes that perspective. Analyzing the costs of the different configurations shows remarkably little difference from N_{GU} = 5 to N_{GU} = 10, as enclosed in Appendix D.

When referring to practice, the problem of the design model is recognized. In practice, an increase in units constrains the problem solving. While having more units to distribute the functionalities into, more compromises occur. The compromises follow, to some extent, the delimited individual unit sizes in accordance with the increased numbers of units.

The design model struggles with operating with increased N_{GU}, and the functionality distribution appears weaker while constraining the problem by increasing N_{GU}.

There was an expectation that an increase in N_{GU} would correlate functionalities within professional unisons defined by the biased functionalities of the correlation matrix. The correlation matrix entails biased functionalities, where data has encouraged correlation with similar functionalities for professional unisons. This was expected to influence the results of increased N_{GU}, and thus having this subsection reflect the tendency from practice of operating with more or less fixed entities of defined departments. However, the preferred correlations did not influence the results. An increase in units contradicted this expectation significantly, as the pattern in functionality distributions vanished and randomness appeared to be a driver.

Previous exemplifications have provided remarkable differentiation in the cost function across configuration, while the functionality distributions are similar. For differentiation in $N_{GU,}$ the functionality distributions are remarkably different, while the cost functions enclosed in Appendix D show quite similar costs.

This corresponds with the fact that N_{GU} is not directly inherent in the cost functions like the other principal drivers. The indexation by principal drivers consists of the terms by the matrices of B_T, L_T and O_T, respectively.

According to this subsection, the sensitivity of N_{GU} is very high in terms of the functionality distributions. An increase in N_{GU} implies the operation of the design model, because the solution space becomes more constrained.

The sensitivity of N_{GU} in terms of costs appears to be low, because the similarities in the summarized costs are extensive. This can be a consequence of the constrained design space. The final perspective is that the constrained problem of $N_{GU} = 10$ increases the complexity in the problem solving and a result with decreased quality is the outcome. Consequently, it is recommended to vary N_{GU} from 5-8, which reflects the tendency of practice. Hospitals with 8-10 clusters are rarely seen, commonly there are 5-7 clusters.

9.5. Exemplification of two ‘best’ simulations of one configuration

This subsection elaborates on the usability of the model from a practical perspective. While discussing the usability of the design model the previous use of the mean distributions does not reflect practice. In practice, the approach is to find the best and not average solutions. Accordingly, it is interesting to analyze the best exemplification of one simulation (consisting of 10 generations) and not the mean, because it will reflect practice’s approach. This subsection processes the second research question of the usability of systemized design models when applied to hospital functionality by analyzing the best simulations, as the examples for further architectural exploration. This reflects the applicability of the design model in practice, where the previous subsections elaborates on the functionalities and the evaluations of the design model.

Consequently, the following subsection outlines the two ‘best’ configurations of one simulation. This subsection uses a different presentation of the design configurations, because the configurations both originate from the same simulation, in order to compare the results. Therefore, the unit sizes consist of the same numbers of layout entities, and so the summarized costs are similar, see Appendix E. The functionality distribution differs in the configurations, because of the different optimization procedures of the two generations according to the GA, driving the optimization procedure. The different functionality distributions cause different performances of the units. The costs of the units are essential for illustrating the differentiation of the design configurations, which is why they are illustrated initially.

The costs functions in Figure 9-10 clearly illustrate a functional distribution of a very high number of functionalities in one unit, which Figure 9-10 verifies with the several functionalities in unit 4. The unit consists of more or less all wards and examination rooms.

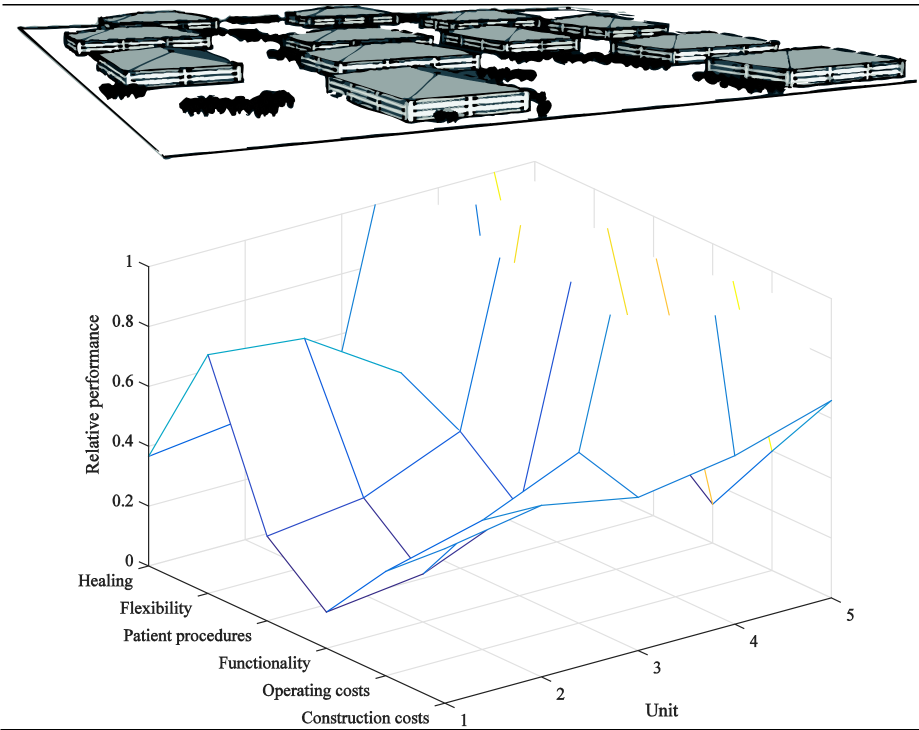
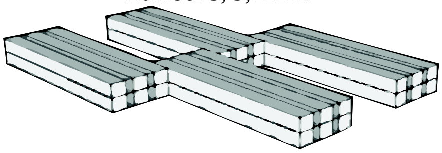


Figure 9-10 Costs of functional distributions, B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally-split), N_{GU} = 5.

The remaining units are defined with a clear definition of the units to psychiatrics, operation, administration and emergency facilities, respectively. This configuration proposes a clear understandable distribution of functionalities that is very consistent with general practice.

Table 9-7 Functional distribution generated by B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally-split), N_{GU} = 5.

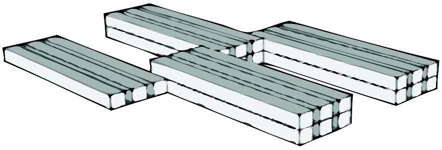
Number 5, 9,722 m^2



Functionalities in unit

53	Psykiatri, admin
62	Ernæringsenheden
63	Ergoterapi og fysioterapi
65	Køkken og kantine
66	Apotek

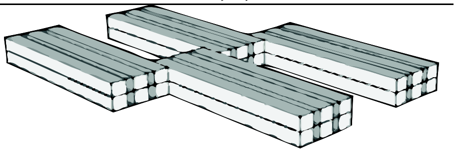
Number 1, 12,960 m^2



Functionalities in unit

1	Akutseng, somatik
5	Intensiv, seng
6	OP
61	Patienthotel

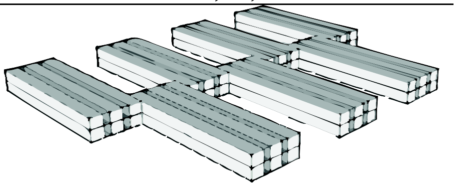
Number 2, 9,626 m^2



Functionalities in unit

9	Diagnostik
48	Psykiatri, seng
49	Psykiatri, v, us
50	Psykiatri, b/u, seng
51	Psykiatri, b/u, us
52	Psykiatri, us

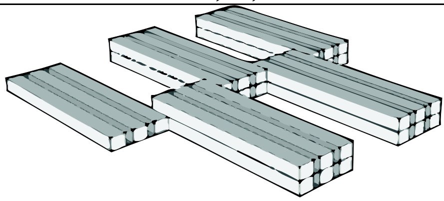
Number 3, 33,914 m^2



Functionalities in unit

2	Akutseng, psyakiatri
3	Akut, us, diag, skadest
4	Akut, admin, vagtvær
8	Intensiv, admin
10	Laboratorium
11	Diagnostik, admin
24	Admin, lung, kar, endo, reuma, intern,
37	orto, arbejds
42	Admin, kirurgi, urologi, gastro, Nefro,
47	gyn, otologi
59	Admin, onkologi, hæmatologi
60	neuro, admin
64	Obstetrik/Pædiatri, admin
	Administration og forskning
	Kirkerum og kapel

Number 4, 21,784 m^2



Functionalities in unit

7	Opvågning
12	Lungemed, seng
13	Lungemed, us
14	Kardiologi, seng
15	Kardiologi, us
16	Endokrinologi, seng
17	Endokrinologi, us
18	Reumatologi, us
19	Intern medicin, seng
20	Intern medicin, us
21	Ortopædkirugi, seng
22	Ortopædkirurgi, us
23	Arbejdsmedicin, us
25	Kirurgi, seng
26	Kirurgi, us
27	Urologi, seng
28	Urologi, us
29	Gastroenhed, seng
30	Gastroenhed, us
31	Nefrologi, seng
32	Nefrologi, us
33	Gynækologi, seng
34	Gynækologi, us
35	Otologi, seng
36	Otologi, us
38	Onkologi, seng
39	Onkologi, us
40	Hæmatologi, seng
41	Hæmatologi, us
43	Neurologi, seng
44	Neuroreha/fysiol, seng
45	Oftalmologi, seng
46	Neuro, us
54	Pædiatri, seng
55	Pædiatri, us
56	Fødestue
57	Obstetrik, seng
58	Obstetrik, us/føde

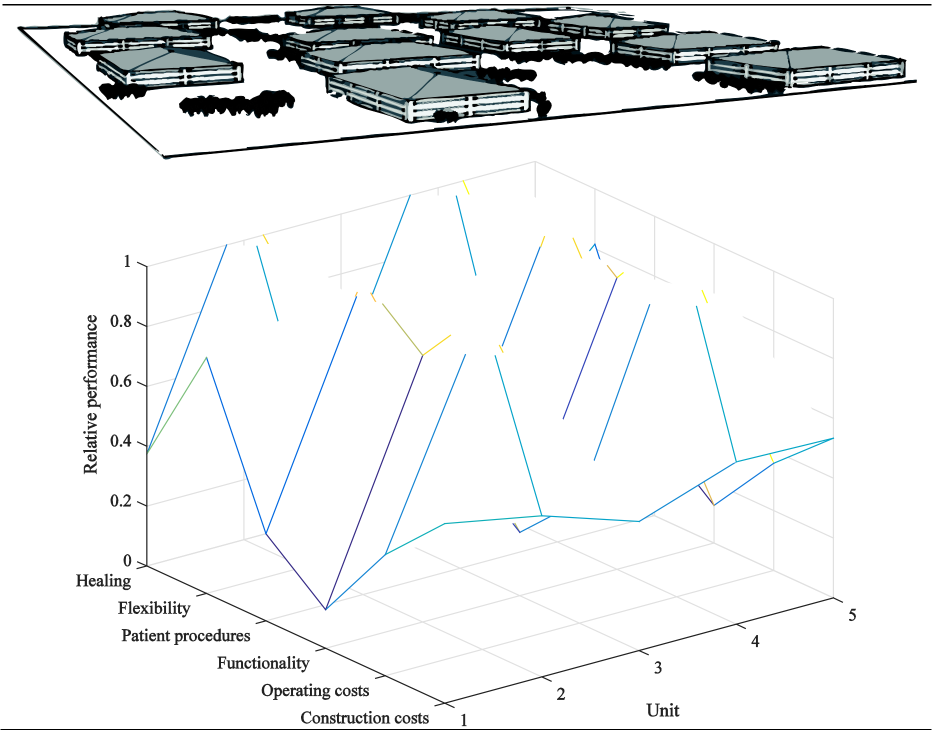
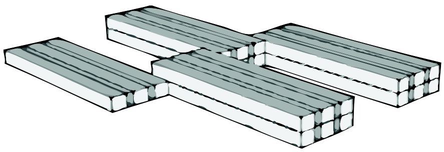
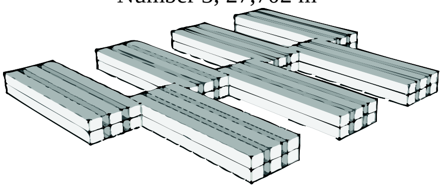
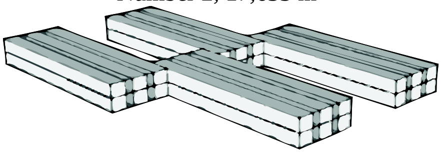


Figure 9-11 Costs of functional distributions, B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally-split), N_{GU} = 5.

Table 9-8 Functional distribution generated by B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally-split), N_{GU} = 5 units.

Number 1, 10,572 m²		Number 3, 27,702 m²	
			
Functionalities in unit		Functionalities in unit	
49	Psykiatri, v, us	2	Akutseng, psyakiatri
53	Psykiatri, admin	3	Akut, us, diag, skadest
62	Ernæringsenheden	4	Akut, admin, vagtvær
63	Ergoterapi og fysioterapi	8	Intensiv, admin
65	Køkken og kantine	10	Laboratorium
66	Apotek	11	Diagnostik, admin
		48	Psykiatri, seng
		50	Psykiatri, b/u, seng
		51	Psykiatri, b/u, us
		52	Psykiatri, us
		60	Administration og forskning

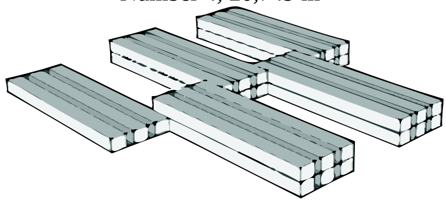
Number 2, 17,633 m^2



Functionalities in unit

7	Opvågning
12	Lungemed, seng
14	Kardiologi, seng
16	Endokrinologi, seng
19	Intern medicin, seng
21	Ortopædkirugi, seng
25	Kirurgi, seng
27	Urologi, seng
29	Gastroenhed, seng
31	Nefrologi, seng
33	Gynækologi, seng
35	Otologi, seng
38	Onkologi, seng
40	Hæmatologi, seng
43	Neurologi, seng
44	Neuroreha/fysiol, seng
45	Oftalmologi, seng
47	neuro, admin
54	Pædiatri, seng
57	Obstetrik, seng
61	Patienthotel
64	Kirkerum og kapel

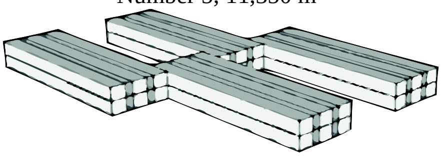
Number 4, 20,749 m^2



Functionalities in unit

9	Diagnostik
13	Lungemed, us
15	Kardiologi, us
17	Endokrinologi, us
18	Reumatologi, us
20	Intern medicin, us
22	Ortopædkirurgi, us
23	Arbejdsmedicin, us
24	Admin, lung, kar, endo, reuma, intern, orto, arbejds
26	Kirurgi, us
28	Urologi, us
30	Gastroenhed, us
32	Nefrologi, us
34	Gynækologi, us
36	Otologi, us
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi
39	Onkologi, us
41	Hæmatologi, us
42	Admin, onkologi, hæmatologi
46	Neuro, us
55	Pædiatri, us
56	Fødestue
58	Obstetrik, us/føde
59	Obstetrik/Pædiatri, admin

Number 5, 11,350 m^2



Functionalities in unit

1	Akutseng, somatik
5	Intensiv, seng
6	OP

The cost functions in Figure 9-11 illustrate a distribution of functionalities into two primary units, number 2 and 4. The upper boundary is reached in these units for the cost functions, except for the construction costs. Table 9-8 verifies the anticipation of a distribution of the functionalities into two main units. All wards correlate in unit 2, and all examination rooms correlate in unit 4.

The functionality distributions show two different ‘best’ simulations, where the organization typology affects the design concepts differently. However, several parallels characterize them and the essential difference is in the distributions of wards and examination rooms. Table 9-7 correlates the wards and examination rooms, and Table 9-8 separates them. The latter follows the anticipation of the organization typology in the functional separation of the two functional typologies, and the former argues for the fact that the total correlation improves the overall quality of the hospital regardless of the biased input matrix.

These examples show the input for further architectural exploration. The high quality in correlation corresponds with the fact that the functionalities are distributed likewise the tendencies of the general practice.

The summarized costs, as enclosed in Appendix E, are equal for the two very different functional distributions. This demonstrates how the objective function of the weighted sum cost function can generate very different design concepts and yield the same objective function. This perspective is an important contribution to practice, because it can qualify the discussions on the functional distributions and the overall performance of the hospital.

9.6. Application of the hospital design model

As stated, the examples are design concepts for further architectural exploration. The resulting geometry of the design model is a representation as presented above, and it take part of the initial design phases of Analysis and Planning & Design, as illustrated in Table 1-2. The design model shows applicability in these phases in design concept generation within the different typological frameworks.

The design concept generation operates with the typologies as contributors to the formal description and evaluators of the concepts. The definition of design concepts on a typological level corresponds with the detailing in the first half of the main phase of Planning & Design and in the main phase of Analysis. In these phases evaluations and visualizations of consequences of design choices give the most value. Contribution of analyses in this early design phases, as illustrated in Figure 1-7, can influence the design more easily than in the late design phases, when the design and construction are developed, and the costs of changes are high. Consequently, the design model contributes with transparency of design consequences and outcome in the initial design phases. Accordingly, the design can develop and architectural design will be developed and explored on qualified information.

The design model can beneficially contribute to analyze project possibilities, project definitions and project planning, in the phases, where practice spends large amounts of time and resources. These phases are, in general, interdisciplinary and the model can contribute in the dialogue where architects, engineers and hospital planners define the framework for the detailed design. The design model contributes with clarification of the sensitivity of the different performance evaluators in terms of typologies, as outlined in 9.3. E.g. Figure 9-6 - Figure 9-9 illustrate fast and reliably the sensitivities in the performance evaluators of the layout typologies.

The figures illustrate the generation and evaluation of alternates in the exploration of design strategies in Planning & Design. These phases are expensive in practice, because the studies traditionally are time-consuming and several professions and persons contribute. Furthermore, the phases are characterized by opaqueness because the consequences of design choices are difficult to estimate and put in perspective of the interdisciplinary problem.

The contribution to the design phase can potentially affect the final hospital designs, where considerations of implication of the performances drive the design. Today, several cost reductions are performed throughout the design process. Potentially, it is possible to avoid some of these. For the ones that will remain, the reductions can be performed with a holistic consideration on all six performance evaluators and their implication respectively.

Furthermore, the design concepts by typologies and especially the sensitivity of the typologies are valuable in the strategic analysis and in the business and technical analysis. These project phases are part of Analysis, typically defining the tender documents in practice, setting the framework for e.g. competitions or the construction projects. In tender documents, preferred correlations outline the requirements. The contour plots of e.g. Figure 9-4 define the preferences and so, they can contribute to set a systematic and evidence-based framework for the design.

The design model can contribute with information while the politicians and those responsible for the hospital define the requirements and preferences of a given hospital. The design model provides visualizations of e.g. prioritization of correlations and prioritizing the performance evaluators, as elaborated in the costs functions of e.g. Figure 9-10 and Figure 9-11. The cost functions, illustrated by surface diagrams, show the sensibilities of the costs and illustrate how the different parameters influence the design.

9.7. Summary

This chapter exemplifies and evaluates different design configurations in terms of discussing the usability of the model. The model shows two perspectives in its usability: one is the evaluation of design concepts and two is the generative design configuration. The model evaluates different configurations by costs functions, and clear differentiations emerge in the cost functions driven by different configurations – even from the mean simulations. It is possible to normalize the cost functions by using the mean simulations and likewise it is possible to produce greater differentiation in the costs functions, as illustrated in 9.5, by using the more differentiated simulations.

The objective function is the weighted sum of the cost functions. The correlation factor, *cf* is an evident contributor to the objective function. Some simulations provide design concepts, where the upper boundary for the cost function is reached because of a high correlation factor, *cf*. These examples are outcome of simulations, where the constraints are satisfied, and the optimization has continued improving the objective function, extensively. These examples provide an interesting perspective to computational architectural design modeling, because they confirm how different degrees of optimized solutions are derived from the constrained problems. When convergence is weak, the coefficient of the variation is high.

Practice focus on increasing the required correlations, and so the intermediate construction is defined. Total correlation is not an option, because it means all functionalities are within the same place or the same unit. Clearly, the present design model attempts to improve the correlations in terms of optimizing the objective function of weighted summarized costs. This implies the design model in an unexpected manner, when the two different organization typologies cause similar design concepts. It is remarkable how the model attempts correlating wards with examination rooms even in the functionally split typology, as exemplified in Table 9-7, and not like Table 9-8 where the wards correlate in one unit and the examination rooms in another. The latter was expected to characterize the design concepts generated by this organization typology

The design model optimizes with the same weighted summarized objective function. Even with bias input data, the generation creates similar configurations. This fact provides diverging arguments for the different organization typologies. Perhaps, the optimized functionality configuration is consistent for the two different typological approaches? This perspective is very interesting for the first main phase of analysis, where the developer and politicians set the foundation for a given project. This design model contributes with elaborating the initial preferences and requirements and so it can frame the actual implication thereof.

The sensitivity analysis responds to this perspective. The sensitivity of the performances and the costs across the units regards the functionalities and the geometric configuration. Some performance evaluators significantly depend on design choices, and others are insensitive to the design choices. The examples of this chapter have normalized evaluations with the mean simulations as the design concept of the exemplifications, and so it is possible to emphasize the cost functions for all configurations by using the minimum or maximum as the reference, as illustrated in 9.5. Moreover, it is possible to weight the objective cost function differently. This perspective is very important in the practical application of the model in order to analyze the sensitivities of design choices regarding the six performance evaluators and as a generator of prioritized design concepts.

This chapter uses the mean generation, as a consistent reference, the 10 generations one simulation consists of. However, this approach is very rarely seen. Most designers want to take the best as point of departure, instead of something that they know can be improved. The best configurations generated by the design model possessed several similarities to general practice, which verifies the usability of the model in terms of design generation. Moreover the functionality distributions are clearly more qualified and reflect practice's approach extensively.

The use of GAs for searching wide design space causes some of the design concepts to be too random. This is especially seen in the mean generations. However, the randomness reflects a differentiation from the general practice, and so it contributes with proposals of new organizations of the work and the functionality in the hospital, because, even though the generations appear to be random, they fulfill the weighted summarized optimization objective and create equivalent overall correlation in the hospital functionalities.

The objective function and the input data are the cornerstones of the numerical design model. The design model facilitates data operation, and the data can easily be evidence-based, it is merely a question of updating data on hospital operation and treatment technologies. Moreover, the matrix handles the complexity of the several functionalities in the hospital, and computation facilitates the search for the best trade-off in the wide design space. This computational search reflects the manual processes of practice, but the costs of the process and especially repetitions of the process are minimal. The advantage in computation is in the easy generation of alternates to illustrate a problem from several perspectives.

Chapter 10.
Summary and Discussion

This PhD project titled 'Optimal Hospital Layout Design' proposes an architectural design model as a contribution to improved hospital functionality. The hypothesis is that improved hospital functionality can be achieved by improved hospital design, and improved hospital design can be achieved by increased transparency in the design process, because it improves and informs the decision-foundation. The contribution of this PhD project to this problem is an architectural design model.

The proposal of the architectural design model is derived from the research questions of the thesis. The research questions are:

- How can hospitals be designed conceptually as building entities that respond to functionalities?
- What is the usability of systemized design models when applied to hospital functionality?

The development of the architectural design model follows the parametric design paradigm and uses established mathematical models for layout design. Throughout the thesis, the usability of systemized design models is discussed and, especially for complex design objects such as hospitals, the benefits are extensive for the involved participants.

10.1. Summary

Chapter 1 discusses the framework for architectural design modeling, and the need for solving the architectural design problem systematically. By doing so, the framework for the research questions is set. The motivation is improved hospital functionality, which reflects the societal focus by The Quality Reform and in general, where hospitals are under ongoing economic pressure. The hypothesis is that architectural design modeling can contribute to this perspective, because it entails the potential of initial identification of consequences of design choices in the design process. Several benefits follow this approach: improvement of the actual process, improved decision foundation, and most importantly the actual design outcome.

For the complex hospital, the consequences of the design choices are especially difficult to quantify in the initial design phases. Current research has solved design problems of complex facilities with focus on computer power and how to solve the design problem from a computational perspective. This contribution is based on the development and attempts to solve the architectural design problem based on the established research in scientific computing. Consequently, this contribution is to solve the architectural design problem based on the functionalities of the architectural case. The hospital design model leaves the numerical method development for further elaboration by computer scientists.

Chapter 2 sets the framework for hospital design and architectural modeling. The performance-based design models exemplify the utilization of computation in the design generation. With thoughtful use of simulations and analysis, they can drive the design process of a specific design. This perspective is inherent in several fields related to architectural design. However, the architectural understanding and perspectives of aesthetics, usability and functionality are difficult to describe formally and to implement in design models, and therefore the implementation is rarely seen.

Chapter 1 and Chapter 2 outline the research fields of hospital design and architectural design modeling. The chapters define the first part of the thesis defining the research questions and describe the methodology of the thesis. The methodological framework of architectural design modeling is based on state-of-the art in architectural modeling as one part and the methodologies and the related philosophies of science as the other.

Chapter 3 introduces the theory and defines the framework for the architectural design modeling of the thesis by the parametric design model. The parametric model is an architectural design model promoting the generation of design concepts, which respond to parameters and rules. The parametric design model is hierarchical. It consists of principal drivers at the highest hierarchical level. They inform and contribute with overall principles for design generation. The principal drivers influence the design on all levels and throughout the design process. While setting the principal drivers, it is important to pay attention to the subsequent influence they provide, both the required and preferred influences, but also in their inherent restrictions and limitations.

This chapter expands on the understanding of hospitals as building entities as introduced earlier. The building entities are described as typologies of practice reflecting the principal drivers of the parametric design model. They refer to practice as physical design frameworks rather than performance requirements. The definition of typologies as principal drivers binds the design model with practice’s general design approach, and so they combine the traditional approach and contribute to visualizing and clarifying the consequences of the design choices in the design process.

Chapter 4 outlines the formal description of the architectural typologies for the architectural design modeling. Formal descriptions in architecture are rare, because architecture deals with with qualities, intentions and behavior, which it is difficult to describe formally. When defining a numerical design model, the formal descriptions are necessary, and so the formal definitions of this chapter are corner stones in this research project, because they contribute to the overall research in architectural design that focuses on qualifying architecture quantitatively. The chapter provides the formal description of the architectural understanding of hospitals as building entities, which is an essential part of the first research question.

Consequently, this chapter provides formal descriptions of architectural design approaches for implementation in numerical design models. This work facilitates evidence-based design, because the formal framework it set. This contributes to practice that encourage evidence-based design but has difficulties in proving a scientific handling of evidence. Today, practice has no designated method for assuring scientific handling of evidence.

This is one on the benefits of defining a design model for conceptual design that responds to functionalities. The framework of the design model becomes a framework that facilitates and promotes evidence-based design.

The formal definition of functionalities is a correlation matrix that describes the requirements and preferences of the functionalities. The correlation matrix is implementable in numerical models, because mathematical descriptions define the architectural requirements and preferences as correlations. These correlations originate from evidence on the most frequent patient treatments and their processes.

The definition of the correlation matrix takes its point of departure in the traditional analog design approach of bubble diagrams describing the requirements. The correlation matrix is a formal definition of the bubble diagram, where it is possible to update knowledge. Having the correlation matrix as a separate element of the design model facilitates an ongoing update of knowledge, evidence and practice.

An essential part of this research project is the definition of the correlation matrix, because it defines the link between the architectural understanding of functionalities and their requirements and preferences and numerical modeling. However, more attention can easily be paid to the definition of the correlation matrix. For the current state of this work, the correlation matrix is defined by coding for evaluators qualitatively. It could be very interesting to elaborate on the definition of the correlation matrix with more knowledge of patient treatments, treatment technologies, professional clusters and statistics for a given demography. This could indubitably qualify the design configurations by the design model.

Chapter 5 describes schematically the evaluators of hospital design. The evaluators consist of architectural, engineering and functional requirements and preferences on hospital design. They are schematic and formal descriptions prepared for implementation in a design model. The definition of the evaluators continues the work of transforming the architectural perspectives into a formal description. The evaluators provide a holistic perspective on hospital design by six performance evaluators.

The respective evaluators consist of the two perspectives: evaluation subject to the principal drivers, and evaluation as a function of the design variables, defined in the functionality distribution. Both perspectives relate to the hierarchical construction of the design model. The explicit description of performances given – as indexations – by principal drivers indicates the qualities and limitations within the principal drivers in terms of design generation and design evaluation. The tables of this chapter formally describe these perspectives. The performances clearly visualize the contradictions of the evaluators. Some encourage dense and compact typologies while others require light and transparent typologies.

Listing the evaluators in tables facilitates the implementation in the design model and visualizes the contradicting performances. Moreover, it is possible to update the schematic description, which facilitates the implementation of ongoing updates in the research. Finally, the tables are more readable for practice than the matrices presented in Chapter 7.

Currently, the evaluators derived from the principal drivers closely connect to the dimensioning of the typologies. This is defined in correspondence with the architectural typological understanding. However, it is possible to update the schematic descriptions continuingly with evidence on hospital design and hospital evaluation. Hospital evaluation is broadly treated in research as clinical, patient-related and economic sub-issues.

10.2. How can hospitals be designed conceptually as building entities that respond to functionalities?

Chapter 3, Chapter 4 and **Chapter 5** conclude the first research question of how designing hospitals conceptually can respond to functionalities by setting a framework for a conceptual design model.

The decomposition of the hospital facility into functionalities describes a systematical method for designing with several functionalities and contradicting performance objectives. The decomposition is a transformation of the established method of bubble diagrams so that practice can relate to the method.

The decomposition and definition of a correlation matrix list the functionalities and requirements of the bubble diagrams that are broadly recognized and valued. The correlation matrix provides a formal definition of that method, and it is applicable in numerical models. Moreover, the correlation matrix can be used manually similar to the use of the bubble diagrams, and so it does not require numerical modeling.

The first step – in the definition of a conceptual design model that responds to functionalities – is to understand the hospital as a response to its inherent functionalities. To do so, the decomposition is essential. The decomposition liberates the participants in the design process from traditional thinking, because all functionalities are described by their respective requirements and preferences. Accordingly, the prejudged perceptions of departments, professional cluster etc. are irrelevant – and the relevant perceptions of correlations are inherent. Consequently, the correlation matrix facilitates exploration of new ways of organizing the work, because the decomposition facilitates the distinction from the traditional ways of thinking and takes its point of departure in the actual requirements and preferences.

The typologies are another central element in this part of the thesis. They provide a formal description of the architectural understanding of hospitals as a building entity. They describe and define the framework for the conceptual design in a manner, which can be implemented into a numerical design model. Moreover, the typological definitions reflect the existing designs of hospitals.

Chapter 3, Chapter 4 and Chapter 5 present the framework by typologies and the entities by the correlation matrix of how hospitals can be designed conceptually as building entities that respond to functionalities. However, exemplifications and the value creation remain. This is elaborated on in the following chapters, where the usability and applicability is developed and discussed.

10.3. Summary, continued

Chapter 6 sets the framework for solving the second research question by discussing the theories and use of numerical design models. The basis is established models and established research in layout design conducted by computer scientists. With this basis, the metaheuristic search approach with GAs searching for near-optimal solutions in wide design spaces is found appropriate. GAs are easy to interpret, and they show excellent results for traditional facilities and large design spaces.

A dataset from a project competition of a Danish regional hospital describes the hospital design problem. The data set is decomposed into 66 functionalities, and thus 66 variables. That is a very high number of variables in comparison to current research on layout problem solving. With this number of variables, search methods for wide design spaces are required. QAP, as elaborated on in Chapter 6, surely possesses the potential for layout design. However, the number of variables present, when solving the hospital facility design problem from a functionalistic perspective, requires extensive skills in computer programming and strong computer power. This research deals with architectural design modeling and architectural problem solving, which is why GAs are used, because they are easy to interpret and appropriate for the wide search spaces.

Chapter 7 defines the numerical implementation of a hospital design model, which is the definition of the intermediate construction of the design model, and so the chapter develops on the framework of the conceptual design model of Chapter 3, Chapter 4 and Chapter 5. The design model operates with an objective function of the weighted sum of costs, based on geometric conditions as well as functionalistic conditions referred to as the correlation factor. The physical constraints, defined by the typologies, and the functional requirements and preferences drive the design generation. Through iterations, the functionalities are distributed, while the configuration searches for maximizing the objective function, the weighted summarized cost function. The correlation factor derived from the functionality distribution is a decisive variable in the cost function.

The cost functions consist of two terms: an indexation by principal drivers and a function of the functional distribution. The indexation by principal drivers outlines how some cost functions increase while others decrease. The chapter outlines and visualizes the inherent contradictions of the different performances. Moreover, it outlines the indifferences and sensitivities of typologies in terms of the cost functions.

The other term of the cost function is the function of the functionality distribution, and the derived geometry consists extensively of the correlation factor. It is essential to pay attention to the fact that the objective function potentially optimizes the correlation factor extensively, because it is a recurring term in the respective formulations of the cost functions. Here, the weight factor can be valuable to assign priorities to minimize the impact of the optimized correlation factor, or to simply prioritize the different costs functions in general.

The objective functions prioritize the geometric optimizations in the search for feasible solutions. This has shown promising tendencies because remarkably different configurations emerge from the same configuration of typologies, both in terms of the cost functions and the functional distributions. While prioritizing flexibility, the collaboration across functionalities is deprioritized in order to easily be able to change one functionality, while upholding the nearby operation. This perspective on flexibility is based on practice’s ongoing renovation of 8-10 % of the built framework characterizes hospital operation. Ongoing development in demography and treatment technologies causes a need to change the built framework, and this will continue in the future, because of the remarkable technology development and prioritizations. Today, changes in one functionality cause large areas to close, because the functionalities depend on each other, and especially in order to change medical equipment according to the technological development, these challenges are ongoing.

Chapter 8 discusses the implementation of the design model and its design configurations The studies of the design model cause the definition of additional constraints involving some of the informal perspectives inherent in traditional architectural hospital design. The perspectives inherent in the architectural and engineering understanding are not formally described. These perspectives involve the concentration of similar technically requiring area, and weighing the achieved correlations with the potential correlations for the given configurations. These perspectives are not drivers in the architectural development, but traditionally they work as constraints for the design generation. Accordingly, they are implemented in the design model as constraints as well as the traditional architectural design process

The additional constraints narrow the search space for the objective function. Especially for design configurations of N_{GU} = 10 where the search space is already narrow which impedes the optimization of the objective function. The fact that additional constraints narrow the search space, and that the design problem becomes more constrained is the same in practice. However, the design model’s difficulties in operating become very explicit. In practice, the difficulties related to satisfying the constraints will cost attention, but the design process will go on, and so the constraints may not be satisfied. In numerical modeling, the constraints must be satisfied in order for the optimization procedure to start. The chapter explores the problem solving in its complexity.

The design model visualizes the complexity of the problem when the design model has difficulties operating in the constrained design space. The design model handles the situation by producing several simulations, where the constraints are not satisfied. Statistics on satisfied and not-satisfied constraints explain the extent of the constrained problem.

N_{GU} is decisive in constraining the problem; moreover, the layout typologies in terms of sizes constrain the problem. This perspective reflects the problem solving from practice. While the numbers of unit increase, the problem becomes more complex to solve as the constraints are increased, because the requirements in relation to splitting up functionalities increase.

Chapter 9 discusses the usability of the design model. The chapter outlines several exemplifications by their respective functionality distributions and cost functions. The illustrations describe the ability and the functionality of the design model. It becomes evident how the correlation factor implies the cost functions in several terms and so the objective function. In the definition of the design model, optimization subject to the correlation factor was rejected because, the weighted sum of the costs functions inform better in the prioritization of the hospital performances. The ability of weighing cost functions for different configurations is central when defining a tool for an informed decision basis and discussion of prioritizations.

The model shows two perspectives in its usability: evaluation of design concepts and generation of design concepts. In terms of evaluations, the model shows clear differentiations in cost functions for different configurations, which verifies the different contributions the performance evaluators have. The clear differentiated cost functions can inform the decision base and visualize the prioritizations. This is valuable in the dialogue with developers, politicians, hospital managers, etc. when discussing the prioritization of the hospital. Well, it concerns the process previous to the design process of architects, hospital planners and engineers.

The design configurations are exemplifications of distributions, and not final design concepts. In the chapter, the mean simulations define the examples for comparison. In terms of usability, the functional distributions should take be based on the best simulations as argued in the last subsection. The generative design configuration is a process to be handled with caution, because some configurations carry potential and others do not. It is evident to have a professional understanding to evaluate the design concepts. Some configurations have to be discharged and others explored, because they explore possibly design configurations and potentially new ways of organizing the work, which has to be related to practice.

The objective function and the input data are essential for the applicability and usability of the design model. The definition of the correlation matrix facilitates operating with evidence-based data, because a formal framework is set. Moreover, evidence can be included in the objective functions in the evaluators.

The examples show a high sensitivity of the correlations and the respective costs, which express the current trend of coherent patient treatments. This reflects today's practice, where emphasis is on starting with the patient and the treatment processes of the patient.

10.4. What is the usability of systemized design models on hospital functioning?

Chapter 6, Chapter 7, Chapter 8 and **Chapter 9** conclude the second research question with the analyses of Chapter 9, which exemplifies the usability of systemized models, when applied to hospital functionality.

The chapters exemplify how a numerical design model can solve the hospital design problem. The design model shows applicability in the early phases of Analysis and Planning & Design with contributions to conceptual design modeling and the evaluation thereof. The contribution of evaluation is a concretization of the consequences of design choices. It is valuable for eased development of the hospital design from a design perspective. Moreover, it is valuable in the analysis of project possibilities, project definition and project planning, not only in the design process, but also in the previous process involving developers, politicians and hospital managers.

The evaluation visualizes the design outcome schematically which facilitates prioritizations in the early phases. Either the prioritizations can be on the hospital functioning, on the six performance evaluators, or it can be on design choices. The concretization of the different performance evaluators is fast and reliable, and so the hospital responsible or politicians can make choices and prioritizations on an informed decision basis.

With the clarification of the performance evaluators of the final hospital designs, it is possible to minimize today's numerous cost reductions throughout the design process, but most importantly, it will be possible to make informed decisions during the cost reductions with holistic considerations of all six performance evaluators and their implication. This will indubitably influence hospital functionality, because the design choices will be made with visualization of hospital functionality. Moreover, the numerical operation of the correlation matrix defines a scientific handling of design requirements and preferences according to the positivistic methods for increased functionality by increased correlation where preferred and required. Furthermore, practice can benefit from this. When a design is subject to cost reductions, it is either because of sudden cost reductions from external parts or because the design has exceeded the budget. Either way, it is costly for the practitioners to produce alternate design concepts with reduced costs. Because of the eased generation of alternates, the design model is also valuable for the practitioners.

The definition of the six performance evaluators contributes with a nuanced perspective in terms of cost reductions and in prioritizations in general. In the architectural understanding, the performance evaluators are informal and implicit and they are difficult to estimate and include, e.g. the operation costs are defined broadly in terms of sustainability, personnel conditions and logistics, by general considerations and good intentions. There are several occasions in especially the hospital constructions of The Quality Reform, where construction costs compromise the operating costs, probably because of the lack of numerical implementation.

The typological implementation of the design model facilitates a sensitivity analysis of the performance evaluators, whereby prioritizations can follow the informed decision basis. By analyzing the sensitivity of typologies on performances, the prioritizations pursue the highest impact in the compromise while the compromises balance the respective consequences.

Using a design model implies cost reductions for practice. In the initial design phases, architects, engineers and hospital planners produce several alternates in order to define of the framework for the project. In these phases architects, engineers and hospital planners define the framework for the design through interdisciplinary collaboration. These phases are expensive, because the studies are time-consuming and several professions and persons contribute. Furthermore, opaqueness characterizes the phases because the consequences of the design choices are difficult to estimate and put in the perspective of the interdisciplinary problem.

Contribution with transparency in these design phases facilitates the design process and decision-making on several levels. The decision-making is informed and the consequences follow the anticipations. Moreover, it is quite easy to generate and evaluate several alternates, which inform and extend the foundation for architectural exploration.

10.5. Discussion

The hospital design process [in Denmark] has a strong history of interdisciplinary collaboration. Moreover, the design process, for the large and complex facilities, is formed as project competitions, where consortiums of architects, engineers and hospital planners cooperate across companies. The basis for the cooperation is the tender documents defining the project competition by pre-defined limitations, foci, prioritizations etc. This research project deals with the phases of Analysis and

Planning & Design, as described, and the design model actually operates in the intersection of the two main phases. Analysis is the phase of defining the tender material, and Planning & Design is the first phase of the project competition, where the feasibility study is defined. When this design model operates in the intersection of these two main phases it also operates in the intersection where the companies of the consortiums do not cooperate yet, and may have conflicting interest.

With the construction of the design process based on competitions, the companies defining the tender documents and the companies developing the design cannot be the same, and so the design model may fall between two stools.

However, the design model concerns both phases, and influences the design on both levels. In the definition of tender material, the model provides a method and model for analyzing and prioritizing. This helps the developer and politicians define the strategic design and its prioritizations. It is in this phase, the societal benefits are the greatest, because the decision-making is informed. Application of the design model in this phase is in client consultancy in opposition to traditional architectural or engineering consultancy. The design model is applicable in this consultancy specialty, and the consultancy specialty can surely benefit from the quantification of architectural and engineering qualities in the early definition of a construction project.

In the actual design, initiated by Planning & Design, the design model assists through generations of alternates. Here the design model provides a major benefit to practice by minimizing the time-consuming processes of manually distributing the functionalities and exploring the initial geometric configurations.

For architectural problem solving, the design model proposes an approach, where the hospital design is the configuration of functionalities instead of rearrangement of departments. This approach facilitates better organizing of functionalities regarding requirements and preferences in terms of qualities, capacities and times, because of numerical operations on the correlation matrix. This approach facilitates new ways of organizing the work, as it is liberated from the traditional practice of departmental thinking. The numerical design model attempts to generate design proposals based on the systematic knowledge defined in the correlation matrix. Hence, ongoing evidence on collaboration, patient treatments etc. can drive the design generation, because it defines the requirements and preferences of the correlation matrix.

However, this requires cautious handling, as stated earlier. It is not possible automatically to produce hospital designs. In the design model, several assumptions and choices are made. The model is based on variables that are easily updated; some variables are project specific and others define the foundation of the model as background knowledge. An understanding of the variables is important in order to make the design model contribute with qualified design concepts.

There are several dependencies according to the variables inherent in the design model, and the main contributors are the principal drivers, defining the highest hierarchical level. The variables describing the typologies are based on a qualitative analysis of hospitals in Scandinavia, and so the variables are chosen from existing hospitals. This choice relates practice to the design model, and practice can reflect itself in the generative design model, the inputs and the outputs. This is chosen in order to promote the applicability of the model, but it surely impedes the non-constrained generation of design concepts, deliberated from traditional thinking.

However, variables define the numerical implementations and so they are easily updated when knowledge of hospital design or hospital operation develops, when practice accustoms itself to the design model and its methods, or when the assumptions inherent in the model are clarified or elaborated on.

The typologies are defined by differentiations and described by variables. The typological definitions and differentiations reflect current tendencies in Scandinavia. The comparison across typologies, as presented through this thesis may not be relevant in practice, because of the contextual premises. If that is the case, the variables can be adjusted, and so the differentiation of the typologies is reduced. Such adjustments will influence all layers in the design model, because the typologies are defined as principal drivers at the highest hierarchical level. Consequently, changes and adjustments of the typologies will influence the design, and the cost functions will probably behave with increased or decreased differentiation, according to the adjustments. As exemplified in Chapter 9 by the ‘best’ configurations, the correlation factor is dominating in the influence of the cost functions, and so decreased differentiation between typologies may not cause remarkably different cost functions. This perspective is a subject for further investigation as part of the future work with the design model. In the present work, the sensitivities of the established variables are analyzed and adjusted in order to fine-tune the design model to practice. Adjustments of variables and definitions will require similar sensitivity analyses.

As stated above, the correlation factor is decisive in the definition of the cost functions. The correlation factor’s high impact on the objective function follows the definition of the intermediate construction and especially the performance evaluators. The correlation factor influences all performances, and so it becomes decisive in the optimization procedure. When this is the case, attention has to be paid to the correlation matrix and the definition of the performance evaluators. The performance evaluators are closely related to the typologies as described above, and so they will change in accordance with changes in the typological definitions and differentiations.

The correlation matrix on the other hand is fed information on patient treatments and hospital operation. For this PhD project, the focus is on making a design model operating with performance objectives while setting a framework that facilitates evidence-based design and shows promising results. The result is the design model and surely, the correlation matrix can be updated with new and enhanced knowledge. This is a premise of the design model to define a framework for evidence-based design. The construction of the matrix is valuable, because it reflects the design approach from practice, and breaks down the potential borders between practice and architectural design modeling. This can be a perspective impeding the acceptance of the design model in practice, because practitioners feel intimidated or substituted by the design mode.

However, attention has to be paid to the fact that the correlation matrix also is a model prepared for updated knowledge, as research, technologies and patient treatments develop. With this perspective combined with the focus of the PhD project – to provide a feasible design model for optimized hospital design – attention has not been paid to the input data and the development thereof. The data on hospital operation is used and combined with the data from the descriptions of the 20 most frequent patient procedures. The data is a representation of the variable input data, and the design model’s operation with the data is analyzed in the sensitivity analyses. The analyses focus on the numerical definition and not the input.

The developed design model with the correlation matrix contributes, as one approach out of many, towards better hospitals. The construction of the design model relies on the parametric model, and so it entails advantages in flexibility and the extensive possibilities of updating, adjusting, etc. This construction is very beneficial in terms of complex designs, because some prioritized parameters are included on the highest hierarchical level, and they influence the design on all levels while other parameters are at lower hierarchical levels influencing appropriately.

10.6. Concluding remarks

The definition of this design model follows the hypothesis that increased transparency contributes to improved hospital design. The design model is a contribution to this, and it shows promising results while it does not ensure optimized design. The design model provides a basis for dialogue in the design process, it visualizes the qualities in different prioritizations and so it informs the participants in the design process.

The results of Chapter 9 underline this ability of the design model. E.g., the results of the correlated wards and examination rooms in both organization typologies contribute to the discussion of the advantages and disadvantages of the different typologies. It provides diverging arguments for the different organization typologies reflecting the uncertainty of practice, where the preferences go from one typology to the other with the same arguments. Perhaps, the optimized functionality configuration does not consist of two different typological approaches as practice indicates. Consequently, the design model contributes to the discussion of preferences in hospital design, which are weakly defined and poorly dealt with in research.

It was expected that different and diverging ways of organizing the work, e.g. in professional clusters would emerge along with an increase in N_{GU}. Instead, the optimization objective searched for a total correlation. This perspective might represent a limitation in the design model, where the impact of the correlation factor is too decisive. Instead, it can be seen as a contribution to the discussion and preferences of the different typologies, and clarify the qualities of the typologies. The latter emphasizes the design model as a tool for dialogue and informed decision-making in practice.

This PhD project emphasizes the general applicability and practice's utilization of the design model. At first, it is evident to focus on the actual contribution of the design model. It provides a framework for architectural exploration facilitating evidence-based design. In order to do so, the design model must be able to undergo an ongoing elaboration according to practice. This perspective is emphasized in the flexible construction of the model, open for updates and changes. However, using this construction of a design model secures neither efficient design, improved hospital design nor improved hospital operation. It is the input parameters and their ongoing development, which assure optimized hospitals. The design model facilitates the perspective.

The justification of the design model is in the operation and use of the design model. For practice to use the design model, it is evident that the produced design concepts have parallels to existing hospitals. The design model adds value through its use and application, and for this reason it is essential that practice accepts and uses the design model. The use of the model is expected to follow practice's recognition of the design concepts. The sectorized hospital characterizes the recent hospital construction of e.g Det Nye Universitetshospital in Aarhus, Odense Universitetshospital and Køge Universitetssygehus. Meanwhile, the functionally spilt approach characterizes Aalborg Universitetssygehus. The functionality distribution of the design model contributes with perspectives to the discussion of the preferences in the different approaches; meanwhile, it generates alternates with strong similarities to practice.

Det Nye Universitetshospital in Aarhus is actually organized with strong similarities to the functionality distributions of the model. The design of Aarhus Hospital started with several smaller units, which due to cost savings were combined. Today, the hospital's primary units are 1) a high-rise unit for operation, intensive care etc., 2) a unit for research and administration, 3) a unit for a children's hospital, 4) a unit for psychiatric facilities and several entities within the same typography representing wards and examination rooms. This distribution of functionalities is parallel to the functionality distributions produced by the design model. One argument against the design model could be that it merely mirrors the configurations of practice, and so it does not add value. However, the configuration is significantly faster to generate by the digital model than the manual pen and paper, and so it contributes to remarkable cost savings in practice. The fast generations are moreover emphasized by the choice of GAs that support usability of the model by the fast searches in the wide design space of the complex hospital. Furthermore, the ability of alternatives provides insight into the hospital qualities of the different configurations.

Another characteristic hospital in Denmark is Herlev Hospital, constructed in the 1970s. It consists of two main units: a high-rise building of wards and a low building accessible from several points consisting of examination rooms. The typography of the hospital is very clear. Using the terminology of this PhD project, the hospital consists of several geometric units combined differently. In Aarhus, the architectural configuration of the geometric units is within the campus typology, and at Herlev the configuration is within the high-rise typology. The design concepts presented in Chapter 9 showed functionality distributions parallel with the ones seen in existing hospitals, and the main contribution to the design is the fast generations of design concepts. Accordingly, the main contribution for the client is the visualization of the cost functions for informed prioritizations. The chosen compromises throughout the design process follow the sensitivities in the design, so the prioritized performances contribute the most in the given configurations.

10.7. Main contributions and future work

As an Industrial PhD project, the work of this dissertation has two perspectives on the contributions of this work; contributions to research and contributions to practice.

10.7.1. Research

The main contribution is the definition of a design model that solves the architectural optimization problem with its point of departure in functionalities and not merely geometric constraints. Throughout the thesis this perspective has been elaborated on. Solving the architectural design problem with geometric constraints usually causes exhaustive searches because of the high-dimensional search spaces. This research definition of typologies as different geometric entities and performance evaluators facilitates the search, which is eased by use of GAs.

The definition of the correlation matrix and the intermediate construction operating with the correlation matrix are the essential parts of this perspective. The correlation matrix proposes a formal description of the architectural understanding, which traditionally has been difficult to formulate formally. The definition of the matrix draws parallels to the intuitive bubble diagrams and formalizes them. Moreover, it uses data on patient treatment from a social scientist discipline, where the qualitative analyses are coded for quantification. The definition of the correlation matrix on qualitative analyses of patient treatment and qualitative analyses on hospital contacts sets a framework. This PhD focuses on the definition of the framework in this interdisciplinary field. However, it could be very interesting to let this research project go into the different disciplinary fields and strengthen the different disciplines. Undoubtedly, this will throw more light on perspectives not dealt with in this interdisciplinary project, which will strengthen the quality of the design model. One of the first perspectives is the data analyses. The design model sets a framework for evidence-based design, however, the treatment of the data needs to be analyzed more systematically from a scientific perspective, this goes for both the qualitative and the quantitative data. However, research into and elaboration on all related disciplines could define interesting research projects valuable for practice and developing this architectural problem solving further.

The construction of the correlation matrix facilitates especially the quantitative perspective. It is easy to update and advance with e.g. statistic operations such as Bayesian statistics, which allow ongoing updating and qualifying the samples of evidence. Research in Bayesian statistics for updating knowledge in design models is briefly treated in research. However, there are several perspectives within the subject, where research can contribute with new knowledge.

From the qualitative perspective, several advancements can be applied. The first is the evidence-based framework, as mentioned several times throughout the thesis: an elaboration of the patient treatments, in the number and quality of the analyses. Research in design and healing architecture includes several recommendations and perspectives that easily can be included in the correlation matrix. Furthermore, the intuitive procedures of practice can be analysed and quantified. This will qualify the correlation matrix as the transformation of functionalities into a numerical operational concept. Moreover it will continue, qualify and combine the existing research in the field, whereby new knowledge will emerge.

The performance evaluators are another perspective that easily can undergo advancements, especially in the data defining the constraints. They rely heavily on the typological definitions which, as stated previously, easily can be updated according to a given context. This perspective reflects the construction of the model, which has been a focus area and so the required variability and flexibility is integrated. However, the evaluators could benefit from the implementation of research into the different qualities and analyses from practice. The objective function of the performance evaluators summarized the performances and so they continue the transformation of the qualitative architectural approach into a numerically implementable concept.

The contribution of this research project is the knowledge of and method for transforming the architectural qualitative knowledge into a numerically implementable concept. Consequently, this research project defines the framework for numerical architectural design. However, the definition of the design model can be improved by more work in the different disciplines the project encompasses. The numerical implementation can benefit from the work of computer scientists. The qualitative analyses can benefit from the work of social scientists. The data of the performance evaluators and the correlation matrix can benefit from the implementation of research. Undoubtedly, this will improve the design model and the quality of its results from a scientist's perspective. However, this research project contributes with a new method for and knowledge of quantifying and combining the architectural and engineering perspectives while they actively generate design concepts.

10.7.2. Practice

The main contribution of this PhD project to practice regards three perspectives: streamlining the design process of the architect and engineer, the developer's ability to make informed decisions, and finally more cost-effective hospitals.

The design model operates in the intersection of Analysis and Planning & Design, and as stated earlier it conflicts with the traditional ways of working in architectural and engineering design. The operation of the design model conflicts with practice's defined phases, because it operates iteratively in the two first main phases, which in practice are separated by traditions and contractual terms.

Computer advancement in architectural design by e.g. Computer Aided Design (CAD) and Building Information Modeling (BIM), which through the last decades have been integrated, has also conflicted with the established main phases. While working with CAD and BIM practitioners have experienced that the required information for modeling conflicts with the traditionally available information. This design model takes these conflicts to another level because the design model operates in the two first main phases, where the contractual basis is set. The fact that the design model operates iteratively in the two main phases as well as the fact that it is constructed on a combination of architectural, engineering and functional perspectives means that the design model sets a new framework how to work practice.

The design model breaks down the borders between the architectural, engineering and hospital planning profession. The interdisciplinary design model requires participation of and input and commitment from all disciplines. The design model sets a framework for interdisciplinary collaboration and dialogue, where quantification of the disciplines' individual performances defines a foundation for prioritization. The interaction with the three disciplines defines an interesting and relevant subject for future work. The design model can benefit from an analysis of it as a tool for interaction and dialogue. Research in the defined collaboration and separation of phases and responsibilities will contribute with new knowledge to research, and practice will undoubtedly benefit from breaking down the borders between the established professions for the benefit of solving the architectural design problem.

This research project is concluded by the definition of a feasible method for optimizing the design process. However, it could be very interesting to continue work on the design model with a focus on applicability. The applicability in terms of practice can be analyzed by using the design model in interdisciplinary design teams and analyzing the contributions and the conflict, the design model inflicts on the different disciplines. This work would emphasize the applicability of the design model in practice, and the different disciplines' reception of the design model. Using the design model, as it is today, may cause difficulties, because the different disciplines do not identify themselves with it, and so, they may fear their profession is compromised by a generative tool.

Throughout the PhD project, this perspective has raised questions and the different disciplines have cautiously contributed. No disciplines have an interest in selling out of their specialty to be substituted by a generative tool. Because of this conflict of interests, emphasis has been on the generative tool as a tool for providing transparency and visualization of the consequences of the design choices. This is a design model, all disciplines of practice can benefit from, because it saves expensive time. However, the threat is relevant, because the full value of the design model will result in a new organization of practice.

The design model influences the organization of consultants (architects, engineers and hospital planners) and the design process. However, it also influences the processes before the design process. The design model contributes with quantifications of design choices based on typologies. This contribution regards the developer, the people responsible for the hospital, and politicians, because the design model contributes with knowledge of the consequences of the design prioritizations at this early stage. This early contributions continue the change in the organization of practice, because it prompts more qualified quantifications in the early stages, which can influence the overall prioritization of hospitals – even on a political level.

This contribution to prioritization adds the ability of analyzing project possibilities, project definitions and project planning, in the very vaguely defined phases. The design model contributes with a clarification of the sensitivity of the different performance evaluators in terms of typologies, as outlined in Chapter 9. Fast and reliably, the sensitivities and the prioritizations can be clarified, which is not possible today, because the information available at this stage is insufficient for these evaluations. This is a main contribution to the developers, because they can make informed and qualified decisions.

The transparency and the ability to prioritize moreover contribute to the optimized hospital design. This perspective combined with the visualizations of the design concepts of Chapter 9, show efficient distributions of functionalities, which objectively (by the cost functions) contributes to more cost effective hospitals. The cost effective hospitals follow the functionality distributions defined by the requirements and preferences, initially defined as contributors to cost effective hospitals.

10.7.3. Concluding

The design model generates design concepts for hospital design. It utilizes a framework that is prepared for ongoing updates in the knowledge of hospital design, hospital operation and technology. The design model is constructed to solve the architectural design problem of the complex hospital facility, and the framework of the design model is constructed to answer to the complex design problem.

The future work – building on this thesis – can focus on specialization within hospitals through more thorough analyses of hospital data, patient treatments, participants in the design process etc. Accordingly, the future work can take the contrary perspective and focus on a specialization in general design. The design model is constructed to answer to the complex design problem of a hospital. Accordingly, the design model can be generalized to answer to all complex design problems.

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APPENDICES

Appendix A. Correlation matrix, Functionally split

i	FT	Beskrivelse	m2	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1		Eksterior		1,0													
2	3	Akutseng, somatik	2070	0,8	1,0												
3	3	Akutseng, psyakiatri	90	0,8	0,0	1,0											
4	3	Akut, us, diag, skadest	2720	1,0	1,0	1,0	1,0										
5	3	Akut, admin, vagtvær	2474	0,0	0,8	0,8	1,0	1,0									
6	4	Intensiv, seng	3730	1,0	1,0	0,5	0,5	1,1	1,0								
7	4	OP	5550	0,0	0,5	0,0	1,0	0,5	1,0	1,0							
8	4	Opvågning	1024	0,0	0,0	0,0	0,0	0,0	0,8	0,8	1,0						
9	4	Intensiv, admin	3372	0,0	0,0	0,0	0,0	1,0	0,8	0,8	0,5	1,0					
10	4	Diagnostik	4270	0,0	0,0	0,0	0,8	0,0	0,3	1,0	0,0	0,0	1,0				
11	4	Laboratorium	7928	0,0	0,8	0,5	1,0	0,5	0,5	0,8	0,3	0,3	1,0	1,0			
12	4	Diagnostik, admin	2951	0,0	0,0	0,0	0,0	1,0	0,0	0,5	0,0	1,0	1,0	1,0	1,0		
13	3	Lungemed, seng	1750	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	1,0	
14	3	Lungemed, us	198	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,5	1,0
15	3	Kardiologi, seng	1015	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,5	0,0
16	3	Kardiologi, us	454	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	1,0
17	3	Endokrinologi, seng	105	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,5	0,0
18	3	Endokrinologi, us	221	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	1,0
19	3	Reumatologi, us	200	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	1,0
20	3	Intern medicin, seng	1120	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,5	0,0
21	3	Intern medicin, us	129	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	1,0
22	3	Ortopædkirugi, seng	1470	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,5	0,0
23	3	Ortopædkirurgi, us	740	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	1,0
24	3	Arbejdsmedicin, us	30	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,5	1,0
25	2	Admin, lung, kar, endo, reuma, intern, orto, arbejds	2951	0,0	0,0	0,0	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,0	0,8	0,8	0,8
26	3	Kirurgi, seng	1750	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
27	3	Kirurgi, us	230	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
28	3	Urologi, seng	525	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
29	3	Urologi, us	230	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
30	3	Gastroenhed, seng	525	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
31	3	Gastroenhed, us	164	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
32	3	Nefrologi, seng	490	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
33	3	Nefrologi, us	2102	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
34	3	Gynækologi, seng	140	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
1,0																						
0,5	1,0																					
1,0	0,0	1,0																				
0,0	1,0	0,5	1,0																			
0,0	1,0	0,0	1,0	1,0																		
1,0	0,0	1,0	0,0	0,0	1,0																	
0,0	1,0	0,0	1,0	1,0	0,5	1,0																
1,0	0,0	1,0	0,0	0,0	1,0	0,0	1,0															
0,0	1,0	0,0	1,0	1,0	0,0	1,0	0,5	1,0														
0,0	1,0	0,0	1,0	1,0	0,0	0,5	0,0	0,5	1,0													
0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	1,0												
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	1,0											
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,5	1,0										
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	1,0	0,0	1,0									
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,0	1,0	0,5	1,0								
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	1,0	0,0	1,0	0,0	1,0							
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,0	1,0	0,0	1,0	0,5	1,0						
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0					
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,0	1,0	0,0	1,0	0,0	1,0	0,5	1,0				
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0			

i	FT	Beskrivelse	m2	1	2	3	4	5	6	7	8	9	10	11	12	13	14
35	3	Gynækologi, us	275	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
36	3	Otologi, seng	105	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
37	3	Otologi, us	230	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
38	2	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	2741	0,0	0,0	0,0	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,0	0,8	0,0	0,0
39	3	Onkologi, seng	525	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
40	3	Onkologi, us	565	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
41	3	Hæmatologi, seng	175	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
42	3	Hæmatologi, us	329	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
43	2	Admin, onkologi, hæmatologi	1475	0,0	0,0	0,0	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,0	0,8	0,0	0,0
44	3	Neurologi, seng	735	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
45	3	Neuroreha/fysiol, seng	630	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
46	3	Oftalmologi, seng	35	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
47	3	Neuro, us	280	0,8	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,8	0,3	0,0	0,0	0,8
48	2	neuro, admin	1264	0,0	0,0	0,0	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,0	0,8	0,0	0,0
49	3	Psykiatri, seng	2905	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,0
50	3	Psykiatri, v, us	850	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,3	0,0	0,0	0,0
51	3	Psykiatri, b/u, seng	350	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,0
52	3	Psykiatri, b/u, us	312	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,3	0,0	0,0	0,0
53	3	Psykiatri, us	939	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,3	0,0	0,0	0,0
54	2	Psykiatri, admin	6233	0,0	0,0	0,5	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,0	0,8	0,0	0,0
55	3	Pædiatri, seng	1200	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,0	0,0
56	3	Pædiatri, us	260	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
57	4	Fødestue	140	0,8	0,0	0,0	0,3	0,0	0,0	1,0	1,0	0,0	0,3	0,0	0,0	0,0	0,0
58	3	Obstetrik, seng	840	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
59	3	Obstetrik, us/føde	848	0,8	0,0	0,0	0,3	0,0	0,0	1,0	1,0	0,0	0,3	0,3	0,0	0,0	0,3
60	3	Obstetrik/Pædiatri, admin	1687	0,0	0,0	0,0	0,0	0,8	0,0	0,0	0,3	0,8	0,0	0,0	0,8	0,0	0,0
61	2	Administration og forskning	3661	0,8	0,0	0,0	0,0	0,8	0,0	0,0	0,0	0,8	0,3	0,8	0,8	0,0	0,0
62	3	Patienthotel	1.610	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
63	1	Ernæringsenheden	280	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
64	1	Ergoterapi og fysioterapi	1.080	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
65	2	Kirkerum og kapel	600	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
66	1	Køkken og kantine	1.329	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
67	1	Apotek	800	0,0	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
68	1	Service og logistik	12350	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

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0	0,5	1,0		
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0	
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0	0,0	1,0	0,5	1,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8
0,0	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	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,3	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0
0,8	0,0	0,8	0,0	0,0	0,3	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0
0,0	0,8	0,0	0,8	0,8	0,0	0,8	0,0	0,8	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8
0,0	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	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3
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	0,0	0,0	0,0
0,8	0,0	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0
0,0	0,3	0,0	0,3	0,3	0,0	0,8	0,0	0,8	0,8	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8
0,0	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	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,8	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,5	0,0	0,0	0,0	0,5	0,0	0,5	0,0	0,5	0,0	0,5	0,0	0,5	0,0	0,5	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

i	FT	Beskrivelse	m2	38	39	40	41	42	43	44	45	46	47	48	49	50	51
38	2	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	2741	1,0													
39	3	Onkologi, seng	525	0,0	1,0												
40	3	Onkologi, us	565	0,0	0,5	1,0											
41	3	Hæmatologi, seng	175	0,0	0,8	0,0	1,0										
42	3	Hæmatologi, us	329	0,0	0,0	1,0	0,5	1,0									
43	2	Admin, onkologi, hæmatologi	1475	1,0	0,8	0,8	0,8	0,8	1,0								
44	3	Neurologi, seng	735	0,0	0,8	0,0	0,8	0,0	0,0	1,0							
45	3	Neuroreha/fysiol, seng	630	0,0	0,8	0,0	0,8	0,0	0,0	1,0	1,0						
46	3	Oftalmologi, seng	35	0,0	0,8	0,0	0,8	0,0	0,0	1,0	1,0	1,0					
47	3	Neuro, us	280	0,0	0,0	0,8	0,0	0,8	0,0	0,5	0,5	0,5	1,0				
48	2	neuro, admin	1264	1,0	0,0	0,0	0,0	0,0	1,0	0,8	0,8	0,8	0,8	1,0			
49	3	Psykiatri, seng	2905	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0		
50	3	Psykiatri, v, us	850	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,8	1,0	
51	3	Psykiatri, b/u, seng	350	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0	0,3	1,0
52	3	Psykiatri, b/u, us	312	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,8	0,8
53	3	Psykiatri, us	939	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,8	0,8	0,8
54	2	Psykiatri, admin	6233	1,0	0,0	0,0	0,0	0,0	1,0	0,0	0,0	0,0	0,0	1,0	0,8	0,8	0,8
55	3	Pædiatri, seng	1200	0,0	0,3	0,0	0,3	0,0	0,0	0,3	0,3	0,3	0,0	0,0	0,0	0,0	0,0
56	3	Pædiatri, us	260	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0
57	4	Fødestue	140	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
58	3	Obstetrik, seng	840	0,0	0,8	0,0	0,8	0,0	0,0	0,8	0,8	0,8	0,0	0,0	0,0	0,0	0,0
59	3	Obstetrik, us/føde	848	0,0	0,0	0,8	0,0	0,8	0,0	0,0	0,0	0,0	0,8	0,0	0,0	0,0	0,0
60	3	Obstetrik/Pædiatri, admin	1687	1,0	0,0	0,0	0,0	0,0	1,0	0,0	0,0	0,0	0,0	1,0	0,0	0,0	0,0
61	2	Administration og forskning	3661	1,0	0,0	0,0	0,0	0,0	1,0	0,0	0,0	0,0	0,0	1,0	0,0	0,0	0,0
62	3	Patienthotel	1.610	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
63	1	Ernæringsenheden	280	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0
64	1	Ergoterapi og fysioterapi	1.080	0,0	0,0	0,0	0,0	0,0	0,0	0,8	0,8	0,0	0,8	0,0	0,0	0,0	0,0
65	2	Kirkerum og kapel	600	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
66	1	Køkken og kantine	1.329	0,0	0,5	0,0	0,5	0,0	0,0	0,5	0,0	0,5	0,0	0,0	0,0	0,0	0,0
67	1	Apotek	800	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
68	1	Service og logistik	12350	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68
1,0																
0,8	1,0															
0,8	0,8	1,0														
0,0	0,0	0,0	1,0													
0,0	0,0	0,0	0,5	1,0												
0,0	0,0	0,0	0,3	0,8	1,0											
0,0	0,0	0,0	1,0	0,5	1,0	1,0										
0,0	0,0	0,0	0,3	0,8	1,0	0,8	1,0									
0,0	0,0	1,0	0,8	0,8	0,8	0,8	0,8	1,0								
0,0	0,0	1,0	0,0	0,0	0,0	0,0	0,0	1,0	1,0							
0,0	0,0	0,0	1,0	0,0	0,8	0,8	0,8	0,3	0,0	1,0						
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	1,0					
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,5	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	1,0			
0,0	0,0	0,0	0,5	0,0	0,0	0,5	0,0	0,0	0,0	0,5	0,8	0,3	0,0	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	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	0,8	0,8	1,0

Appendix B. Correlation Matrix, Sectorized

i	FT	Beskrivelse	m2	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1		Eksterior		1,0													
2	3	Akutseng, somatik	2070	0,8	1,0												
3	3	Akutseng, psyakiatri	90	0,8	0,0	1,0											
4	3	Akut, us, diag, skadest	2720	1,0	0,8	0,8	1,0										
5	3	Akut, admin, vagtvær	2474	0,0	0,8	0,8	1,0	1,0									
6	4	Intensiv, seng	3730	1,0	0,3	0,0	0,0	0,0	1,0								
7	4	OP	5550	0,0	0,5	0,0	0,8	0,0	1,0	1,0							
8	4	Opvågning	1024	0,0	0,0	0,0	0,0	0,0	0,5	0,8	1,0						
9	4	Intensiv, admin	3372	0,0	0,0	0,0	0,0	0,5	0,8	0,8	0,5	1,0					
10	4	Diagnostik	4270	0,0	0,0	0,0	0,0	0,0	0,0	0,8	0,0	0,0	1,0				
11	4	Laboratorium	7928	0,0	0,8	0,0	0,8	0,0	0,3	0,8	0,0	0,0	1,0	1,0			
12	4	Diagnostik, admin	2951	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0	0,3	1,0	1,0	1,0		
13	3	Lungemed, seng	1750	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	1,0	
14	3	Lungemed, us	198	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,3	0,0	1,0	1,0
15	3	Kardiologi, seng	1015	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,8	0,0
16	3	Kardiologi, us	454	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
17	3	Endokrinologi, seng	105	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,8	0,0
18	3	Endokrinologi, us	221	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
19	3	Reumatologi, us	200	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,8
20	3	Intern medicin, seng	1120	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,5	0,0
21	3	Intern medicin, us	129	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,0
22	3	Ortopædkirugi, seng	1470	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,5	0,0
23	3	Ortopædkirurgi, us	740	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,5
24	3	Arbejdsmedicin, us	30	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,8	0,8
25	2	Admin, lung, kar, endo, reuma, intern, orto, arbejds	2951	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,0	0,3	0,8	0,8
26	3	Kirurgi, seng	1750	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
27	3	Kirurgi, us	230	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
28	3	Urologi, seng	525	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
29	3	Urologi, us	230	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
30	3	Gastroenhed, seng	525	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
31	3	Gastroenhed, us	164	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
32	3	Nefrologi, seng	490	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
33	3	Nefrologi, us	2102	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
34	3	Gynækologi, seng	140	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
1,0																						
1,0	1,0																					
0,8	0,0	1,0																				
0,0	0,8	1,0	1,0																			
0,0	0,8	0,0	0,8	1,0																		
0,8	0,0	0,8	0,0	0,0	1,0																	
0,0	0,8	0,0	0,8	0,8	0,5	1,0																
0,8	0,0	0,5	0,0	0,0	0,5	0,0	1,0															
0,0	0,5	0,0	0,5	0,5	0,0	0,5	1,0	1,0														
0,0	0,8	0,0	0,8	0,8	0,0	0,5	0,0	0,5	1,0													
0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	1,0												
0,5	0,0	0,5	0,0	0,0	0,5	0,0	0,5	0,0	0,0	0,0	1,0											
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	1,0	1,0										
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,8	0,0	1,0									
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,8	1,0	1,0								
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,8	0,0	0,8	0,0	1,0							
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,8	0,0	0,8	1,0	1,0						
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	1,0					
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,8	0,0	0,8	0,0	0,8	1,0	1,0				
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	1,0			

i	FT	Beskrivelse	m2	1	2	3	4	5	6	7	8	9	10	11	12	13	14
35	3	Gynækologi, us	275	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
36	3	Otologi, seng	105	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
37	3	Otologi, us	230	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
38	2	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	2741	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,0	0,3	0,0	0,0
39	3	Onkologi, seng	525	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
40	3	Onkologi, us	565	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
41	3	Hæmatologi, seng	175	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
42	3	Hæmatologi, us	329	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,3
43	2	Admin, onkologi, hæmatologi	1475	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,0	0,3	0,0	0,0
44	3	Neurologi, seng	735	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
45	3	Neuroreha/fysiol, seng	630	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
46	3	Oftalmologi, seng	35	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
47	3	Neuro, us	280	0,8	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,8	0,3	0,0	0,0	0,3
48	2	neuro, admin	1264	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
49	3	Psykiatri, seng	2905	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,0
50	3	Psykiatri, v, us	850	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,3	0,0	0,0	0,0
51	3	Psykiatri, b/u, seng	350	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,0
52	3	Psykiatri, b/u, us	312	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,3	0,0	0,0	0,0
53	3	Psykiatri, us	939	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,3	0,0	0,0	0,0
54	2	Psykiatri, admin	6233	0,0	0,0	0,5	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0
55	3	Pædiatri, seng	1200	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,0	0,0
56	3	Pædiatri, us	260	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,3	0,0	0,0	0,0
57	4	Fødestue	140	0,8	0,0	0,0	0,3	0,0	0,0	1,0	1,0	0,0	0,3	0,0	0,0	0,0	0,0
58	3	Obstetrik, seng	840	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,5	0,0	0,3	0,0
59	3	Obstetrik, us/føde	848	0,8	0,0	0,0	0,3	0,0	0,0	1,0	1,0	0,0	0,3	0,3	0,0	0,0	0,0
60	3	Obstetrik/Pædiatri, admin	1687	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,5	0,0	0,0	0,0	0,0	0,0
61	2	Administration og forskning	3661	0,8	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,3	0,3	0,8	0,0	0,0	0,0
62	3	Patienthotel	1.610	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
63	1	Ernæringsenheden	280	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
64	1	Ergoterapi og fysioterapi	1.080	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
65	2	Kirkerum og kapel	600	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
66	1	Køkken og kantine	1.329	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
67	1	Apotek	800	0,0	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
68	1	Service og logistik	12350	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

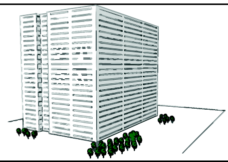
15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	1,0	1,0		
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,5	0,0	0,5	0,0	1,0	
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	0,0	0,8	1,0	1,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0
0,0	0,3	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0
0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	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	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0
0,3	0,0	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,8	0,0	0,3	0,0
0,0	0,0	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,3	0,0	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,5	0,8	0,0	0,3
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,3	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	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	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	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	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,8	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,5	0,0	0,0	0,0	0,5	0,0	0,5	0,0	0,5	0,0	0,5	0,0	0,5	0,0	0,5	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

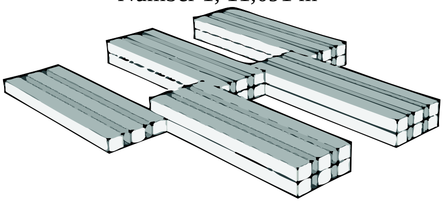
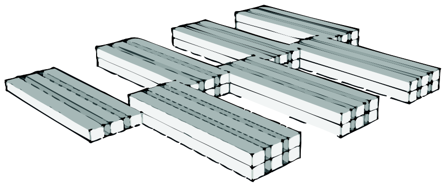
i	FT	Beskrivelse	m2	38	39	40	41	42	43	44	45	46	47	48	49	50	51
38	2	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	2741	1,0													
39	3	Onkologi, seng	525	0,0	1,0												
40	3	Onkologi, us	565	0,0	1,0	1,0											
41	3	Hæmatologi, seng	175	0,0	0,8	0,0	1,0										
42	3	Hæmatologi, us	329	0,0	0,0	0,8	1,0	1,0									
43	2	Admin, onkologi, hæmatologi	1475	0,3	0,8	0,8	0,8	0,8	1,0								
44	3	Neurologi, seng	735	0,0	0,3	0,0	0,3	0,0	0,0	1,0							
45	3	Neuroreha/fysiol, seng	630	0,0	0,3	0,0	0,3	0,0	0,0	1,0	1,0						
46	3	Oftalmologi, seng	35	0,0	0,3	0,0	0,3	0,0	0,0	0,8	0,8	1,0					
47	3	Neuro, us	280	0,0	0,0	0,3	0,0	0,3	0,0	1,0	0,8	0,8	1,0				
48	2	neuro, admin	1264	0,3	0,0	0,0	0,0	0,0	0,3	0,8	0,8	0,8	0,8	1,0			
49	3	Psykiatri, seng	2905	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0		
50	3	Psykiatri, v, us	850	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0	1,0	
51	3	Psykiatri, b/u, seng	350	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,5	1,0
52	3	Psykiatri, b/u, us	312	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,5	1,0
53	3	Psykiatri, us	939	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0	1,0	0,5
54	2	Psykiatri, admin	6233	0,3	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,3	0,8	0,8	0,8
55	3	Pædiatri, seng	1200	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
56	3	Pædiatri, us	260	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
57	4	Fødestue	140	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
58	3	Obstetrik, seng	840	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
59	3	Obstetrik, us/føde	848	0,0	0,0	0,3	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
60	3	Obstetrik/Pædiatri, admin	1687	0,3	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0
61	2	Administration og forskning	3661	0,3	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0
62	3	Patienthotel	1.610	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
63	1	Ernæringsenheden	280	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0
64	1	Ergoterapi og fysioterapi	1.080	0,0	0,0	0,0	0,0	0,0	0,0	0,8	0,8	0,0	0,8	0,0	0,0	0,0	0,0
65	2	Kirkerum og kapel	600	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
66	1	Køkken og kantine	1.329	0,0	0,5	0,0	0,5	0,0	0,0	0,5	0,0	0,5	0,0	0,0	0,0	0,0	0,0
67	1	Apotek	800	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
68	1	Service og logistik	12350	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68
1,0																
0,5	1,0															
0,8	0,8	1,0														
0,0	0,0	0,0	1,0													
0,0	0,0	0,0	1,0	1,0												
0,0	0,0	0,0	0,8	0,8	1,0											
0,0	0,0	0,0	1,0	0,5	1,0	1,0										
0,0	0,0	0,0	0,8	0,8	1,0	1,0	1,0									
0,0	0,0	0,3	0,8	0,8	0,8	0,8	0,8	1,0								
0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,3	1,0							
0,0	0,0	0,0	1,0	0,0	1,0	1,0	1,0	0,3	0,0	1,0						
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	1,0					
0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3	0,0	0,5	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	1,0			
0,0	0,0	0,0	0,5	0,0	0,0	0,5	0,0	0,0	0,0	0,5	0,8	0,3	0,0	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	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	0,8	0,8	1,0

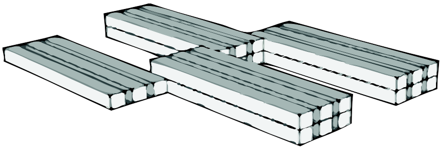
Appendix C. Design configuration by building typologies (9.1)

Table 10-1 Functional distribution, referring the costs illustrated in Figure 9-1. The functional distribution is generated by B_T=1 (High-rise), L_T=3 (Double corridor), O_T=1 (Functionally split), N_{GU} = 5 units.



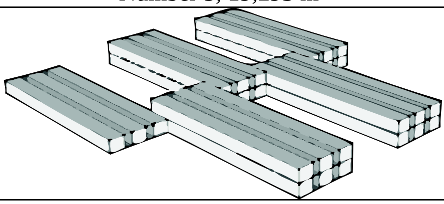
Number 1, 11,091 m²		Number 2, 31,395 m²	
			
	Functionalities in unit		Functionalities in unit
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	9	Diagnostik
54	Pædiatri, seng	10	Laboratorium
60	Administration og forskning	20	Intern medicin, us
62	Ernæringsenheden	22	Ortopædkirurgi, us
63	Ergoterapi og fysioterapi	24	Admin, lung, kar, endo, reuma, intern, orto, arbejds
65	Køkken og kantine	25	Kirurgi, seng
66	Apotek	48	Psykiatri, seng
		49	Psykiatri, v, us
		50	Psykiatri, b/u, seng
		52	Psykiatri, us
		53	Psykiatri, admin
		56	Fødestue
		61	Patienthotel
		64	Kirkerum og kapel

Number 4, 13,802 m^2



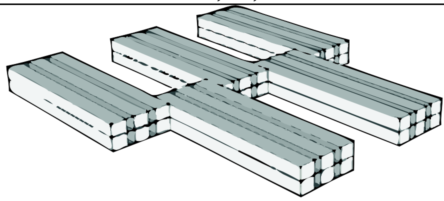
Functionalities in unit	
11	Diagnostik, admin
29	Gastroenhed, seng
31	Nefrologi, seng
40	Hæmatologi, seng
42	Admin, onkologi, hæmatologi
44	Neuroreha/fysiol, seng
51	Psykiatri, b/u, us
59	Obstetrik/Pædiatri, admin

Number 5, 19,293 m^2



Functionalities in unit	
1	Akutseng, somatik
3	Akut, us, diag, skadest
6	OP
8	Intensiv, admin

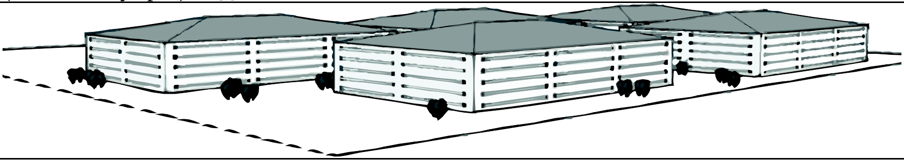
Number 3, 23,563 m^2



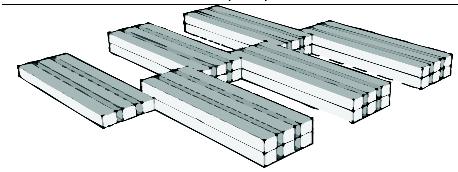
Functionalities in unit	
2	Akutseng, psyakiatri
4	Akut, admin, vagtvær
5	Intensiv, seng
7	Opvågning
12	Lungemed, seng
13	Lungemed, us
14	Kardiologi, seng
15	Kardiologi, us
16	Endokrinologi, seng
17	Endokrinologi, us
18	Reumatologi, us
19	Intern medicin, seng
21	Ortopædkirugi, seng
23	Arbejdsmedicin, us
26	Kirurgi, us
27	Urologi, seng
28	Urologi, us
30	Gastroenhed, us
32	Nefrologi, us
33	Gynækologi, seng
34	Gynækologi, us
35	Otologi, seng
36	Otologi, us
38	Onkologi, seng
39	Onkologi, us
41	Hæmatologi, us
43	Neurologi, seng
45	Oftalmologi, seng
46	Neuro, us
47	neuro, admin
55	Pædiatri, us
57	Obstetrik, seng
58	Obstetrik, us/føde

The functionality distribution shows a distribution, where all wards correlated with their respective examination rooms are in Unit 3. As anticipated by the cost function reaching the upper boundary, the unit possess several functionalities and thereby a high correlation factor. One unit consists of administrative facilities and another of psychiatrics. Unit 5 is the ‘acute hospital’ of the emergency department, operation rooms and some intensive care.

Table 10-2 Functional distribution, referring the costs illustrated in Figure 9-2. The functional distribution is generated by B_T=2 (Urban), L_T=3 (Double corridor), O_T=1 (Functionally split), N_{GU} = 5 units.

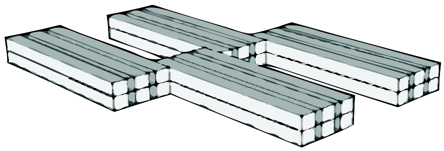


Number 3, 13,802 m^2



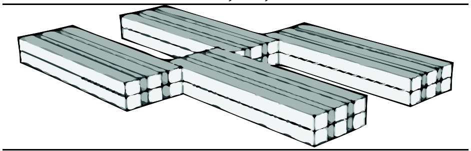
	Functionalities in unit
2	Akutseng, psyakiatri
3	Akut, us, diag, skadest
23	Arbejdsmedicin, us
24	Admin, lung, kar, endo,
27	reuma, intern, orto, arbejds
32	Urologi, seng
41	Nefrologi, us
48	Hæmatologi, us
50	Psykiatri, seng
54	Psykiatri, b/u, seng
64	Pædiatri, seng
	Kirkerum og kapel

Number 2, 18,464 m^2

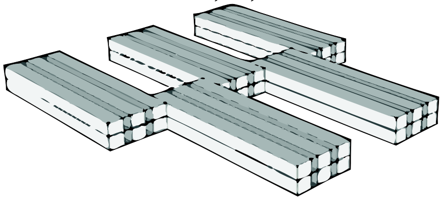
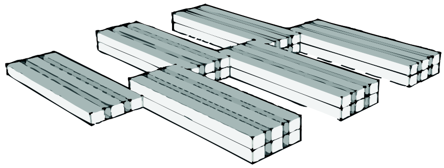


	Functionalities in unit
12	Lungemed, seng
13	Lungemed, us
14	Kardiologi, seng
15	Kardiologi, us
16	Endokrinologi, seng
17	Endokrinologi, us
18	Reumatologi, us
19	Intern medicin, seng
20	Intern medicin, us
21	Ortopædkirugi, seng
22	Ortopædkirurgi, us
26	Kirurgi, us
28	Urologi, us
30	Gastroenhed, us
31	Nefrologi, seng
33	Gynækologi, seng
34	Gynækologi, us
35	Otologi, seng
36	Otologi, us
38	Onkologi, seng
39	Onkologi, us
40	Hæmatologi, seng
44	Neuroreha/fysiol, seng
46	Neuro, us
47	neuro, admin
49	Psykiatri, v, us
51	Psykiatri, b/u, us
55	Pædiatri, us
58	Obstetrik, us/føde
62	Ernæringsenheden
63	Ergoterapi og fysioterapi
65	Køkken og kantine
66	Apotek

Number 5, 19,293 m^2

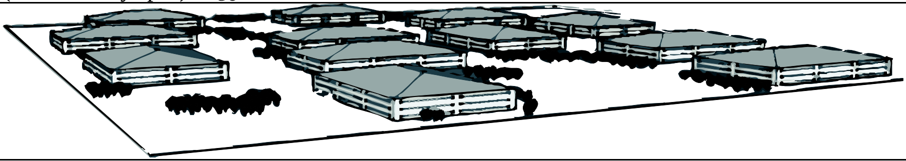


	Functionalities in unit
1	Akutseng, somatik
6	OP
10	Laboratorium
29	Gastroenhed, seng
43	Neurologi, seng
45	Oftalmologi, seng
57	Obstetrik, seng
61	Patienthotel

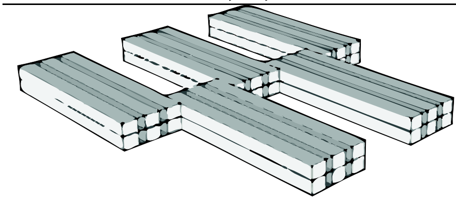
	Number 1, 14,481 m^2		Number 2, 21,966 m^2
			
	Functionalities in unit		Functionalities in unit
5	Intensiv, seng	4	Akut, admin, vagtvær
8	Intensiv, admin	7	Opvågning
11	Diagnostik, admin	9	Diagnostik
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi	25	Kirurgi, seng
		42	Admin, onkologi, hæmatologi
59	Obstetrik/Pædiatri, admin	52	Psykiatri, us
		53	Psykiatri, admin
		56	Fødestue
		60	Administration og forskning

The urban configuration in Table 10-2 has parallel to the high-rise configuration above, in Table 10-1. As expected one unit, Unit 3 consists of correlated wards and examination rooms. Intensive care correlates diagnostics' administration and further administrations. Operation rooms, acute wards and laboratory correlate some wards and the patient hotel.

Table 10-3 Functional distribution, referring the costs illustrated in Figure 9-3. The functional distribution is generated by B_T=3 (Campus), L_T=3 (Double corridor), O_T=1 (Functionally split), N_{GU} = 5 units.

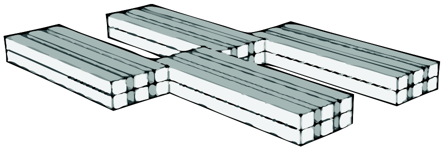


Number 3, 21,048 m^2



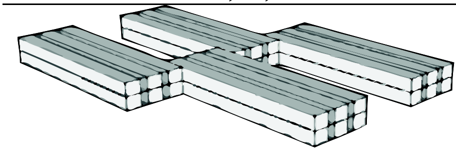
	Functionalities in unit
56	Fødestue
57	Obstetrik, seng
59	Obstetrik/Pædiatri, admin
64	Kirkerum og kapel

Number 2, 17,346 m^2

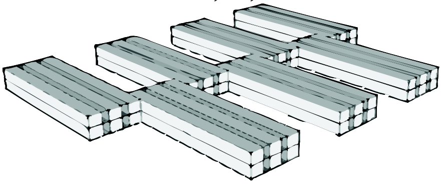
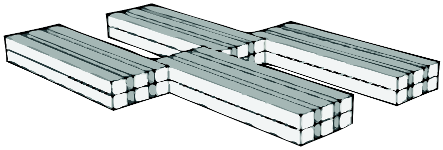


	Functionalities in unit
1	Akutseng, somatik
13	Lungemed, us
15	Kardiologi, us
19	Intern medicin, seng
20	Intern medicin, us
21	Ortopædkirugi, seng
24	Admin, lung, kar, endo, reuma, intern, orto, arbejds
26	Kirurgi, us
27	Urologi, seng
28	Urologi, us
30	Gastroenhed, us
32	Nefrologi, us
33	Gynækologi, seng
34	Gynækologi, us
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi
38	Onkologi, seng
39	Onkologi, us
41	Hæmatologi, us
46	Neuro, us
58	Obstetrik, us/føde

Number 5, 10,612 m^2



	Functionalities in unit
44	Neuroreha/fysiol, seng
53	Psykiatri, admin
55	Pædiatri, us
62	Ernæringsenheden
63	Ergoterapi og fysioterapi
65	Køkken og kantine
66	Apotek

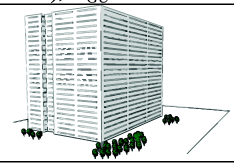
Number 1, 23,263 m^2		Number 2, 15,737 m^2	
			
	Functionalities in unit		Functionalities in unit
9	Diagnostik	4	Akut, admin, vagtvær
10	Laboratorium	5	Intensiv, seng
11	Diagnostik, admin	17	Endokrinologi, us
12	Lungemed, seng	25	Kirurgi, seng
40	Hæmatologi, seng	42	Admin, onkologi, hæmatologi
43	Neurologi, seng	47	Neuro, admin
48	Psykiatri, seng	49	Psykiatri, v, us
52	Psykiatri, us	51	Psykiatri, b/u, us
61	Patienthotel	60	Administration og forskning

These three functional distributions correspond the cost diagrams of 9.1 and thus conclude the analysis of sensitivity of building typologies.

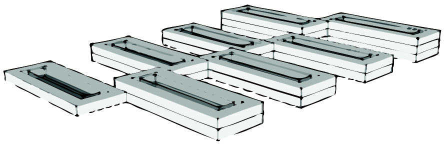
Appendix D. Design configuration by N_{GU} (9.4)

Firstly, the functional distribution are listed.

Table 10-4 Example of functional distribution generated by B_T=1 (High-rise), L_T=4 (Courtyard, exterior), O_T=2 (Sectorized), N_{GU} = 5 units.



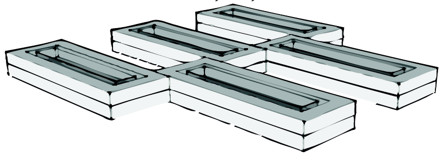
Number 1, 34,665 m²



Functionalities in unit

2	Akutseng, psyakiatri
3	Akut, us, diag, skadest
4	Akut, admin, vagtvær
10	Laboratorium
12	Lungemed, seng
13	Lungemed, us
30	Gastroenhed, us
31	Nefrologi, seng
33	Gynækologi, seng
35	Otologi, seng
38	Onkologi, seng
40	Hæmatologi, seng
42	Admin, onkologi, hæmatologi
44	Neuroreha/fysiol, seng
45	Oftalmologi, seng
47	neuro, admin
50	Psykiatri, b/u, seng
53	Psykiatri, admin
54	Pædiatri, seng
58	Obstetrik, us/føde
60	Administration og forskning
61	Patienthotel
64	Kirkerum og kapel

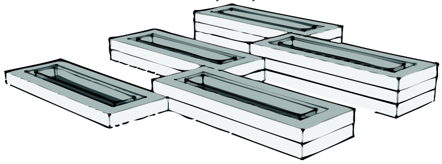
Number 2, 10,667 m²



Functionalities in unit

7	Opvågning
8	Intensiv, admin
16	Endokrinologi, seng
22	Ortopædkirurgi, us
25	Kirurgi, seng
43	Neurologi, seng
49	Psykiatri, v, us
51	Psykiatri, b/u, us
52	Psykiatri, us
57	Obstetrik, seng

Number 3, 11,447 m²



Functionalities in unit

19	Intern medicin, seng
21	Ortopædkirugi, seng
27	Urologi, seng
32	Nefrologi, us
37	Admin, kirurgi, urologi, gastro, Nefro,
62	gyn, otologi
63	Ernæringsenheden
65	Ergoterapi og fysioterapi
66	Køkken og kantine
	Apotek

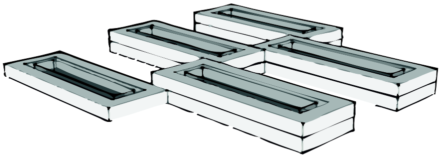
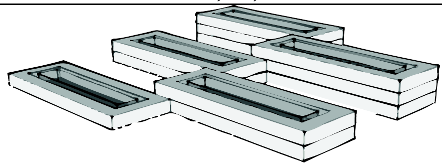
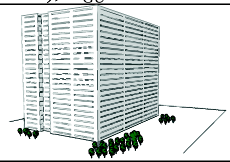
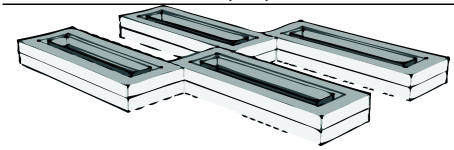
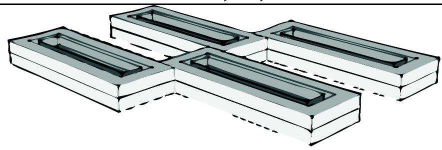
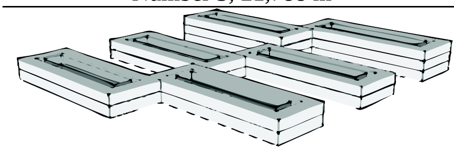
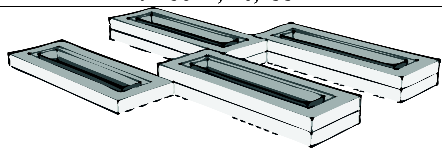
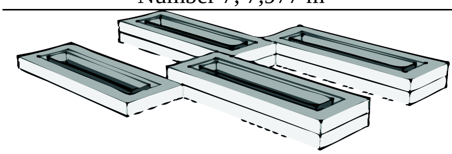
Number 4, 8,930 m^2		Number 5, 22,297 m^2	
			
Functionalities in unit		Functionalities in unit	
14	Kardiologi, seng	1	Akutseng, somatik
15	Kardiologi, us	5	Intensiv, seng
17	Endokrinologi, us	6	OP
18	Reumatologi, us	9	Diagnostik
20	Intern medicin, us	11	Diagnostik, admin
23	Arbejdsmedicin, us	29	Gastroenhed, seng
24	Admin, lung, kar, endo, reuma, intern,	34	Gynækologi, us
26	orto, arbejds	36	Otologi, us
28	Kirurgi, us	41	Hæmatologi, us
39	Urologi, us	46	Neuro, us
48	Onkologi, us	55	Pædiatri, us
	Psykiatri, seng	56	Fødestue
		59	Obstetrik/Pædiatri, admin

Table 10-5 Example of functional distribution generated by B_T=1 (High-rise), L_T=4 (Courtyard, exterior), O_T=2 (Sectorized), N_{GU} = 7 units.



Number 1, 16,817 m^2		Number 6, 87,89 m^2	
			
Functionalities in unit		Functionalities in unit	
9	Diagnostik	1	Akutseng, somatik
10	Laboratorium	15	Kardiologi, us
28	Urologi, us	26	Kirurgi, us
36	Otologi, us	32	Nefrologi, us
46	Neuro, us	33	Gynækologi, seng
50	Psykiatri, b/u, seng	34	Gynækologi, us
55	Pædiatri, us	48	Psykiatri, seng
		53	Psykiatri, admin
		64	Kirkerum og kapel

Number 3, 21,788 m^2		Number 4, 16,199 m^2	
			
Functionalities in unit		Functionalities in unit	
3	Akut, us, diag, skadest	2	Akutseng, psyakiatri
7	Opvågning	5	Intensiv, seng
11	Diagnostik, admin	8	Intensiv, admin
13	Lungemed, us	14	Kardiologi, seng
17	Endokrinologi, us	16	Endokrinologi, seng
19	Intern medicin, seng	21	Ortopædkirugi, seng
20	Intern medicin, us	22	Ortopædkirurgi, us
25	Kirurgi, seng	42	Admin, onkologi, hæmatologi
27	Urologi, seng	Number 7, 7,977 m^2	
31	Nefrologi, seng		
37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi		
41	Hæmatologi, us		
44	Neuroreha/fysiol, seng		
45	Oftalmologi, seng	Functionalities in unit	
49	Psykiatri, v, us	24	Admin, lung, kar, endo, reuma, intern, orto, arbejds
51	Psykiatri, b/u, us	39	Onkologi, us
52	Psykiatri, us	60	Administration og forskning
		66	Apotek

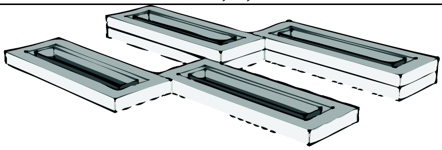
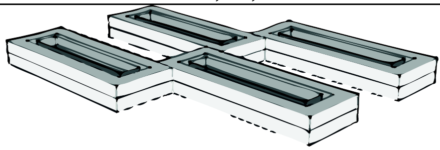
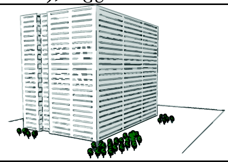
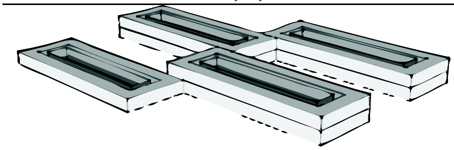
Number 5, 8,924 m^2		Number 2, 15,489 m^2	
			
Functionalities in unit		Functionalities in unit	
4	Akut, admin, vagtvær	6	OP
18	Reumatologi, us	12	Lungemed, seng
30	Gastroenhed, us	23	Arbejdsmedicin, us
38	Onkologi, seng	29	Gastroenhed, seng
43	Neurologi, seng	35	Otologi, seng
47	neuro, admin	40	Hæmatologi, seng
59	Obstetrik/Pædiatri, admin	54	Pædiatri, seng
61	Patienthotel	56	Fødestue
62	Ernæringsenheden	57	Obstetrik, seng
63	Ergoterapi og fysioterapi	58	Obstetrik, us/føde
65	Køkken og kantine		

Table 10-6 Example of functional distribution generated by B_T=1 (High-rise), L_T=4 (Courtyard, exterior), O_T=2 (Sectorized), N_{GU} = 9 units.



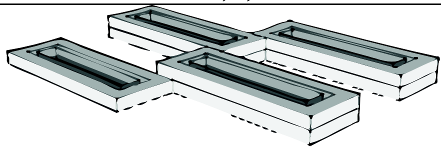
Number 1, 6,921 m²



Functionalities in unit

32	Nefrologi, us
61	Patienthotel
63	Ergoterapi og fysioterapi
65	Køkken og kantine
66	Apotek

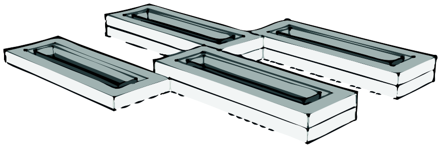
Number 2, 6,673 m²



Functionalities in unit

32	Nefrologi, us
61	Patienthotel
63	Ergoterapi og fysioterapi
65	Køkken og kantine
66	Apotek

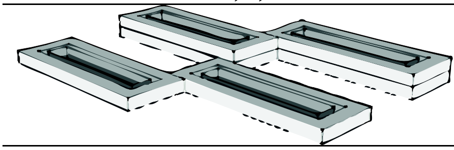
Number 3, 6,776 m²



Functionalities in unit

8	Intensiv, admin
33	Gynækologi, seng
38	Onkologi, seng
42	Admin, onkologi, hæmatologi
47	neuro, admin

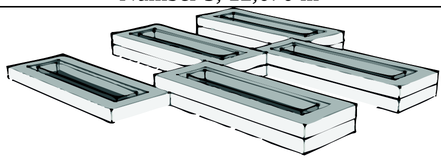
Number 4, 5,092 m²



Functionalities in unit

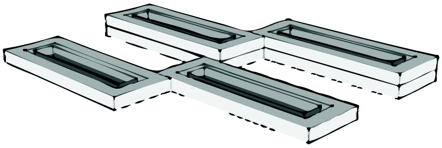
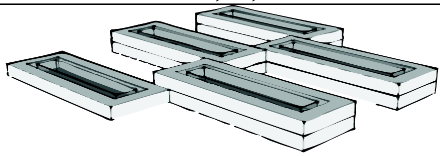
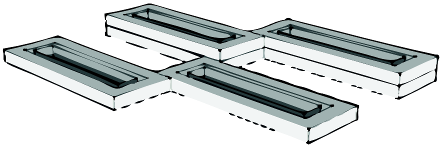
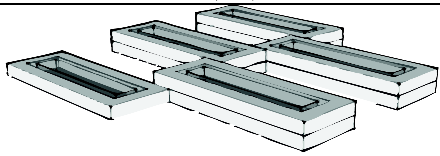
2	Akutseng, psyakiatri
13	Lungemed, us
15	Kardiologi, us
17	Endokrinologi, us
18	Reumatologi, us
20	Intern medicin, us
22	Ortopædkirurgi, us
27	Urologi, seng
58	Obstetrik, us/føde
59	Obstetrik/Pædiatri, admin

Number 5, 12,070 m²



Functionalities in unit

7	Opvågning
9	Diagnostik
16	Endokrinologi, seng
21	Ortopædkirugi, seng
23	Arbejdsmedicin, us
24	Admin, lung, kar, endo, reuma, intern, orto, arbejds
29	Gastroenhed, seng
31	Nefrologi, seng
40	Hæmatologi, seng
44	Neuroreha/fysiol, seng
55	Pædiatri, us
56	Fødestue

Number 6, 9,654 m^2		Number 7, 17,356 m^2	
			
Functionalities in unit		Functionalities in unit	
1	Akutseng, somatik	5	Intensiv, seng
3	Akut, us, diag, skadest	6	OP
28	Urologi, us	14	Kardiologi, seng
41	Hæmatologi, us	19	Intern medicin, seng
43	Neurologi, seng	36	Otologi, us
45	Oftalmologi, seng	49	Psykiatri, v, us
46	Neuro, us	54	Pædiatri, seng
48	Psykiatri, seng	60	
50	Psykiatri, b/u, seng		
Number 8, 11,434 m^2		Number 9, 12,030 m^2	
			
Functionalities in unit		Functionalities in unit	
10	Laboratorium	11	Diagnostik, admin
25	Kirurgi, seng	35	Otologi, seng
26	Kirurgi, us	37	Admin, kirurgi, urologi, gastro, Nefro, gyn, otologi
34	Gynækologi, us	53	Psykiatri, admin
51	Psykiatri, b/u, us		
52	Psykiatri, us		

The functionality distribution demanded 14 generations to achieve 10 generations of satisfied constraints.

The following illustrates the cost functions.

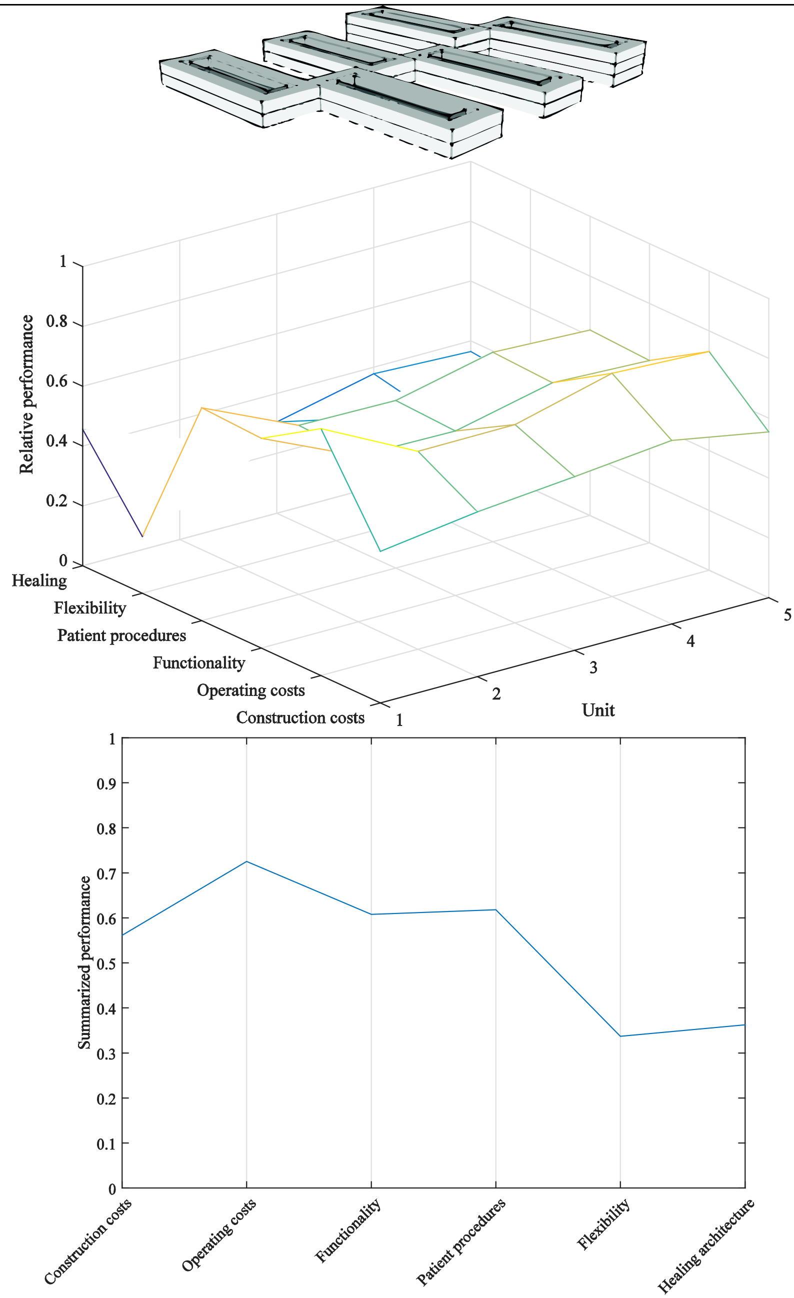


Figure 10-1 Mean costs of functional distributions after 10 simulations, B_T =2 (Urban), L_T = 4 (Courtyard, exterior), O_T = 2 (Sectorized), N_{GU} = 5.

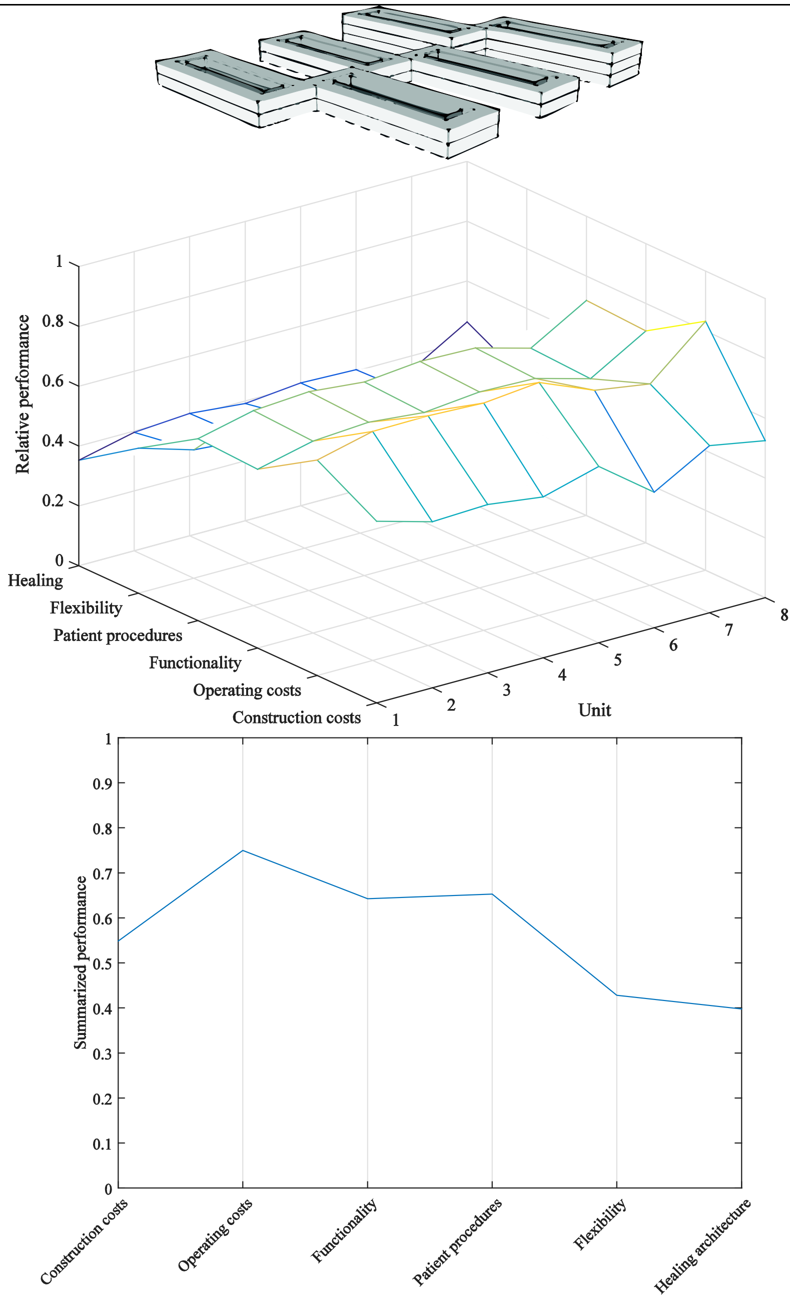


Figure 10-2 Mean costs of functional distributions after 10 simulations, B_T =2 (Urban), L_T = 4 (Courtyard, exterior), O_T = 2 (Sectorized), N_{GU} = 8.

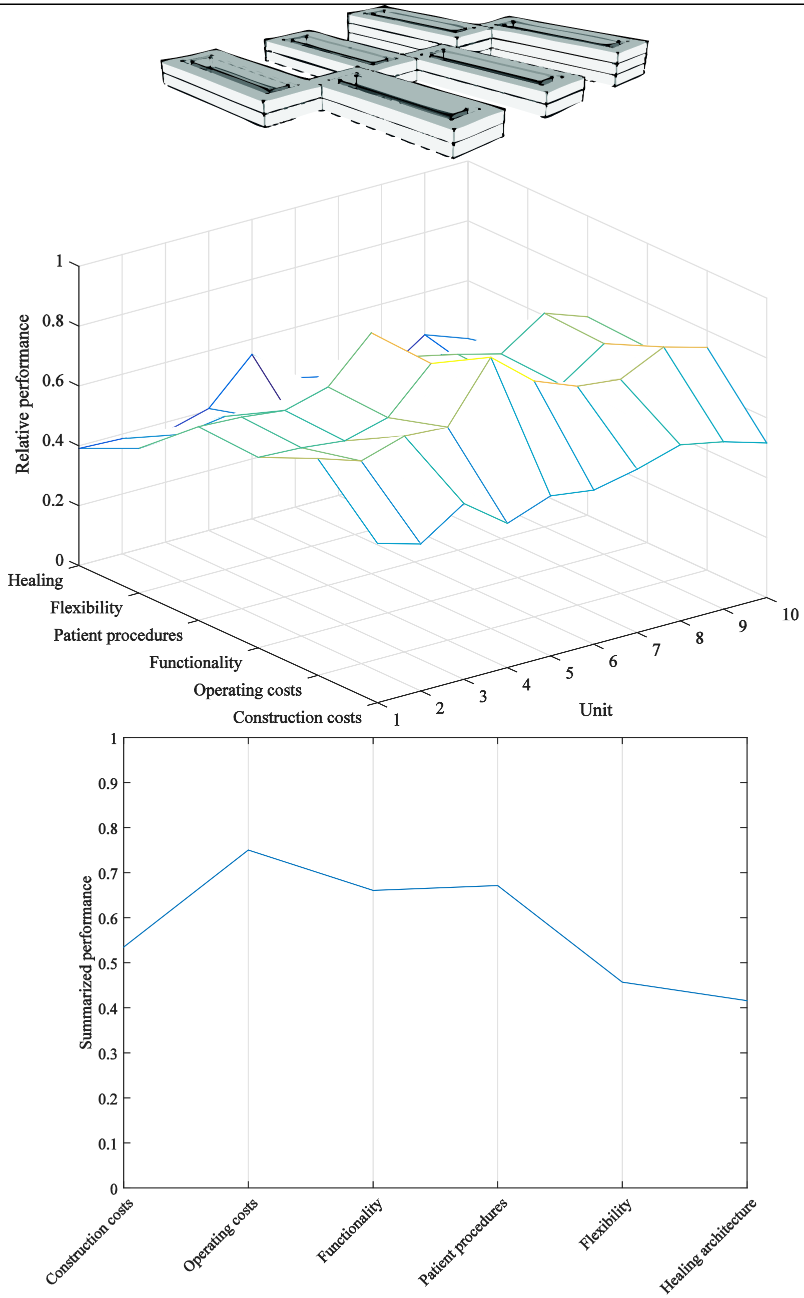
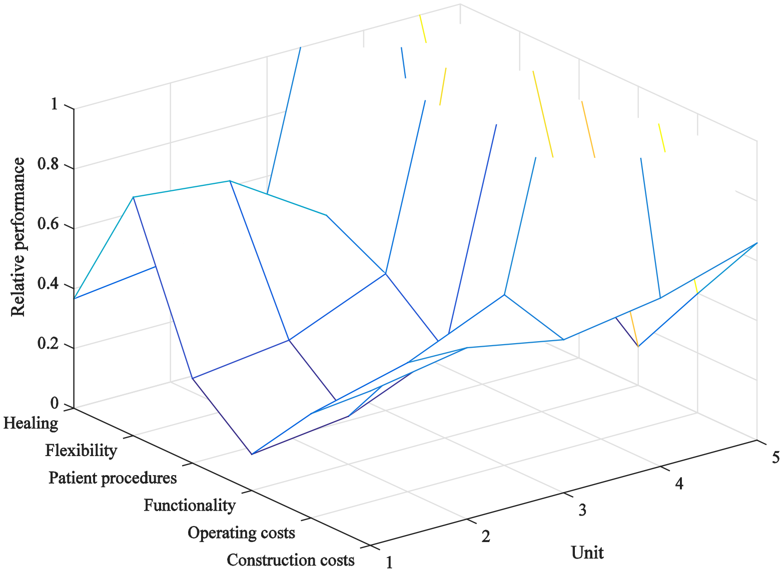


Figure 10-3 Mean costs of functional distributions after 10 simulations, B_T =2 (Urban), L_T = 4 (Courtyard, exterior), O_T = 2 (Sectorized), N_{GU} = 10.

Appendix E. Design configuration by ’best’ distributions (9.5)

The summarized costs functions are parallel, despite the remarkable different functional distributions.



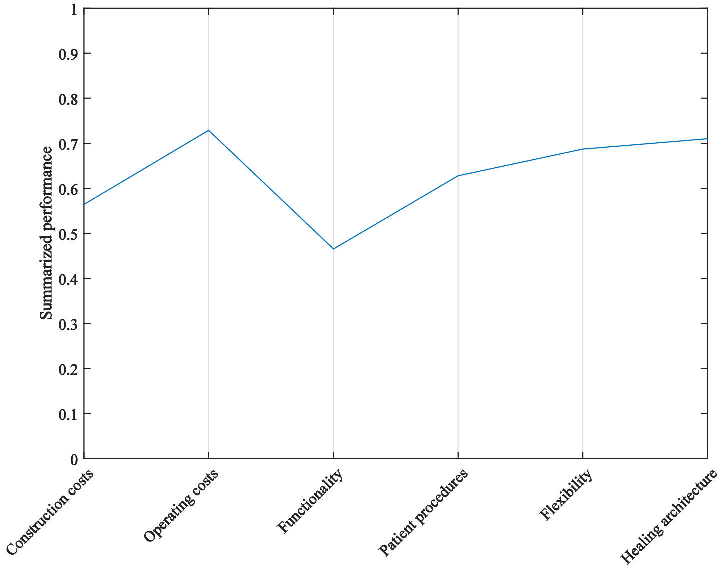


Figure 10-4 Costs of functional distributions referring Table 9-7 (correlated wards and examination rooms), B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally-split), N_{GU} = 5.

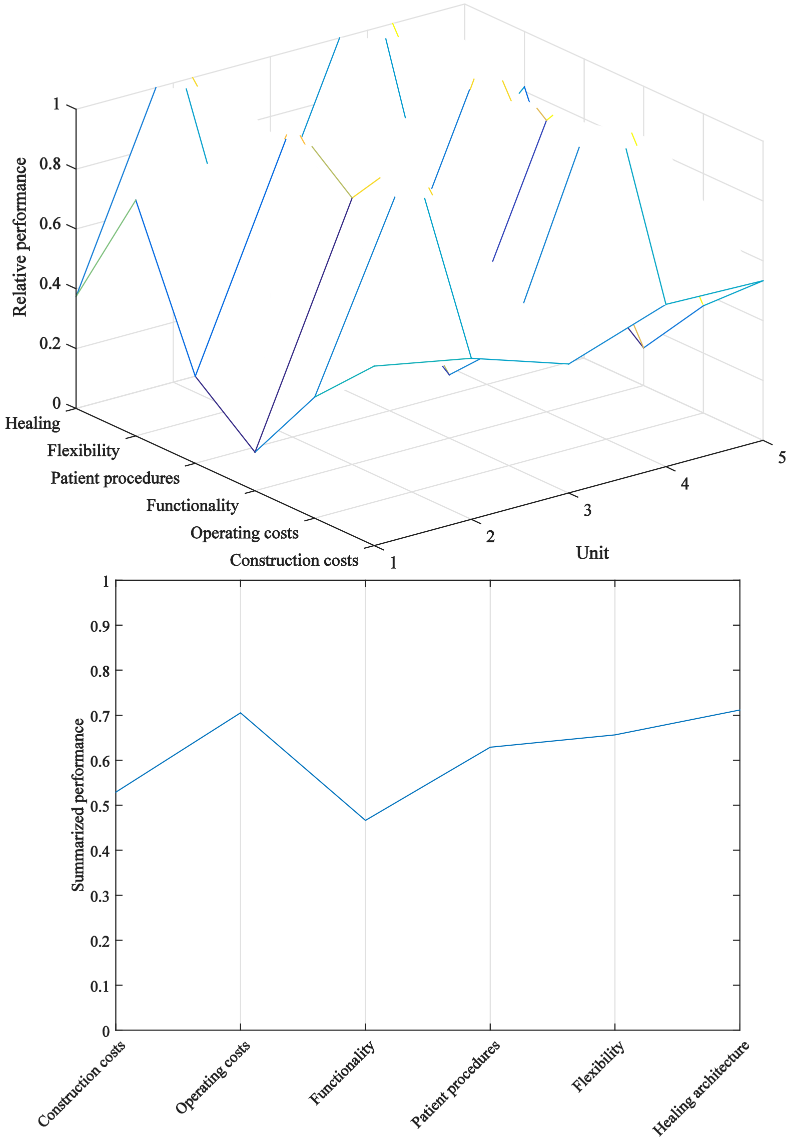
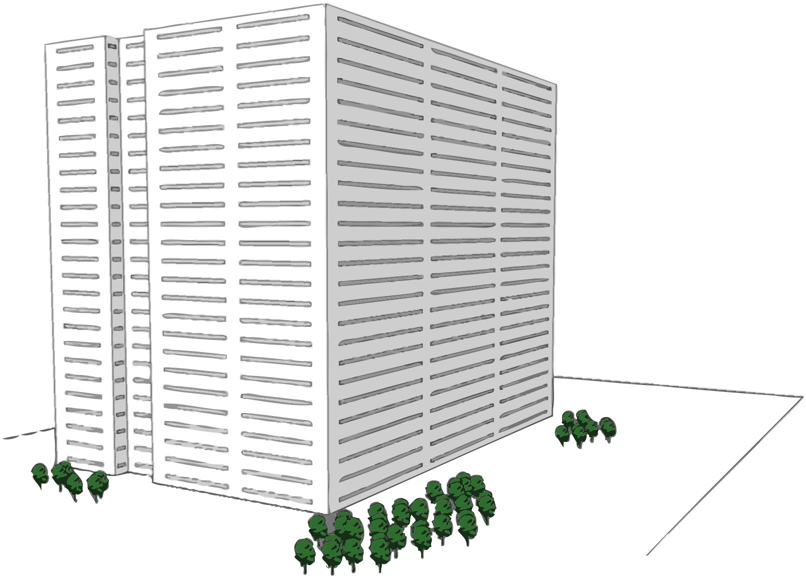


Figure 10-5 Costs of functional distributions referring Table 9-8 (functionally split), B_T =3 (Campus), L_T = 3 (Double corridor), O_T = 1 (Functionally-split), N_{GU} = 5.



SUMMARY

This PhD project presents a design model generating and evaluating hospital designs from a holistic perspective. By visualizing and quantifying the different performances inherent in hospital design, the design model facilitates qualified and profound decision. This approach contributes to optimized hospital design and finally improved hospitals.

The present study aims to solve the architectural design problem as a response to the requirements and preferences of the functionalities and performances. This approach emphasizes the practical applicability of the design model for architects, engineers and hospital planners. The design model consists of formal descriptions of hospital functionalities, architectural qualities and engineering qualities.

By the formal descriptions the design model can weigh and compare the impact of different prioritizations and the design model can visualize and quantify consequences of design choices even in the early design phase. A qualitative study of hospital design and hospital functionality defines the base of the formal descriptions, described by a correlation matrix and a correlation factor. This definition facilitates the implementation of evidence-based design and it is prepared for ongoing updates. The correlation factor drives the generation of the conceptual design, as a basis for further architectural design exploration.

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