A Layout Design Decision-Support Framework and Concept Demonstrator for Rural Hospitals using Mixed Methods

by

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DECLARATION

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ABSTRACT

Layout design is an ever-present problem that has a significant effect on the operations of an organisation, especially in the context of healthcare which deals with the lives of patients. It is a complex problem that has long-term consequences and oftentimes competing objectives. Literature has focused almost exclusively on using either quantitative or qualitative layout design methods for designing layouts. This study develops a generic framework using both quantitative and qualitative layout design methods that will guide the user to design a near optimal layout for a rural hospital while taking into consideration the relevant laws and standards as well as the health outcomes of the surrounding rural community. Rural and urban lifestyles, health, and illnesses differ in many ways. General hospital design methods are therefore not necessarily appropriate for hospitals in these areas. There is thus a need for a framework to be tailored for a rural community.

Following a mixed methods methodology, a systematic literature review of quantitative and qualitative layout design methods along with hospital design considerations were conducted in order to determine the most adequate methods for designing a hospital layout at the block diagram level of detail. Furthermore, the commonalities and differences between rural and urban hospitals were investigated including laws and standards relevant to hospital layouts.

The qualitative layout design methods involved different layout procedures and Muther's Systematic Layout Planning Procedure was found to be most adequate. Furthermore, hospital design considerations such as patient-centeredness, efficiency, flexibility and expandability, sustainability, and therapeutic environment were identified and linked with the quantitative layout methods. It was also found that rural communities have different needs to urban ones with regard to access to medical care, prominent illnesses, and attitudes towards health. The healthcare personnel shortages are particularly problematic for rural communities.

The quantitative layout design methods involved layout models, solution methods (exact methods, metaheuristics, and hybrid metaheuristics), and layout software. Using criteria of objectives, assumptions, inputs, outputs, and hospital design considerations, the Quadratic Set Covering Problem was determined to be the most appropriate model for designing a rural hospital block diagram layout. It was deemed possible to integrate the quantitative and qualitative methods by embedding the qualitative data into this quantitative model. The rural hospital design framework was developed using Excel VBA and RStudio.

The framework was validated via two routes. Firstly, semi-structured interviews were conducted with experts in the field, i.e. expert analyses. Secondly a case study of the Semonkong Hospital Project was employed wherein the framework was applied successfully. The framework was deemed valid according to both the expert analyses and the case study.

OPSOMMING

Die uitleg van 'n gebou het 'n belangrike impak op die bedrywighede van 'n organisasie – veral in die konteks van gesondheidsorg waar daar met pasiënte se lewens gewerk word. Dit is 'n ingewikkelde probleem wat oor langtermyneffekte beskik en dikwels teenstrydige doelwitte. Die literatuur vir uitleg ontwerpsmetodes het meestal gefokus op óf kwantitatiewe óf kwalitatiewe uitleg ontwerpsmetodes. Hierdie studie ontwikkel 'n generiese raamwerk wat beide van hierdie metodes gebruik om 'n gebruiker te lei om die uitleg van 'n plattelandse hospital te ontwerp wat die gepaste wette en standaarde en die gesondheid van die omliggende gemeenskap in ag neem. Landelike- en stedelike gemeenskappe verskil in terme van hul lewenstyl, gesondheid en tipe siektes. Algemene uitleg ontwerpsmetodes is dus nie noodwendig geskik vir 'n plattelandse hospitaal nie. Daar is dus 'n behoefte om 'n raamwerk te ontwikkel wat spesifiek is vir die uitleg van 'n plattelandse hospitaal.

Hierdie studie volg 'n gemengde metode benadering en 'n sistematiese literatuurstudie is gevolglik afsonderlik gedoen op kwantitatiewe- en kwalitatiewe uitleg ontwerpsmetodes met die doel om die mees geskikte ontwerpsmetodes vir 'n hospitaal uitleg te bepaal. Die verskille en ooreenkomste tussen landelike- en stedelike hospitale was ook ondersoek. Hierdie sluit in wette en standaarde wat van toepassing is op hospitaal uitlegte.

Die kwalitatiewe uitleg ontwerpsmetodes het verskillende uitleg prosedures ondersoek en dit is gevind dat Muther se Sistematiese Uitleg Prosedure die mees geskik is vir die probleem van hierdie studie. Daar is gevind dat die hoof ontwerpsoorwegings vir die uitleg van 'n hospitaal pasiënt-gesentreerdheid, doeltreffendheid, aanpasbaarheid, volhoubaarheid en terapeutiese omgewing is. Daar is gevind dat landelike- en stedelike gemeenskappe verskil in terme van hul toegang tot mediese sorg, prominente siektes, en hul houdings teenoor gesondheid. Een van die grootste probleme in landelike hospitale was hul tekort aan personeel.

Die kwantitatiewe uitleg ontwerpsmetodes sluit uitleg modelle, oplossingsmetodes (presiese metodes, metaheuristieke en hibriede metaheuristieke) en uitleg sagteware in. 'n Kriteria van doelwitte, aannames, insette, uitsette en hospitaal ontwerpsoorwegings was gebruik om die mees geskikte uitleg model te kies naamlik: die 'Quadratic Set Covering Problem'. Dit is gevind dat die kwantitatiewe- en kwalitatiewe uitleg ontwerpsmetodes deur middel van 'embedding' geïntegreer kan word. Die uitleg ontwerp raamwerk vir plattelandse hospitale was ontwikkel met behulp van Excel VBA en RStudio.
Die raamwerk is bekragtig deur twee roetes. Eerstens, semi-gestruktureerde onderhoude was gevoer met kundiges in die velde van gesondheidsorg, plattelandse gemeenskappe en uitleg ontwerp. Tweedens, die raamwerk is toegepas op 'n gevallestudie van die Semonkong Hospitaal Projek. Albei roetes dui daarop dat die raamwerk geldig is.

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"Not to us, Lord, not to us but to your name be the glory, because of your love and faithfulness."

Psalm 115:1 NIV

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- First and foremost my supervisor, Ms Louzanne Bam, for her constant guidance, wisdom and patience throughout this study. I wish you every success and happiness.
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LIST OF SYMBOLS

Symbol	Meaning
A	n x n matrix
b_{ijkl}	monetary term of locating department i at location j
c_{jl}	cost of transporting one patient between location j and location l
c_{ij}	cost of transporting one patient between location j and location l
C	Cost matrix with elements $[c_{ij}]$
d_{jl}	distance between the centroids of locations j and l if facility i is assigned to location j and facility k is assigned to location l
D	distance matrix with elements $[d_{kl}]$ where d_{kl} represents the distance between location k and location l
e_{ij}	the double summation of the monetary term of locating department i at location j
E	a set of edges disjoint from V
F	the set of pairs of departments which must not be adjacent in any feasible solution,
f_{ik}	flow of patients between department i and department k
g_i	the distance between the extreme horizontal sides of department i
g_j	the distance between the extreme horizontal sides of department j
G	a weighted graph with V as a nonempty set of departments, E as a set of edges disjoint from V
h_{ik}^{l}	horizontal distance between facilities i and k when facility i is to the left of facility k; 0 otherwise
h_{ik}^{r}	horizontal distance between facilities i and k when facility i is to the right of facility k; 0 otherwise
h_i	the horizontal distance between department i and the v-axis
h_j	the horizontal distance between department j and the v-axis
$I(i)$	Set of candidate locations for department i
$J_i(j)$	Set of blocks occupied by facility i if it is assigned to location j
k_{ij}	minimum distance by which departments i and j are to be separated
l_i	the distance between the extreme vertical sides of department i
l_j	the distance between the extreme vertical sides of department j
M	an arbitrarily large positive number
m	Number of locations of departments
n	number of departments
N	the set of pairs of departments which must be adjacent in any feasible solution,
o_{ij}	variable indicating if department i is adjacent to department j. 1 if department i is

	adjacent to department j; 0 otherwise
p_{kl}	semi-net revenue from the operation of department k at location i. In other words the gross revenue less cost of primary inputs, but before subtracting transportation cost of intermediate products between department
q	number of blocks into which the total area occupied by all departments is divided into
r_{ij}	the closeness rating indicating desirability of locating department i adjacent to department j
s_{ij}^{v}	vertical clearance, i.e. the minimum distance by which departments i and j are to be separated if they are positioned in opposite rows in the layout
s_{ij}^{h}	the horizontal clearance, i.e. the minimum distance by which departments i and j are to be separated if they are positioned in the same rows in the layout
t_{ij}	the time required for a patient to move from department i to department j
u_{kl}	set of non-negative numbers that represent the required commodity flows in weight units from department k to department l. $k \neq 1$. l = 1, ..., n
V	nonempty set of departments
v_{ik}^{a}	vertical distance between facilities i and k when facility i is above facility k; 0 otherwise
v_{ik}^{b}	vertical distance between facilities i and k when facility i is below facility k; 0 otherwise
v_i	the vertical distance between department i and h-axis
v_j	the vertical distance between department j and h-axis
w_{ij}	a function of the assignment of departments and the monetary term of locating department i at location j
X	Permutation n x n matrix with elements $[x_{ij}]$
x_{ij}	assignment of department i to location j. 1 if department i is at location j; 0 otherwise
$x_{kl,ij}$	1 if there is flow from location i to location j of the commodity which is supplied by department k to department l; 0 if there is no flow
x_{il}	1 if department i is at location l; 0 otherwise
$(\bar{x}_i, \bar{y}_i)$	location of facility i
y_{ijkl}	the integer variable of department i at location j in arrangement k of location l
z_{ij}	variable used to ensure that only one of the constraints hold so that the departments do not overlap
α_{ij}	the frequency of trips required between department i and j
θ	real-valued scaling parameter

γ_{ij} fixed cost of locating and operating department i at location j

LIST OF ACRONYMS

CA	Circulation Area
CF	Circulation Factor
CM	Circulation Multiplier
CS	Community Service
CSIR	Council for Scientific and Industrial Research
FLP	Facility Layout Problem
GA	Genetic Algorithm
GTP	Graph Theoretic Problem
IASC	Inter-Agency Standing Committee
IUSS	Infrastructure Unit Support Systems
LCM	Linear Continuous Model
LIPP	Linear Integer Programming Problem
LMIM	Linear Mixed Integer Model
LS	Local Search
MIPP	Mixed Integer Programming Problem
NA	Net Area
OECD	Organisation for Economic Co-operation and Development
QAP	Quadratic Assignment Problem
QSCP	Quadratic Set Covering Problem
UA	Usable Area
WHO	World Health Organisation

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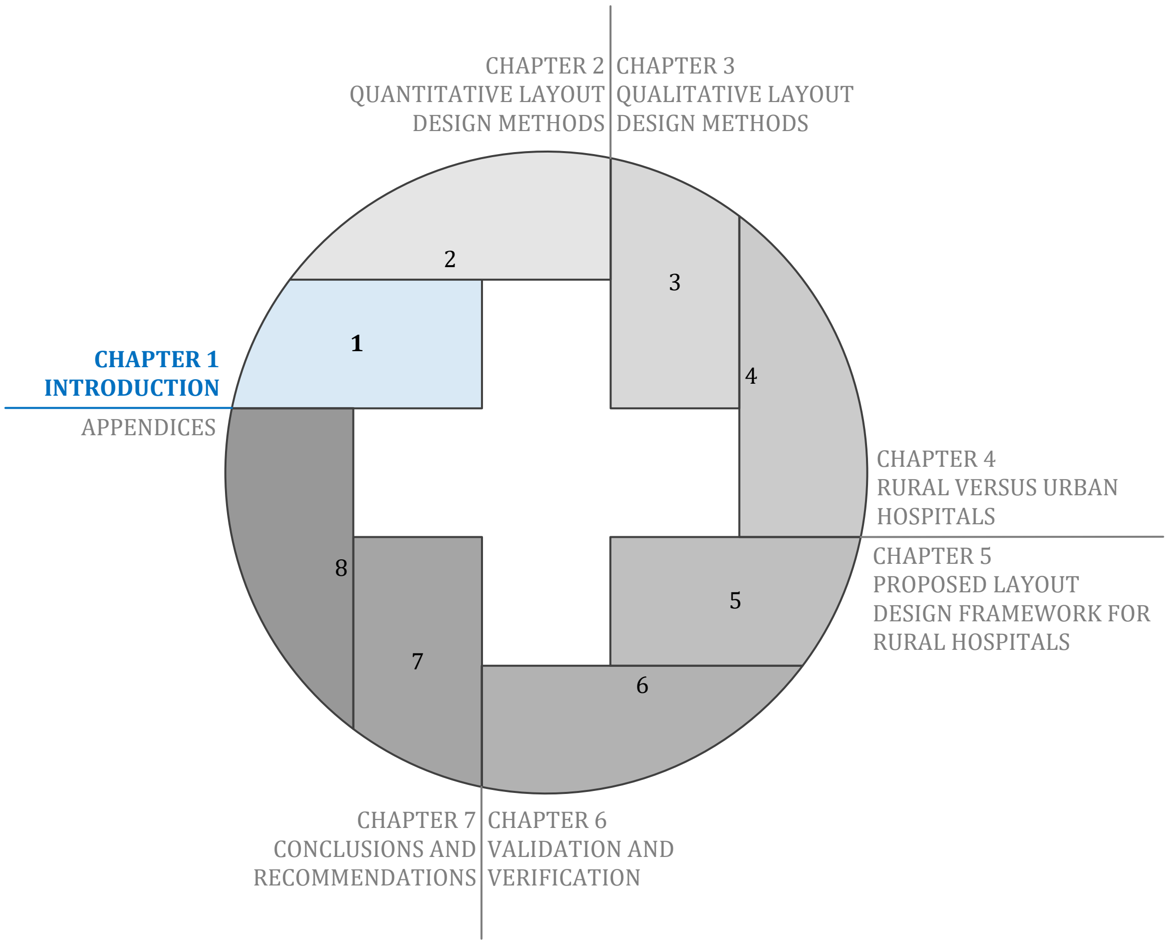
CHAPTER 1

INTRODUCTION

"Measure twice, cut once."

Davis (2010)



1.1 Introduction

To begin with, it is necessary to lay the foundations of the research and ensure its usefulness to the greater body of knowledge. The purpose of this chapter is to introduce the problem of designing a hospital layout for a rural community and therefore provide the rationale for this study. The primary focus of this research is expressed in terms of the aim and objectives listed in Section 1.3. Thereafter, the research design and methodology is discussed in order to achieve these research aims. To conclude this introductory chapter, the outlines of each of the proceeding chapters are given.

1.2 Background

This section introduces facility layout design and the role it plays on the outcome of its organisation. A hospital in particular poses a unique set of challenges and different design concerns. The focus is placed on designing a hospital layout for a rural community. Lastly, facility layout literature is introduced.

1.2.1 FACILITY LAYOUT DESIGN

There is a saying that one should "*measure twice, cut once*" (Davis, 2010). The planning phase of a facility's layout is considerably more important than the actual construction phase. For an organisation to be effective and efficient, it is important to pay special attention to the facility layout. Carr (2011) states that "*a functional design can promote skill, economy, conveniences, and comforts; a non-functional design can impede activities of all types, detract from quality of care, and raise costs to intolerable levels.*" An effective facility layout ensures a smooth and steady flow of production material, equipment, and manpower at a minimum cost. It should consider the available space, final product or service, safety of employees and facility as well as the convenience of operations (Management Study Guide, 2015). The design of a facility, also known as the Facility Layout Problem (FLP), regards the arrangement of units in a specific area that has to satisfy certain constraints and preferences while optimising an objective function value. These preferences are oftentimes subjective, uncertain and complex. According to Youssef, Sait and Ali (2003) the design of layouts are still vague and undefined. Literature mainly focused on rigid and simplified frameworks that lack the appropriate methodologies for using them (Ahmad, Basir, Hassanein & Azam, 2008).

Hospitals in particular are complex systems and their environment has a substantial impact on the health, safety and overall well-being of patients as well as staff. However, safety and improving quality is often not integrated into the design phase of hospital buildings (Barach & Dickerman, 2007). According to Jacobs, Chase and Chase (2010) the layout of a hospital sets physical constraints on its operations. The British Medical Association (2011) (BMA) found that "*the architectural environment can contribute to the treatment of patients and significantly affect their health outcomes.*" More than 600 studies have shown that there is a direct link between healthcare design and medical outcomes (Centre for Health Design, 2004). A few examples of how changing the layout of a hospital can improve the health outcomes of patients include (Centre for Health Design, 2004):

- **Infection rate decline:** when the Bronson Methodist Hospital incorporated private rooms and specially located sinks, the hospital-acquired infections rate declined by 11%;
- **Medical errors minimised:** medical errors at the Barbara Ann Karmanos Cancer Institute were reduced by 30% after extra space was allocated for pharmaceutics, medical supplies were re-organised, and panels were installed to reduce noise levels; and
- **Patient injuries decrease:** the incidence of patient falls decreased by 75% in the intensive care unit at Methodist Hospital when the location of nursing stations were moved to be in closer proximity to patients' rooms.

The BMA (2011) found that badly designed facilities can cause "*anxiety, delirium, high blood pressure and increased use of painkillers.*" Hospitals with little or no regard for their layout often create and heighten stress levels for patients, staff, and visitors. This impact can range from psychological to physiological and behavioural changes (Zimring, Joseph & Choudhary, 2004). The evidence shows that the healthcare environment also has an effect on staff morale, efficiency, and effectiveness (Barach & Dickerman, 2007).

Healthcare is a labour-intensive industry and a big proportion of that labour involves high skill levels and thus also high salaries. 60 to 75% of hospital expenses can be attributed to labour expenses. Thus a layout that promotes efficiency and minimises the strain of staff can have a significant effect on the sustainability of a hospital (Carr, 2011). The negative effects of bad layout design can also be seen in terms of travel time. According to Davis (2010), nurses on average spend time walking back and forth one third of every shift due to badly designed layouts. Since maintenance and operations adds up to 80% of the total cost of a hospital over a life cycle of approximately 50 years, it is essential that facility layout designers reduce the total life-cycle cost as much as possible through correct design (Carr, 2011).

Before one can start designing the layout of a hospital it is important to fully understand what operations a hospital entails, its characteristics, and how they differ from other facilities. Hospitals and other healthcare facilities are characterised by extensive customer contact, a wide variety of providers, and literally the life or death of patients as potential outcomes. The standard definition of a hospital is "*a facility whose staff provides services relating to observation, diagnosis, and treatment to cure or lessen the suffering of patients*" (Jacobs *et al.*, 2010). Observation in this context refers to studying patients and conducting various tests to arrive at a diagnosis. A diagnosis is a medical expert's explanation of the cause of the symptoms. Treatment is the course of action to be followed based upon the diagnosis. All of the services provided in a hospital are usually organised around one or more of these three areas.

There are several characteristics that set the operations of hospitals apart from other organisations. These include (Jacobs *et al.*, 2010):

- **Key personnel:** the key operators are highly trained medical specialists who generate requests for service (orders) but are also involved in delivering the service;
- **Process evaluation:** the relationship between charging money and the actual performance is not as direct as in production environments. The measures of quality and service are largely subjective;
- **Performance evaluation:** hospitals do not have a simple line of command, instead there exists a delicate balance of power between management, medical specialists, nursing staff, and referring doctors and as such each party has different targets to measure performance;
- **Product specifications:** product specifications in hospitals are often vague and subjective as opposed to the complete and explicit specifications of end product requirements and delivery requirements in other industries (i.e. for a hospital the patient is the product); and
- **Service oriented nature:** hospital care cannot be stocked like commodities. It is a resource-oriented service organisation.

What further complicates the design of a hospital layout is the various types of flow that exist. It is not just the end product flow (in this case the treated patient) that is analysed; other flows include staff, specimens, supplies, test results, and waste flow. There are also different users and stakeholders such as patients, visitors, support staff, volunteers, suppliers, and owners (Carr, 2011). With so many design considerations and different role players, the problem of designing a new hospital can be a daunting task. The question thus becomes one of where does one start when designing the layout of a hospital. The following questions are relevant:

- What is the capacity of the hospital?
- Which departments should be included in the hospital layout?
- What is the capacity of each department?
- Which rooms are necessary for each department?
- How much space is required for each room?
- Where should each department be located?
- Which departments should and should not be placed in close proximity to one another?

Furthermore, the type of community plays a role on the hospital's design. According to Kenny and Duckett (2003), policies do not acknowledge or address the differences between rural and urban healthcare facilities. There are many differences between the two that arguably promote that different approaches should be taken. For instance, nurses in rural communities tend to fulfil a role that requires them to have multiple skills and comprehensive knowledge, but are often not equipped or educated for such a role. In these healthcare facilities medical care are often delivered without the presence of the necessary healthcare professionals, especially doctors. This results in nurses having to care for patients exhibiting more complicated problems (Eygelaar & Stellenberg, 2012). It is apparent that rural communities differ from urban communities with regards to the challenges that they face and that a differentiated hospital layout may serve the needs of these communities more adequately.

1.2.2 FACILITY LAYOUT DESIGN LITERATURE

There exist two generally accepted fields of study relating to hospital layout design, including the two interrelated fields of quantitative and qualitative methods. The most regularly used quantitative methods include layout models such as the Quadratic Assignment Problem (QAP), Quadratic Set Covering Problem (QSCP), Linear Integer Programming Problem, Mixed Integer Programming Problem (MIPP), Graph Theoretic Problem (GTP), Linear Continuous Model (LCM), and Linear Mixed Integer Model (LMIM). When finding the optimal solution via these models, using Branch and Bound Algorithms or Cutting Plane Algorithms is commonplace. Alternatively, most commonly when the problem is too large, the model can be approximated using metaheuristics (e.g. Simulated Annealing) or hybrid metaheuristics.

The qualitative approaches on the other hand include layout procedures such as Apple's Plant Layout Procedure, Muther's Systematic Layout Procedure, and Reed's Layout Procedure. There are also various design considerations that should be incorporated for each of these.

Though popular, these methods do not necessarily take into account other important factors that are specific to rural settings. It can therefore be said that there exists a gap in literature in this regard. Remote rural region hospitals have certain challenges, constraints, and needs. This uniqueness of the rural setting makes general hospital design methods inadequate. Furthermore, the field of designing rural hospitals is limited, arguably due to the low economic incentive of investors and the fact that they are oft seen as being in the realm of non-profit or governmental organisations. Therefore there exists a need for an optimal layout design framework tailored specifically to rural communities.

1.3 Problem definition

Hospitals are complex systems and the design of the layout thereof is not a straightforward task. It is suggested that hospitals in rural areas have different constraints and needs than hospitals in cities and towns. It is unlikely that all rural and urban communities share the same lifestyles, health statuses, prominent illnesses and consequently medical needs. Thus a different approach may need to be taken when designing the layout of such a hospital. There exist quantitative as well as qualitative layout design methods and the question is one of how these can be integrated into a framework for a hospital layout. There are also numerous laws, standards and other design considerations with regards to hospital design that the designer may not necessarily have knowledge of.

1.4 Aim and objectives

The primary objective of this study is to develop a generic decision-support framework using both quantitative and qualitative layout design methods that will guide the user to design a near optimal layout for a rural hospital while taking into consideration the relevant laws and standards as well as the health outcomes of the surrounding rural community. The goal is not to replace the design team, but to provide valuable input that can be used as a starting point for the design phase of a rural hospital layout. Figure 1 shows the steps and phases for designing a hospital layout. The shaded blocks indicate the steps that are addressed in this study.

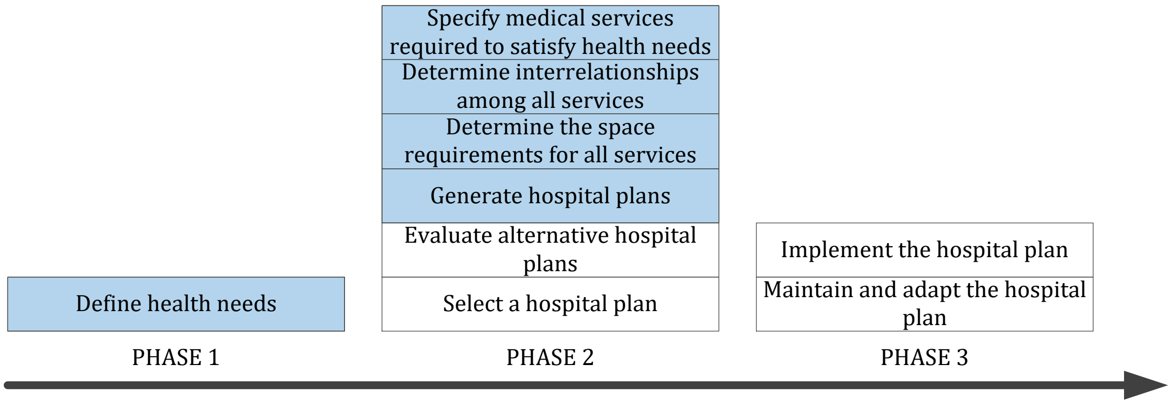


FIGURE 1: HOSPITAL LAYOUT DESIGN STEPS AND PHASES, ADAPTED FROM TOMPKINS, WHITE, BOZER AND TANCHOCO (2010)

The following secondary research objectives, delineated according to chapter, are pursued in this study.

Quantitative layout design methods chapter:

- Identify popular quantitative layout models used to design facility layouts;
- Analyse the various components of these layout models;
- Identify and analyse popular methods for solving these models;
- Investigate other design methods such as layout software; and
- Compare both the layout models, and the solution methods with each other.

Qualitative layout design methods and other design considerations chapter:

- Identify popular qualitative design methods used to plan hospital layouts;
- Analyse the various components of these qualitative design methods;
- Identify design considerations for hospitals; and
- Link the hospital design considerations with the quantitative methods.

Rural vs urban hospitals chapter:

- Determine the commonalities among rural and urban hospitals;
- Determine how laws and standards affect the design of a hospital;
- Identify minimum dimensions and other criteria applicable to the design of a hospital layout;
- Determine rural-specific constraints; and
- Determine the layout implications of the rural-specific constraints.

Proposed rural hospital design framework chapter:

- Describe the real world problem and how it differs from the research literature;

- Select the most adequate layout model and solution method;
- Incorporate qualitative design methods and hospital design considerations into the framework;
- Make necessary adjustments to the framework to accurately model the real world problem; and
- Develop and present the framework.

Validation and verification chapter:

- Determine whether the framework and findings of this study can be used to design a hospital layout.

Conclusions and recommendations chapter:

- Summarise the findings of this study;
- Describe the contributions of this study; and
- Make recommendations for future research.

1.5 Research design

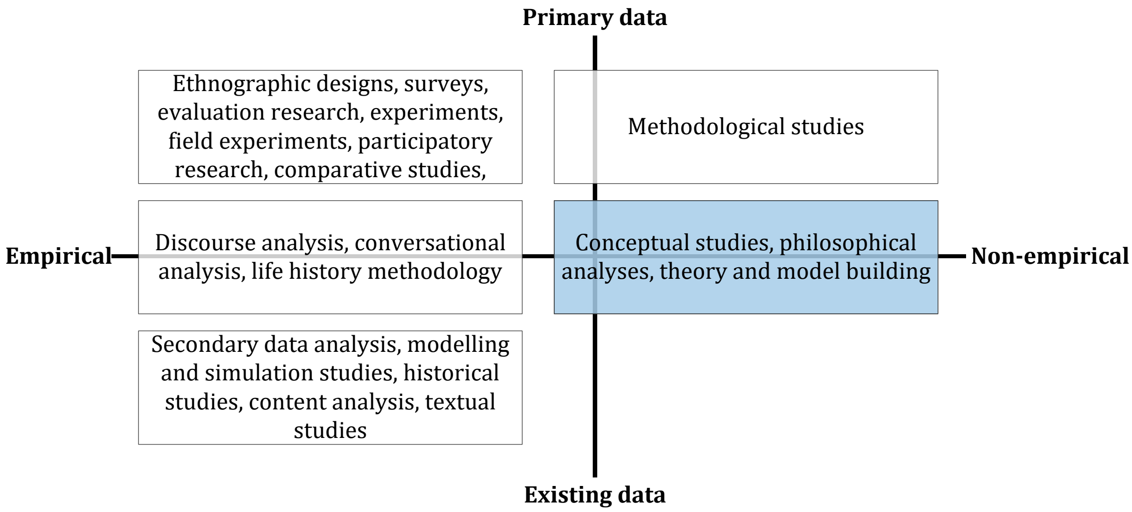


FIGURE 2: RESEARCH DESIGN MAPPING, ADAPTED FROM MOUTON (2011)

The research design method employed in this study is a non-empirical analysis of existing data (a conceptual study), as shown in Figure 2. A range of secondary data (including articles, books, scientific journals, and websites) is used in this study to perform a meta-analysis of existing mathematical formulations regarding the FLP. The data is analysed so as to select the most adequate model to design a hospital layout and make appropriate adjustments as necessary. The data also includes South African laws and standards that add basic constraints to the problem of this study. Furthermore, interviews were used in gathering expert opinions on adjustments, improvement recommendations, and the validity of the framework. The nature of this study is that of operations research, for which reason a case study is conducted to root it in reality.

1.6 Research methodology

Most literature for layout design problems can be classified into procedural and algorithmic approaches (Shahin & Poormostafa, 2011). Algorithmic approaches involve quantitative methods which usually simplifies design objectives and constraints with the aim of arriving at a substitute (surrogate) objective function, through which the solution can more easily be obtained. According to Tompkins, White, Bozer and Tanchoco (2010) most of the existing research take algorithmic approaches. These algorithms can generate layout alternatives efficiently, but the results often fail to capture all of the design objectives (Ahmad, 2005). Procedural approaches on the other hand are qualitative methods consisting of several sequential steps but often include quantitative components. These approaches rely on the experience of the designer and the results may consequently be highly subjective, inefficient, and inferior in nature due to their lack of a sound scientific foundation. Thus, neither of these two approaches are necessarily effective in solving real world problems (Ahmad, 2005). Therefore, the research methodology employed in this study is mixed methods research which involves combining quantitative and qualitative approaches. It is still in its adolescence and thus relatively unknown to many researchers (Leech & Onwuegbuzie, 2009).

Mixed methods research is defined by Creswell, Clark and Garrett (2008) as "*both a method and methodology for conducting research that involves collecting, analysing, and integrating quantitative and qualitative research in a single study or a longitudinal program of inquiry*". Mixed methods utilise the strengths of both quantitative and qualitative research. More insight can be gained from the combination of both research types than by focusing on either form by itself (Creswell, 2015). Mixed methods can be classified into concurrent and sequential designs (Dowbor & Zerger, 2014). Concurrent designs refer to the collection of quantitative and qualitative research simultaneously, whereas in sequential designs one type is collected after the other, classified as sequential explanatory or sequential exploratory. In sequential designs, the emphasis is placed on the data that is collected first and the secondary data is used to explain the first results. The emphasis can also be placed on both quantitative and qualitative research equally, known as a convergent design.

According to Cresswell and Clark (2009) concurrent mixed methods are "*employed to validate one form of data with the other form, to transform the data for comparison, or to address different types of questions*". Quantitative and qualitative research are conducted, analysed separately, and afterwards compared and (or) combined. This is an ideal approach if it is unknown whether and how the two research types can be integrated before conducting an in depth literature study. Thus, a concurrent mixed methods approach is taken in this study. Figure 3 shows an outline of the research methodology followed in this study. At first equal importance is placed on both quantitative and qualitative research and they are analysed separately and in parallel. After this analyses, the method of integration (embedding, connecting or merging) is determined, and as such the discussion of the mixed methods approach is only addressed again in Section 5.2.

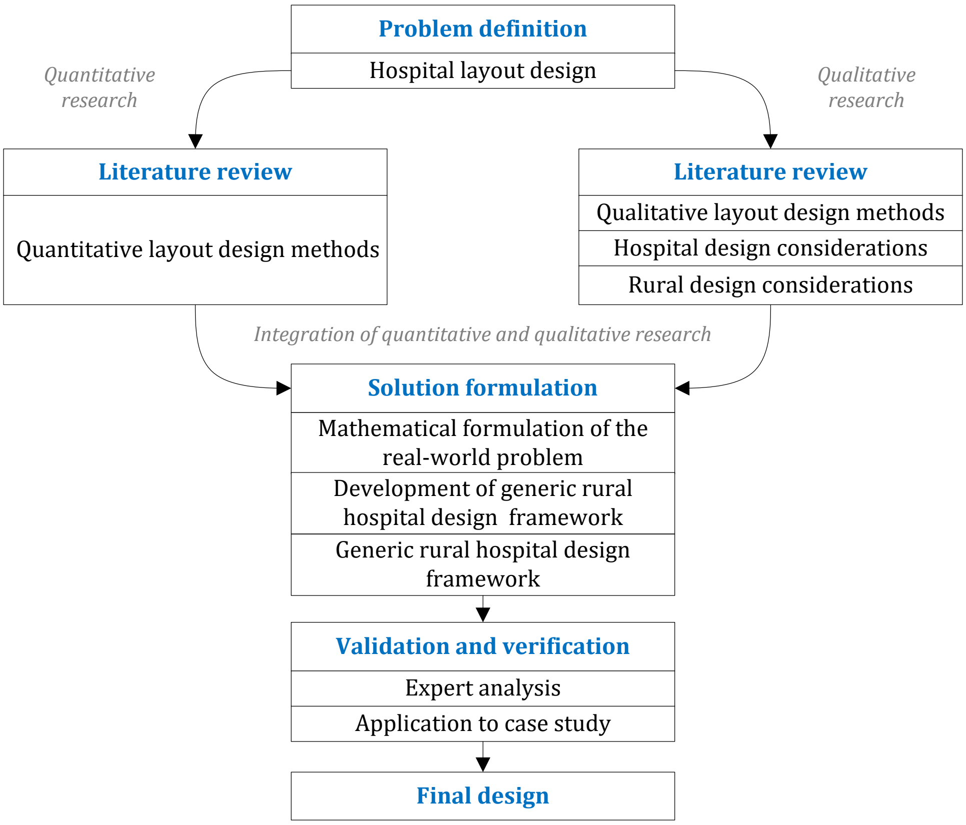


FIGURE 3: RESEARCH METHODOLOGY

1.7 Research scope and nature

There exist various types of hospitals, namely district hospitals (level one care), regional hospitals (level two care), and provincial tertiary hospitals (level three care), central hospitals (level four care), and specialised hospitals (level four care) (Conradie & Steyn, 2014). District hospitals normally receive patients from clinics or health care centres and if a patient cannot be helped, they will be referred to a regional hospital. Regional hospitals (and hospitals above level one care) are typically only located in urban areas. Therefore district hospitals which can provide the basic level of care are placed in rural communities. According to Van der Schyf and Flemming (2015) a district hospital is the base hospital for a health district and is best suited to rural areas. For this reason it is assumed that the hospital layout of this study will be developed for a district hospital.

In the case of a rural hospital, the available site space is usually not as restrictive as with typical urban sites. Due to the relative difficulty of multi-floor building construction in rural regions where resources are scarce and geographies remote, it seems logical to assume that a single floor layout should be sufficient for a rural hospital. Without a low likelihood of being able to install an elevator it is safe to assume that vertical travel between floors would only act so as to increase the complexity and resources necessary for effective functioning. The number and location of vertical handling devices, the resulting congestion and delays, added costs (both monetary and in terms of risk, including the additional safety measures that will need to be put in place), and the possible lack of coordination between departments on separate floors are important factors that detract from the appeal of a multi-floor layout. For the abovementioned reasons, the scope of this study will be limited to single-floor layouts.

The output of the developed framework will be designed to provide a point of departure for the architectural concept design process, and as such will not be involved with detailing the precise location of equipment, storage units, or beds. In other words the study will focus on designing a block layout model which shows the locations and dimensions of the planning departments. Since there are many rooms in each department of a hospital and there are many departments in one hospital, this study will focus on finding a near-optimal arrangement of hospital departments, however not the arrangement of rooms per se. Only the sizes of the rooms will be taken into consideration.

Lastly, due to the often remote and unbounded (unrestricted) nature of rural geographies, it is assumed that the shape and space of the hospital site used in the development of the layout is unrestricted, being determined by the preferences of the user of the framework.

1.8 Document outline

The document chapters are ordered to reflect the logical course of the study, as shown in Figure 4.

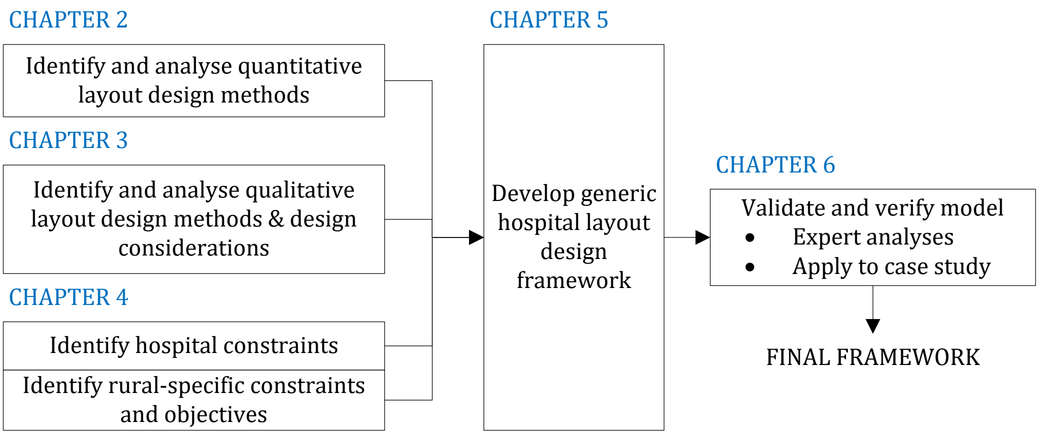


FIGURE 4: OUTLINE OF THESIS CHAPTERS

Each chapter has an introductory paragraph, and is concluded with a summary. The outline of the chapters is now given.

Chapter 2 Quantitative layout design methods

The aim of this chapter is to provide an overview of the existing literature on quantitative layout design methods. The problem of designing a layout is thoroughly discussed and the more popular ways of mathematically modelling it are analysed along with its components. Various ways to solve these models are also analysed. An overview on currently available quantitative layout software is also provided. Lastly, the layout models, and solution methods are compared with each other.

Chapter 3 Qualitative layout design methods and hospital design considerations

This chapter investigates the designing of a hospital layout from a qualitative approach. Firstly, layout types are explored and how hospital layouts are classified is discussed accordingly. Qualitative layout methods are analysed, compared to the studied quantitative methods, and the best method is selected and applied to the context of a hospital. This includes an analysis of each hospital department and the functional relationships between them. The main design considerations of hospitals are described and the relationships with the quantitative methods are established.

Chapter 4 Rural versus urban hospitals

In order to design a rural hospital layout correctly, the focus of this chapter is to determine commonalities among rural and urban hospitals including the standards and laws that they need to adhere to, e.g. minimum room dimensions and associated criteria. Thereafter, this chapter determines rural-specific constraints and how they affect the design of a hospital layout.

Chapter 5 Proposed rural hospital design framework

This chapter combines the key findings from the previous chapters to develop a hospital layout design framework for rural areas. The most adequate layout model is selected based on how well it models the real world problem according to a set of criteria, the best solution method is chosen, and necessary adjustments are then made. The qualitative design methods and hospital design criteria are then integrated with the quantitative methods. Lastly, the development of a user-friendly interface for the framework is fully described and how it is used is then explained.

Chapter 6 Validation and verification

The aim of this chapter is to verify and validate the framework and the key findings of this study. A semi-structured interview process with experts is conducted and the necessary modifications are made before applying it to a case study.

Chapter 7 Conclusions and recommendations

In ending, the chapter summarises the research conducted and concludes with the contribution of this study, in addition to suggestions for future research.

1.9 Conclusion

This chapter introduced the research by first providing a background to the designing of hospital layouts then setting out the research methodology that was followed in order to reach the research objectives and aims.

It was found that the problem of designing a hospital layout is not a straightforward task and requires various considerations, including laws and standards, different flows, patient centeredness, staffing efficiency, and the type of community. A hospital's layout plays an important role its ability to deliver quality care to patients. A direct link was found between healthcare design and the medical outcomes of patients. Furthermore, a hospital's layout can have a substantially positive impact on hospital expenses if its design promotes efficiency and minimising staffing needs.

Two commonly accepted fields that relate to the design of hospital layouts were introduced, namely quantitative layout design methods and qualitative layout design methods. It was established that a concurrent mixed methods approach is a suitable research methodology for this study. It may be possible to integrate the quantitative and qualitative research methods which will be determined after conducting an in depth literature study on both methods.

It was suggested that hospitals in rural areas have different constraints and needs than hospitals in cities and towns. Thus a different approach may need to be taken when designing the layout of such a hospital.

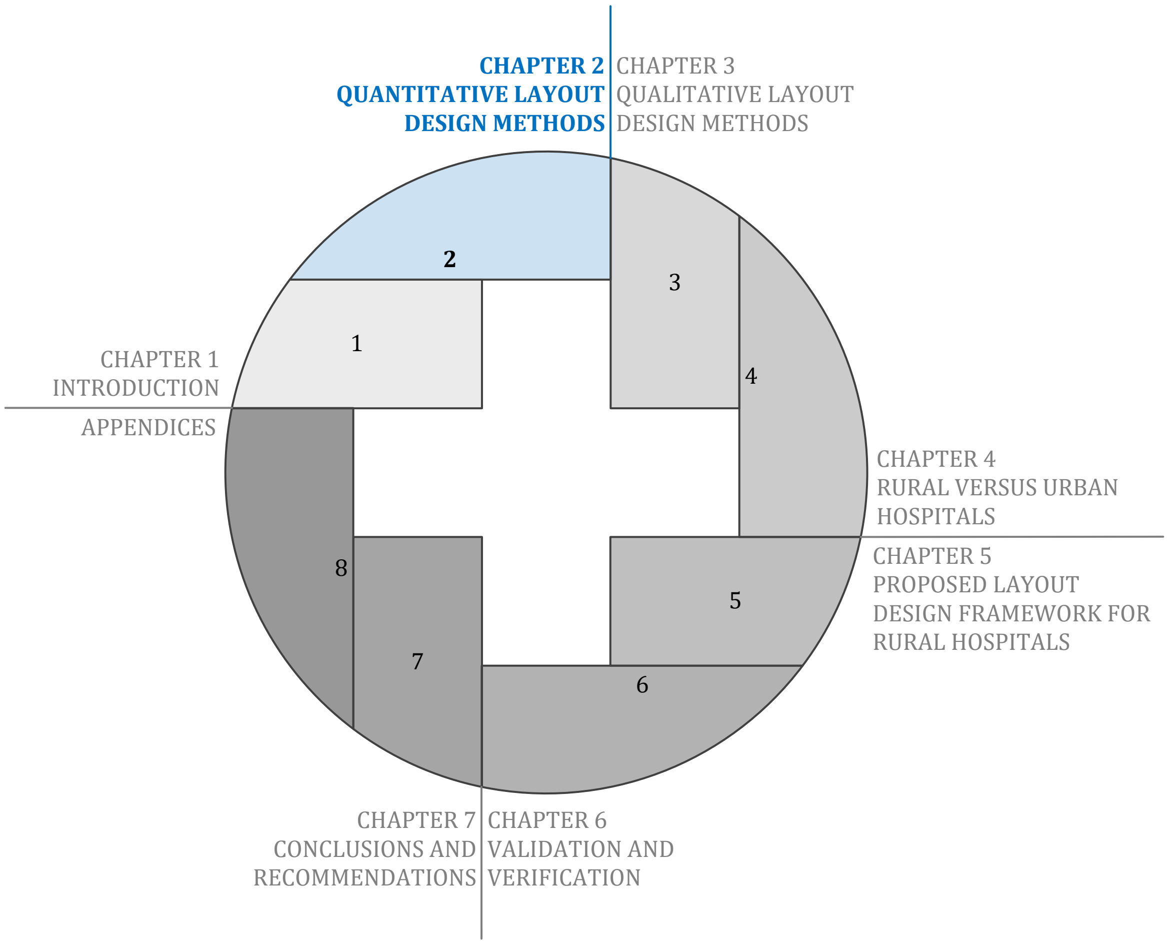
With a foundation in place regarding the approach and aim of the study, it is now necessary to follow the roadmap developed in this chapter and comprehend the quantitative layout design methods found in literature for designing a hospital.

CHAPTER 2

QUANTITATIVE LAYOUT DESIGN METHODS

"Not enough of our society is trained how to understand and interpret quantitative information. This activity is a centrepiece of science literacy to which we should all strive—the future health, wealth, and security of our democracy depend on it. Until that is achieved, we are at risk of making under-informed decisions that affect ourselves, our communities, our country, and even the world."

Tyso (1994)



2.1 Introduction

This chapter contains a review of the literature on topics related to the design of facilities, otherwise known as the Facility Layout Problem (FLP). The focus of this chapter is to provide the reader with a clear understanding of how one may design the layout of a facility using purely quantitative methods. The chapter starts with a background on the field of operations research. Next, the FLP is discussed and an overview of existing quantitative approaches commonly used to solve it is given. The more popular layout models and solution methods are then analysed. Software available for designing layouts is also discussed. The various quantitative methods addressed in this chapter are then compared and the best method is proposed. Lastly, a chapter summary is given.

2.2 Operations Research

Winston and Goldberg (2004) define operations research as "*a scientific approach to decision making that seeks to best design and operate a system, usually under conditions requiring the allocation of scarce resources.*" The system in this context refers to an organisation of components that are interdependent and work together towards the system's goal (Winston & Goldberg, 2004). For example, Mercedes Benz Company is a system that produces quality vehicles for the purpose of maximising its profit. Operations research originated during the Second World War, wherein a group of scientists were tasked with examining the strategies and tactics of various military operations so as to more efficiently allocate scare resources during the war effort. As a result of this research on rendering military operations as effective as possible, the term 'operations research' was coined (Winston & Goldberg, 2004). Since the war involved complicated strategic and tactical problems, one cannot expect adequate solutions from individuals in a single discipline. Therefore, groups of specialists in engineering, economics, mathematics, statistics, and physical science were formed as units to jointly deal with these problems and military operations (Agarwal & Srivastva, 2009). Due to the success of these teams, various groups in the United States formed to study military logistical problems, the effectiveness of aircraft flight patterns, the effective utilisations of electronic equipment of warfare, and the planning of sea mining activities. After the war, the degree of success of the research teams attracted the attention of industrial engineers to apply similar optimisation techniques to the fields of business and industry. Since then, the scope of modern operations research has vastly increased, spilling over into areas such as effective system utilisation and decision making within business and industry, and even further into government and society as a whole.

One discipline that has more recently begun to benefit significantly from the field of operations research, totally opposed to war yet inherently connected to it, is that of healthcare. It is especially helpful in this field since it deals with the optimal usage of limited resources, which can mean the difference between life and death for patients, be they in urban or rural geographies (Operations

Research Society of South Africa, 2014). Operations research highlights the trade-offs inherent in determining the best solutions as well as provide managers with an informed basis for decision making (Romeijn & Zenios, 2008).

2.3 Facility Layout Problem

The Facility Layout Problem (FLP) is a combinatorial optimisation problem that is ever-present in manufacturing, service, and communication industries. It involves the optimal allocation of a set of facilities to locations while conforming to area constraints, shape restrictions and relationships between facilities (Tuzkaya, Gülsün, Tuzkaya, Onut & Bildik, 2013). Another description of the FLP is a means of deciding upon the physical arrangement of a system (Meller & Gau, 1996). FLPs have historically been applied to a large variety of problems, including the allocation of personnel and equipment or the arrangement of buildings and sites (Liggett, 2000). A layout problem can either be used for the arrangement of units in a new building or the relocation of units in an existing building. During the conceptual design stage of a new building, it is worthwhile to test alternative arrangements of spaces which can be used to determine other variables such as the ideal number of floors or the required site space. Existing layouts can relocate units within the building in order to optimise the use of spaces, e.g. the needs of a layout with regards to space often changes with time (Montreuil & Laforge, 1992).

The FLP seeks the most efficient arrangement of a number n of indivisible facilities with either equal or unequal area requirements (Liggett, 2000). The FLP's objective is typically to minimise material handling costs (Tuzkaya *et al.*, 2013). Other possible objectives include minimising total cost, travel distance, flows, or travel time. It can also be rearranged into a maximisation problem, such as the Koopmans and Beckmann formulation of the Quadratic Assignment Problem (QAP) which aims to maximise the total net revenue, or conversely the Graph Theoretic Problem (GTP) which aims to maximise a closeness rating measure. In Chapter 4 (Sections 4.3 and 4.4), exactly what these objectives should be in the context of a rural hospital will be determined.

The FLP is usually subjected to two main constraints: the first involves space requirements and the second facility restrictions such as fixed locations, empty locations or placing units within the available space (Meller & Gau, 1996). Facility locations are generally permanent and therefore the optimal setting is crucial for long term success due to the high impact on operational and logistical decisions. The designed layout must not only perform well in the near future but also in a long term sense so as to ensure lasting profitability. Factors influencing these decisions are largely time dependent, such as but not limited to, environmental factors, population shifts, and evolution of market trends. Robust facility designing is therefore an arduous task which requires much foresight in order to counter the likely changes in the uncertain future (Wolf, 2011). Kumar and Suresh (2009) believe that the key to a good layout lies in balancing and integrating the needs of people (personnel and customers), materials (raw, finished, and in progress) and machinery in a manner which optimises the entire system, however not necessarily the optimal solution for each of the individual needs.

2.3.1 QUANTITATIVE METHODS FOR MODELLING AND SOLVING THE FACILITY LAYOUT PROBLEM

There exist many different ways of modelling and solving the FLP. In this chapter, various layout models and their corresponding solution methods are examined. Each layout model has a certain set of objective(s), assumptions, inputs and outputs and can either be solved optimally, e.g. with exact methods or the optimal solution approximated, e.g. using metaheuristics. An outline of the FLP is provided in Figure 5.

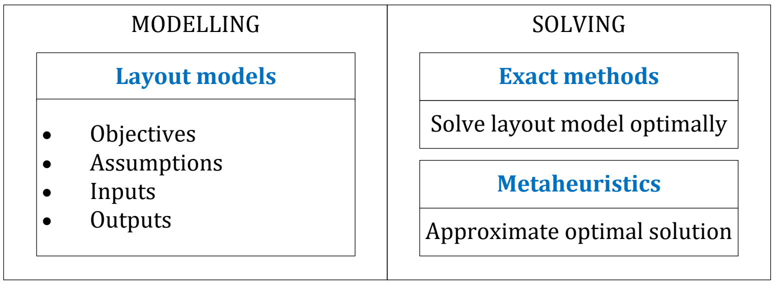


FIGURE 5: MODELLING AND SOLVING METHODS FOR THE FACILITY LAYOUT PROBLEM

A summary of layout models and solution methods found in literature that are used to solve the FLP are shown in Table 1. Only reasonably cited articles found on Google Scholar and Web of Science were included in this analysis. This analysis also includes layout software i.e. computer-based layout algorithms which can be used to solve (and often model) the FLP.

TABLE 1: QUANTITATIVE METHODS USED TO MODEL AND SOLVE THE FACILITY LAYOUT PROBLEM

Author	**Objective**	**Model**	**Solution method**
Bazaraa and Goode (1971)	Minimise material handling cost	QSCP	FORTRAN computer program, Cutting Plane Algorithm that exclude both integer and non-integer solutions are generated at each iteration
Bazaraa (1975)	Minimise material handling cost	QAP, QSCP	Branch and Bound Algorithm
Giffin and Foulds (1987)	Maximise a closeness rating measure	GTP	Shortest Path Heuristic
Heragu and Kusiak (1987)	Minimise transportation costs	QAP, QSCP, Linear Integer Programming Problem, Mixed Integer Programming Problem (MIPP), GTP	Branch and Bound Algorithm, Cutting Plane Algorithm, HC66, ALDEP, CORELAP, MAT, PLANET, FATE, CRAFT, Revised Hiller Algorithm, H63, FRAT, COFAD, Hybrid Algorithms

QUANTITATIVE METHODS USED TO MODEL AND SOLVE THE FACILITY LAYOUT PROBLEM (CONTINUED)

O'Kelly (1987)	Minimise transportation costs	Quadratic Integer Program	Enumeration Heuristic
Smith and MacLeod (1988)	Minimise material handling costs	QAP, QSCP	
Montreuil (1991)	Minimise material handling costs	MIPP	Branch and Bound Algorithm
Heragu and Kusiak (1991)	Minimise material handling costs	Linear Continuous Model (LCM), Linear Mixed Integer model (LMIM), MIPP	Powell method of conjugate direction used with the penalty method
Leung (1992)	Maximise a closeness rating measure	GTP	
Bland and Dawson (1994)	Minimise financial costs, maximise operational efficiency	QAP	Tabu Search (TS), Simulated Annealing (SA), Hybrid of TS and SA gave superior results for large-scale layout problems
Meller and Gau (1996)	Minimise material handling costs	QAP, GTP, MIPP	MATCH, SPIRAL, CRAFT, LOGIC, MULTIPLE, FLEX-BAY
Meller, Narayanan and Vance (1998)	Minimise traveling distance	QAP, MIPP	Branch and Bound Algorithm
Liggett (2000)	Minimise material handling cost	QAP	CRAFT, MULTIPLE, SA, Genetic Algorithm (GA), Hybrid approaches
Caccetta and Kusumah (2001)	Minimise material handling cost	QAP, QSCP, Linear Integer Programming Problem, MIPP, GTP	GTP based heuristics such as Deltahedron Method, Constructive Heuristic, Wheel Expansion Algorithm, Kim-Kim Algorithm, Tessa, Green-Al Hakim Algorithm,
Singh and Sharma (2006)	Minimise material handling cost	QAP, GTP, MIPP	Branch and Bound Algorithm used for small instances, MATCH, SPIRAL, CRAFT, LOGIC, MULTIPLE, FLEX-BAY, SA, GA
Arora and Saxena (2007)	Minimise material handling cost	QSCP, Linear Programming Problem, QAP	Branch and Bound Algorithm
Drira, Pierreval and Hajri-Gabouj (2007)	Minimise material handling cost	QAP, MIPP	Branch and Bound Algorithm, CORELAP, ALDEP, COFAD, SHAPE, CRAFT, FRAT, DISCON, TS, SA, GA, Hybrid methods, Ant Colony Optimisation
Bianchi, Dorigo, Gambardella and Gutjahr (2009)	Minimise material handling cost	Stochastic Combinatorial Optimisation Problems	Ant Colony Optimisation, Evolutionary Computation, SA, TS
Gülsün, Tuzkaya, Onut and Bildik (2013)	Minimize material handling costs, maximize adjacency requirements	QAP	GA, SA, Hybrid approach (HGASA), SA performed best in terms of fitness and time requirements

QUANTITATIVE METHODS USED TO MODEL AND SOLVE THE FACILITY LAYOUT PROBLEM (CONTINUED)

Büyüksaatçi and Baray (2014)	Mmise total cost (overall efficiency of operations and reduces total operating expenses)	Single Row Facility Layout Problem	Bacterial Foraging Optimisation Algorithm, Firefly Algorithm, Bat Algorithm, Particle Swarm Optimisation

2.3.1.1 Modelling the Facility Layout Problem

Table 1 supports the fact that most of the methods aim to optimise the material handling cost as the main objective of the FLP. Other objectives include minimising total cost, transportation cost and maximising a closeness rating measure. According to Tuzkaya *et al.* (2013) most of the FLPs are based on the QAP, LIPP, MIPP and GTP. From Table 1 it is clear that the QSCP is also a prominent layout for modelling the FLP. Two new layout models are developed by Heragu and Kusiak (1991), namely the Linear Continuous Model (LCM) and the Linear Mixed Integer Model (LMIM) (Asl & Wong, 2015). The analysis in Table 1 indicated that the following five layout models are more popular, namely the QAP (included 11 times), MIPP (included 7 times), GTP (included 4 times), QSCP (included 3 times), and LIPP (included 2 times). Therefore, these five layout models along with the relatively less studied LCM and LMIM are chosen to be further discussed in this study. Some of these models have variations, e.g. the Koopmans and Beckmann formulation and the Trace formulation of the QAP (further explained in Section 2.4.2).

2.3.1.2 Solving the Facility Layout Problem

Compared to modelling the FLP, there are many more methods available for solving the FLP. The reason for this could be that it is not straightforward to solve the FLP. Bozer, Meller and Erlebacher (1991) argue that there are two key reasons for this. Firstly, there are no generally accepted objective functions which capture all the relevant aspects of the problem. Secondly, with commonly accepted functions, finding the optimal solution is near-impossible since it often involves large-scale problems. The run-time for solving these layout models usually increases dramatically with the problem size and often only small sized instances can be solved practically. For example, consider the QAP formulation which involves assigning n facilities to n locations in such a way that each facility has one location and each location has only one facility. If 10 facilities are to be assigned to 10 locations, then n! (equal to 3,628,800) permutations has to be checked which requires a large amount of computation time (Bhati & Rasool, 2014).

A timeline of solution methods used in literature to solve the FLP is shown in Figure 6. Solution methods for the FLP may be divided into two categories, namely exact methods, and metaheuristics. Exact methods are able to find the optimal solution to a problem. Examples include the Branch and Bound Algorithm and the Cutting Plane Algorithm. As just explained, the FLP is very difficult to solve for large problems and only FLPs with small problem sizes can be solved optimally using exact methods (Meller, Narayanan & Vance, 1998). It was found that exact methods cannot be used to solve the FLP for problem sizes more than 15 to 20 facilities (Tuzkaya *et al.*, 2013).

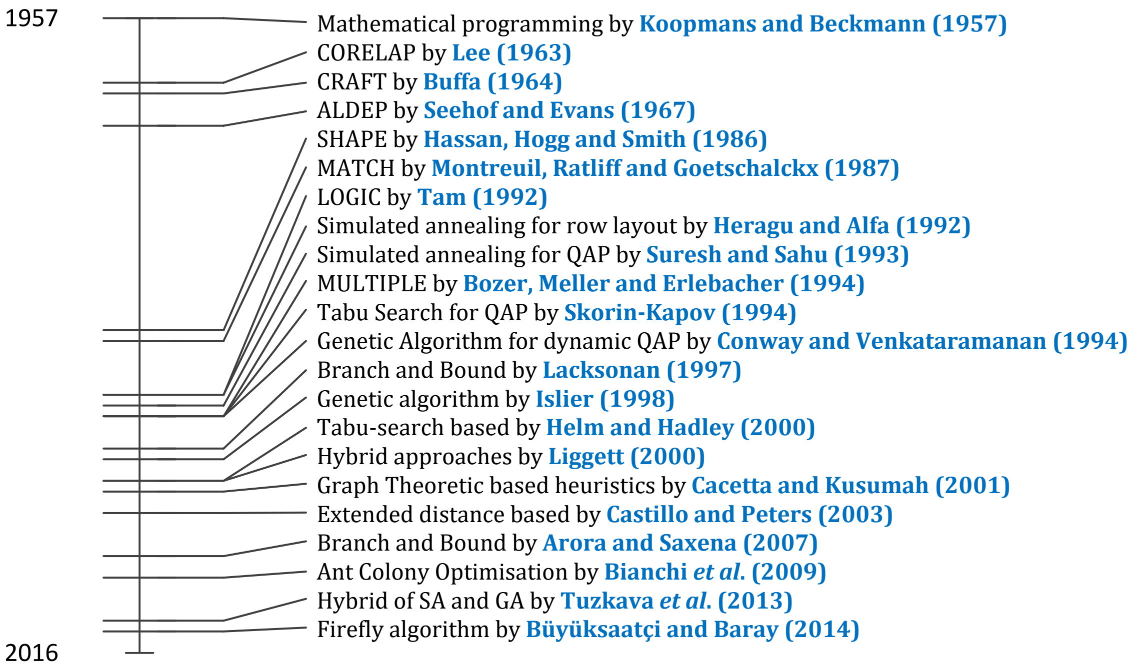


FIGURE 6: TIMELINE OF QUANTITATIVE METHODS USED TO SOLVE THE FACILITY LAYOUT PROBLEM

In order to approximate optimal solutions for large and complex problems, metaheuristics and heuristics were developed to find near optimal solutions within a reasonable computation time. Commonly used methods for solving the FLP are Ant Colony Optimisation (ACO), Genetic Algorithms, Local Search (LS), Particle Swarm Optimisation (PSO), Simulated Annealing (SA), and Tabu Search (TS) (Bhati & Rasool, 2014; Büyüksaatçi & Baray, 2014). These more popular methods are chosen to be further analysed in this study (Section 2.5.2). The combination of metaheuristics, known as hybrid metaheuristics, can also be used for the purpose of finding a superior layout solution and is therefore discussed in more detail in Section 2.5.3.

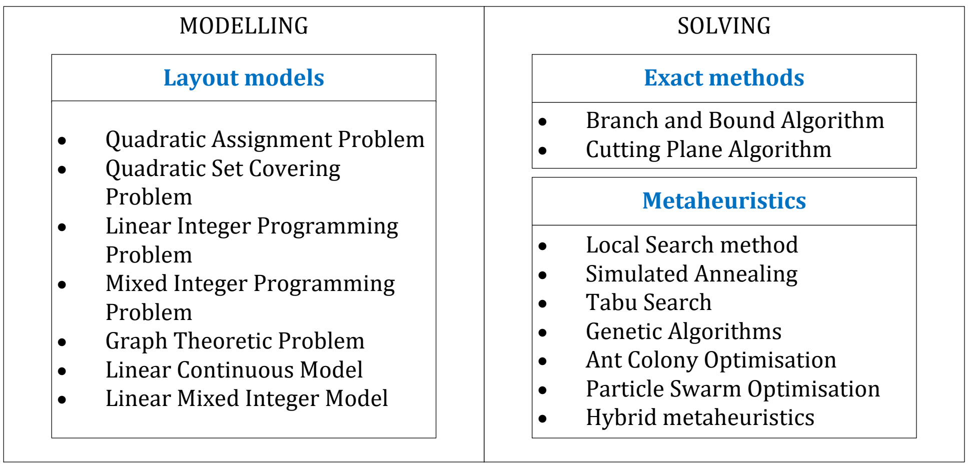


FIGURE 7: CHOSEN LAYOUT MODELS AND SOLUTION METHODS FOR FURTHER ANALYSIS

A summary of the chosen layout models and solution methods that are further analysed in this study are shown in Figure 7.

2.3.2 QUANTITATIVE METHODS SOFTWARE PACKAGES

Another way to quantitatively model and solve the FLP is via layout software. Layout software uses computer-based algorithms, often classified as either construction algorithms or improvement algorithms. There are also algorithms which can be used as both. Figure 6 and Table 1 show timelines of layout software found in literature. Examples of layout software include CRAFT, ALDEP, MATCH, CORELAP, COFA, SPIRAL, MULTIPLE, RAFT, SHAPE, LOGIC, and FLEX-BAY. Table 1 indicates that CRAFT (included 5 times), LOGIC (included 3 times) and MULTIPLE (included 2 times) are common software packages. These methods are chosen to be further discussed in Section 2.6.

2.3.3 APPLICATION OF THE FACILITY LAYOUT PROBLEM TO HOSPITAL LAYOUTS

One of the first applications of the FLP to hospitals was by Elshafei (1977) when the hospital layout was formulated as a QAP in order to minimise the efforts of patients walking within the hospital. Elshafei focussed specifically on one unit of a large hospital, namely the out-patient department and analysed the treatment of patients from 17 clinics within the department. In this example the task at hand was to assign clinics to locations within the department. The problem of this study focuses on the locations of departments within a hospital and from this point onwards, the FLP refers to the assigning of departments within a hospital. Another study by Tobias (1986) used a GTP approach to design a hospital layout and used CORELAP to find a solution. Hahn and Krarup (2001) reviewed solving the QAP for large problems. More recently Feyzollahi, Shokouhi, Yazdi and Tarokh (2009) have designed a hospital layout on the basis of the QAP model.

These studies found the application of the FLP to new or existing hospital layouts valuable. However, very few studies were found in the literature and the focus was only on the GTP and QAP formulations.

Within the context of this study, the FLP refers to assigning n departments to locations within a hospital. Each location can house only one department and each department occupies one (or more locations).

2.4 Layout models

Layout models are used to describe and formulate the FLP. The following layout models are discussed in this section, namely the Quadratic Assignment Problem, Quadratic Set Covering Problem, Linear Integer Programming Problem, Mixed Integer Problem, Graph Theoretic Problem, Linear Continuous Model and the Linear Mixed Integer Model. For each of the models listed, the main objective(s), accompanying notation, assumptions, inputs, outputs, and variations are analysed in the sections that follow.

2.4.1 CLASSIFICATION OF MODELS

The abovementioned layout models can be classified as being either discrete or continuous. Discrete layout models limit the locations of the departments to be placed at a number of predefined positions, otherwise referred to as candidate sites. Continuous layout models allow new departments to be located anywhere within the space being modelled. As a result of this the distances between each pair of departments are continuous variables. This differs from discrete layout models in that the distance between any pair of departments is based on the assignment of departments to defined locations. The advantage of this discrete representation is its allowance for simple linear assignment constraints and the way in which it easily avoids inter-centre overlap, which often poses difficulties for optimising the continuous space (Montreuil, Brotherton & Marcotte, 2002).

TABLE 2 LAYOUT MODELS CLASSIFIED ACCORDING TO DISCRETE AND CONTINUOUS

Discrete	Continuous
Quadratic Assignment Problem	Mixed Integer Programming Problem
Quadratic Set Covering Problem	Graph Theoretic Problem
Linear Integer Programming Problem	Linear Continuous Model
	Linear Mixed Integer Model

Table 2 shows how the seven layout models can be classified. Refer to the following research for more explanation on the classification of each model: Adams (2010) for QAP and QSCP; Drira, Pierreval and Hajri-Gabouj (2007) for QAP, MIPP and LMIM; Schenker, Kandel, Bunke and Last (2005) for GTM; Heragy and Kusiak (1991) for LCM and LMIM. The MIPP Problem and the LMIM contain continuous as well as discrete variables.

2.4.2 QUADRATIC ASSIGNMENT PROBLEM

The QAP is one of the most used methods for designing a facility layout. This being said, in practice FLPs are in general more complex than the QAP formulation since the QAP considers only the problem of assigning n equal-sized departments to n pre-determined locations (Meller, Narayanan & Vance, 1998). This assignment occurs according to a cost function of distance and flow between departments as well as the cost of placing a department at a specific location. Thus, the QAP acts so as to allocate departments to locations in such a way that the total costs will be minimised (Burkard, Cela, Pardalos & Pitsoulis, 1999). However, the objectives of the QAP can also be arranged to either minimise material handling cost, travel time, travel distance or flows (Singh & Sharma, 2006).

According to Heragu and Kusiak (1987) the QAP has been frequently used to model the FLP, but it is not able to serve as a model for all FLPs. The QAP model cannot be applied if how far each location is from another is unknown, e.g. the machine layout problem cannot be solved as a QAP model since the distances between locations depends on the arrangement of the machines. Layout problems on the other hand with equal areas can be solved since the locations have equal distances and are thus independent. Thus, the distances stay the same regardless of the department's arrangement. The general formulation of the QAP is given in Table 3.

TABLE 3: GENERAL FORMULATION OF THE QUADRATIC ASSIGNMENT PROBLEM (HERAGU & KUSIAK, 1987; KONAK, KULTUREL-KONAK, NORMAN & SMITH, 2006)

Objective(s)	Assignment of n departments to n locations Minimise total cost/traveling distance/flows/traveling time
Notation	Minimise $\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} f_{ik}c_{jl}x_{ij}x_{kl} + \sum_{i=1}^{n}\sum_{j=1}^{n}\gamma_{ij}x_{ij}$ (1) Subject to $\sum_{j=1}^{n} x_{ij} = 1,\ i = 1,2,\dots,n,$ (2) $\sum_{i=1}^{n} x_{ij} = 1,\ j = 1,2,\dots,n,$ (3) $x_{ij} \in \{0,1\},\ i,j = 1,2,\dots,n.$ (4) n = total number of departments/locations γ_{ij} = fixed cost of locating and operating department i at location j f_{ik} = flow of patients between department i and department k c_{jl} = cost of transporting one patient between location j and location l x_{ij} = 1 if department i is at location j; 0 otherwise x_{kl} = 1 if department k is at location l; 0 otherwise
Assumptions	t_{ij} includes gross revenues minus cost of primary input but does not include the transportation cost of patients between departments f_{ik} is independent of the locations of the departments c_{jl} is independent of the departments and that it is cheaper to transport patients directly from department i to department k than through a third location The number of departments is equal to the number of locations The available space can be divided into equal blocks Equal sized departments
Inputs	The total number of departments or locations The fixed cost of locating and operating department i at location j The flow of patients between department i and department k The cost of transporting one patient between location j and location l
Outputs	Assignment of departments to locations Minimum total cost/traveling distance/flows/traveling time

The QAP formulation is difficult to solve for even small problem sizes. Cela (1998) found that it can be solved with reasonable limits up to a problem size of 20. As a result of this, other researchers have simplified the QAP formulation. Two special cases of this include the Linear Assignment Problem (LAP) and the Travelling Salesman Problem (TSP). A QAP (in Table 3) is reduced to a LAP when the f_{ik}'s are either zero or identical. The new objective is shown in (5).

Minimise $$\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}x_{ij} \qquad (5)$$

Subject to
$$\sum_{j=1}^{n} x_{ij} = 1, i = 1, \dots, n, \tag{6}$$
$$\sum_{i=1}^{n} x_{ij} = 1, j = 1, \dots, n, \tag{7}$$
$$x_{ij} \in \{0,1\}, i, j = 1, \dots, n. \tag{8}$$

(6) to (8) suggest that if the x_{ij}'s are shown in a matrix ($X = [x_{ij}]$), this matrix will be a permutation matrix (meaning a matrix with zeros and one nonzero entry, i.e. 1, in each row and column) (Heragu & Kusiak, 1987). An additional constraint is that the permutation matrix is cyclic, meaning that all the elements in the permutation matrix are shifted by a fixed offset (elements are shifted off the end and inserted back at the beginning) (Weisstein, 2015).

According to Cela (1998) the QAP is usually defined as in Table 3 since the problem formulation expresses the combinatorial structure of the QAP better than alternative equivalent formulations. However, the alternatives are useful when Subgradient Optimisation (a type of iterative method for solving convex minimisation problems) or MIPP, and Semidefinite Programming (a subfield of convex optimisation concerned with the optimisation of a linear objective function) are applied. There are two alternative formulations of the QAP. They are the Koopmans and Beckmann formulation and the Trace formulation, each of which are outlined now.

2.4.2.1 Koopmans and Beckmann formulation

The QAP was first formulated by Beckmann and Koopmans (1957) in order to model a plant location problem. Since then the number of real-life problems which can be mathematically modelled by QAP has steadily increased, spreading into a number of associated fields. A few examples of these applications are placement problems, manufacturing, scheduling, very-large-scale integration design, parallel and distributed computing, and statistical data analysis (Lawler, 1962). The Koopmans and Beckmann formulation of the QAP is given in Table 4.

TABLE 4: KOOPMANS AND BECKMANN FORMULATION OF THE QUADRATIC ASSIGNMENT PROBLEM (BECKMANN & KOOPMANS, 1957; HERAGU & KUSIAK, 1987)

Objectives	Assign n departments to n locations Maximise the total net revenue
Notation	Maximise $\sum_{k,i} p_{ki}x_{ki} - \sum_{k,l}\sum_{i,j} c_{ij}x_{kl,ij}$ (9) Subject to $x_{ki}u_{kl} + \sum_{i} x_{ki} = x_{li}u_{kl} + \sum_{j} x_{ki,ij}, k, l, i = 1, \dots, n,$ (10) $\sum_{i} x_{ki} = 1, k = 1, \dots, n,$ (11) $\sum_{k} x_{ki} = 1, i = 1, \dots, n,$ (12)

KOOPMANS AND BECKMANN FORMULATION OF THE QUADRATIC ASSIGNMENT PROBLEM (BECKMANN & KOOPMANS, 1957; HERAGU & KUSIAK, 1987) (CONTINUED)

Notation	$$x_{ki} \geq 0, x_{ki,ij} \geq 0, x_{ki,ii} = 0, k, l, i, j = 1, \ldots, n. \quad (13)$$ n = Same formulation as in Table 3 p_{kl} = Semi-net revenue from the operation of department k at location i. In other words the gross revenue less cost of primary inputs, but before subtracting transportation cost of intermediate products between departments u_{kl} = Set of non-negative numbers that represent the required commodity flows in weight units from department k to department l. $k \neq 1$. l = 1, …, n c_{ij} = Same formulation as in Table 3 $x_{kl,ij}$ = 1 if there is flow from location i to location j of the commodity which is supplied by department k to department l; 0 if there is no flow x_{ki} = Same formulation as in Table 3
Assumptions	The flow coefficients u_{kl} are independent of the locations assigned The transportation cost coefficients c_{ij} are assumed independent of the plant assignments and applicable to all amounts and compositions of flows The semi-net revenue from a given fractional plant k in a given location i are proportional to the size x_{ki} of the fraction The input and output flows are proportional to the size x_{ki} of the fraction p_{kl} includes gross revenues minus cost of primary input but does not include the transportation cost of material between plants Equal sized departments
Inputs	Total number of departments and locations Semi-net revenue from the operation of department k at location i Set of nonnegative numbers that represent the required commodity flows in weight units from plant k to plant l Set of positive numbers that represent the cost of transportation for the unit flow from location i to location j
Outputs	Assignment of n departments to n locations Maximised total net revenue

2.4.2.2 Trace formulation

The Trace formulation uses linear algebra and the trace function to determine the lower bounds for a cost objective function (Loiola, De Abreu, Boaventura-Netto, Hahn & Querido, 2007). The trace function involves the summation of the main diagonal elements of a matrix. The trace formulation was used in several works including Handley (1994), Karisch and Rendl (1995), and Anstreicher and Brixius (2001). It can also be used as a tool for manipulating the algebraic problem data (Cela, 2013). The trace formulation is shown in Table 5.

TABLE 5: TRACE FORMULATION OF THE QUADRATIC ASSIGNMENT PROBLEM (BURKARD *ET AL.*, 2009; COMMANDER, 2003)

Objectives	Assignment of n departments to n locations Minimise total cost/traveling distance/flows/traveling time
Notation	Minimise $trace(CXD^tX^t)$ (14) Subject to $X \in X_n$ (15) $trace(A) = \sum_{i=1}^{n} a_{ii}$ (16) A = n x n matrix C = Cost matrix. $C = [c_{ij}]$ where c_{ij} is defined the same as Table 3 n = Same formulation as in Table 3 D = Distance matrix. $D = [d_{kl}]$ where d_{kl} represents the distance between location k and location l X = Permutation matrix. $X = [x_{ij}]$ an n x n matrix where x_{ij} is similar as defined in Table 3
Assumptions	The trace of a square matrix is defined as the sum of its diagonal elements Equal-sized departments
Inputs	Cost matrix Distance matrix Permutation matrix
Outputs	Assignment of n departments to n locations Minimum total cost/traveling distance/flows/traveling time

One of the main disadvantages of the QAP formulation is assuming that the departments are equal-sized since that is often difficult to justify in practical cases. According to Konak, Kulturel-Konak, Norman and Smith (2006), it is possible to adjust the QAP formulation to include unequal departments by using small equal area grids and forbidding separating the grids of the same department via the assignment of very high flows between them. This allows departments to have various sizes and rectangular shapes. However, this leads to a large number of integer variables which means that even small problem sizes cannot be optimally solved. Since the high artificial flows enforce unintended constraints between grids of the same department, it is likely to lead to a poor layout solution (Bozer & Meller, 1997).

2.4.3 QUADRATIC SET COVERING PROBLEM

Bazaraa and Goode (1971) developed an improved formulation for Bellmore and Ratliff's linear set-covering algorithm for the quadratic case. The new formulation enables the algorithm to solve problems of the inequality type as well as problems of equality and mixed types by incorporating an additional penalty term in the objective function. The QSCP divides the available floor space into equal blocks (Heragu & Kusiak, 1987). Grid-points are formed which serve as the available locations for the centres. The constraints of the QSCP formulation ensure that each department has one location and each location is occupied by at most one department (Welgama & Gibson, 1995). Several candidate locations are made available for each centre of a department which prevents each location from being available to every centre and allows the accommodation of different centre sizes. This implies that the number of combinations being evaluated is smaller. The QSCP is shown in Table 6.

TABLE 6: QUADRATIC SET COVERING PROBLEM (HERAGU & KUSIAK, 1987; BESTER, 2006)

Objectives	Assignment of n departments to locations Minimisation material-handling cost (as well as the relocation cost of centres)
Notation	Minimise $\sum_{i=1}^{n}\sum_{k=1}^{n}\sum_{j=1}^{I(i)}\sum_{l=1}^{I(k)} f_{ik}x_{ij}x_{kl}d_{jl} + \sum_{i=1}^{n}\sum_{j=1}^{I(i)} t_{ij}x_{ij}$ (17) Subject to $\sum_{j=1}^{I(i)} x_{ij} = 1, i = 1,2, \dots, n,$ (18) $\sum_{i=1}^{n}\sum_{j=1}^{I(i)} a_{ijt}x_{ij} \leq 1, t = 1,2, \dots, q,$ (19) $x_{ij} \in \{0,1\}, i = 1,2, \dots, n; j = 1,2, \dots, I(i).$ (20) q = Number of blocks into which the total area occupied by all departments is divided into d_{jl} = Distance between the centroids of locations j and l if department i is assigned to location j and department k is assigned to location l f_{ik} = Similar to Table 3 t_{ij} = Fixed cost of locating and operating department i at location k $I(i)$ = Set of candidate locations for department i $J_i(j)$ = Set of blocks occupied by department i if it is assigned to location j x_{ij}, x_{ik} = Same definitions as in Table 3 a_{ijt} = 1 if block $a \in J_i(j)$; 0 otherwise
Assumptions	The candidate locations for each centre have to be established in advance The available space is divided into blocks of equal size t_{ij} includes gross revenues minus cost of primary input but does not include the transportation cost of patients between departments f_{ik} is independent of the locations of the departments The number of departments is equal to the number of locations
Inputs	Fixed cost of locating and operating department i at location k Flow of patients between department i and department k Distance between the centroids of locations j and l if f department i is assigned to location j and department k is assigned to location l Number of blocks into which the total area occupied by all departments is divided into Set of candidate locations for department i
Outputs	Assign n departments to locations Set of blocks occupied by department i if it is assigned to location j Minimum material handling cost

One must note that d_{jl} refers to the rectilinear distance (e.g. $|x_i - x_j|+|y_i - y_j|$) between two locations since the departments are laid out in the form of a rectangular grid and a straight line of travel is unlikely. The objective function given in (17) consists of two terms that do not have the same units. The first term represents flow between departments (measured in m³/s) multiplied by the distance (measured in m), which results in a term with a unit of m⁴/s. The second term is the monetary unit. Since there is no known conversion rule between these units, Bester (2006) incorporated a real-valued scaling parameter ($0 < \theta < 1$) which compensates for this discrepancy. This parameter may be varied manually in order to test different conversion rules. The new objective function is shown in (21).

$$\text{Minimise} \quad \theta\left(\sum_{i=1}^{n}\sum_{k=1}^{n}\sum_{j=1}^{I(i)}\sum_{l=1}^{I(k)} f_{ik}x_{ij}x_{kl}d_{jl}\right) + (1-\theta)\left(\sum_{i=1}^{n}\sum_{j=1}^{I(i)} t_{ij}x_{ij}\right) \qquad (21)$$

A disadvantage of the QAP formulation is that by dividing the floor space into smaller blocks to accommodate different sizes, it leads to an increase in the problem size thus making it harder to solve (Bazaraa & Goode, 1971). Furthermore, the candidate solutions for each centre have to be established in advance and the specification of centre shapes might not be practical in the sense that some centres have L-shapes but the model assigns rectangular shapes to them.

2.4.4 LINEAR INTEGER PROGRAMMING PROBLEM

Linear Integer Programming Problems (LIPP) are optimisation problems that exhibit both linear objective functions and linear inequality constraints (Suo, 2012). A wide variety of real life problems can be formulated as a LIPP besides the FLP, for example, the knapsack-capital budgeting problem, machine layout problem, maximum flow problems, weighted matching problems, and scheduling problems (Genova & Guliashki, 2011). In such problems, the variables are constrained to be integers. It is possible to transform some optimisation problems with non-linear objective functions and linear constraints into a LIPP by approximating the non-linear function via piecewise linear functions. Refer to Bertsekas (2003) for this transformation. The FLP was first modelled as a LIPP by Lawler (1962). In his article he proves that the formulation that is shown in Table 7 is equivalent to the QAP. The QAP has n^2 variables and $2n$ constraints, while LIPP has a total of $n^4 + 2n + 1$ constraints (Suo, 2012).

TABLE 7: LINEAR INTEGER PROGRAMMING PROBLEM (LAWLER, 1963; HERAGU & KUSIAK, 1987)

Objectives	Minimise total cost Assignment of n departments to n locations
Notation	Minimise $\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}y_{ijkl}$ (22) Subject to $\sum_{j=1}^{n} x_{ij} = 1, i = 1,2,\ldots,n,$ (23) $\sum_{i=1}^{n} x_{ij} = 1, j = 1,2,\ldots,n,$ (24) $\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} y_{ijkl} = n^2,$ (25) $x_{ij} + x_{kl} - 2y_{ijkl} \geq 0, i,j,k,l = 1,2,\ldots,n,$ (26)

LINEAR INTEGER PROGRAMMING PROBLEM (LAWLER, 1963; HERAGU & KUSIAK, 1987) (CONTINUED)

Notation	$$y_{ijkl} = x_{ij}.x_{il} \quad (27)$$ $$x_{ij} \in \{0,1\}, i,j = 1,2,\dots,n, \quad (28)$$ $$y_{ijkl} \in \{0,1\}, i,j,k,l = 1,2,\dots,n, \quad (29)$$ $$b_{ijkl} = \begin{cases} f_{ik}c_{jl} + t_{ij} & i = k, j = 1 \\ f_{ik}c_{jl} & i \neq k \text{ or } j \neq l \end{cases} \quad (30)$$ x_{ij} = Same definition as in Table 3 x_{il} = 1 if department i is at location l; 0 otherwise c_{jl} = Same definition as in Table 3 y_{ijkl} = The integer variable of department i at location j in arrangement k of location l f_{ik} = Same definition as in Table 3 t_{ij} = Same definition as in Table 3 b_{ijkl} = Monetary term of locating department i at location j n = Same definition as in Table 3
Assumptions	The number of departments is equal to the number of locations The available space can be divided into equal blocks Equal sized departments f_{ik} is independent of the locations of the departments c_{jl} is independent of the departments and that it is cheaper to transport patients directly from department i to department k than through a third location
Inputs	Monetary term of locating department i at location j The integer variable of department i at location j in arrangement k of location l Total number of departments/locations Fixed cost of locating and operating department i at location j Flow of patients between department i and department k Cost of transporting one patient between location j and location l
Outputs	Minimised total cost Assignment of n departments to n locations

A simple integer programming problem formulation of the QAP was developed by Love and Wong (1976). This is shown in Table 8. Take note of the assumptions of this formulation. In this formulation, the positions of departments are defined by rectangular coordinates. It was found that this model cannot be optimally solved for problems with nine or more departments (Bozer & Meller, 1997).

LIPPs are more easily solvable than convex non-linear integer programming problems. The difficulty with solving linear and non-linear integer programming problems is due to the fact that it requires one to search for a set of feasible integer points in order to solve the problem optimally. Integer programming problems have many local solutions which means that one would have to prove that a particular solution is superior to all the other feasible solutions in order to find the global optimum (Love & Wong, 1976). Linear programming uses a feasible region which forms a convex set. The convexity of this problem means that any local solution is a global one. For this reason, this study will further focus on the LIPP formulation in Table 7 rather than nonlinear programming.

TABLE 8: LINEAR INTEGER PROGRAMMING PROBLEM (LOVE & WONG, 1976)

Objectives	Minimise travel distance between departments Assign n departments to n locations
Notation	Minimise $\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}x_{ij} + \sum_{i=1}^{n-1}\sum_{k=i+1}^{n} f_{ik}\left(h_{ik}^{r} + h_{ik}^{l} + v_{ik}^{a} + v_{ik}^{b}\right)$ (31) Subject to $h_{ik}^{r} - h_{ik}^{l} = \overline{x_i} - \overline{x_k}, i = 1,2,\ldots,n; k = i+1,$ (32) $v_{ik}^{a} - v_{ik}^{b} = \overline{y_i} - \overline{y_k}, i = 1,2,\ldots,n; k = i+1,$ (33) $\overline{x_i} + \overline{y_i} = \sum_{j=1}^{n}(\overline{x_j} + \overline{y_j})x_{ij}, i = 1,2,\ldots,n,$ (34) $\overline{x_i} - \overline{y_i} = \sum_{j=1}^{n}(\overline{x_j} - \overline{y_j})x_{ij}, i = 1,2,\ldots,n,$ (35) $\sum_{j=1}^{n} x_{ij} = 1, i = 1,2,\ldots,n,$ (36) $\sum_{j=1}^{n} x_{ij} = 1, j = 1,2,\ldots,n,$ (37) $x_{ij} \in \{0,1\}, i,j = 1,2,\ldots,n,$ (38) $h_{ik}^{r}, h_{ik}^{l}, v_{ik}^{a}, v_{ik}^{b} \geq 0, i - 1,2,\ldots,n; k = i+1,$ (39) $\overline{x_i}, \overline{y_i} \geq 0, i = 1,2,\ldots,n.$ (40) h_{ik}^{l} = Horizontal distance between department i and k when department i is to the left of department k; 0 otherwise h_{ik}^{l} = Horizontal distance between departments i and k when department i is to the right of department k; 0 otherwise v_{ik}^{a} = Vertical distance between departments i and k when department i is above department k; 0 otherwise v_{ik}^{b} = Vertical distance between departments i and k when department i is below department k; 0 otherwise $(\overline{x_i}, \overline{y_l})$ = Location of department i x_{ij} = Same definition as in Table 3 f_{ik} = Same definition as in Table 3
Assumptions	The locations are given as points on a two dimensional plane The transportation costs are proportional to weighted rectangular distances The locations are specified by rectangular coordinates
Inputs	Horizontal distance between departments i and k when department i is to the right of department k Horizontal distance between departments i and k when department i is to the left of department k Vertical distance between departments i and k when department i is above department k Vertical distance between departments i and k when department i is below department k Flow of material between department i at location k
Output	Minimised traveling distance between departments

2.4.5 MIXED INTEGER PROGRAMMING PROBLEM

A Mixed Integer Programming Problem (MIPP) is a model wherein some of the decision variables are constrained to be integer values at the optimal solution (Frontline Systems Incorporated, 2015). In other words, it is an optimisation method that combines continuous and discrete variables. This allows MIPPs to model complex planning and control problems involving both continuous and discrete variables (Richards & How, 2005).

According to Heragu and Kusiak (1987), amongst all integer-programming formulations of the QAP, the MIPP have the smallest number of variables and constraints. The formulation of the MIPP is shown in Table 9. This formulation has n^2 continuous variables, n^2 zero-one variables, and $n^2 + 2n$ constraints. The MIPP formulation was proved by Burkard (1984) to be equivalent to the QAP formulation.

TABLE 9: MIXED INTEGER PROGRAMMING PROBLEM (HERAGU & KUSIAK, 1987)

Objectives	Minimise total cost Assign n departments to locations
Notation	Minimise $\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$ (41) Subject to $\sum_{j=1}^{n} x_{ij} = 1, i = 1,2,\dots,n,$ (42) $\sum_{i=1}^{n} x_{ij} = 1, j = 1,2,\dots,n,$ (43) $e_{ij}x_{ij} + \sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}x_{kl} - w_{ij} \leq e_{ij},$ (44) $w_{ij} = x_{ij}\sum_{k=1}^{n}\sum_{l=1}^{n} b_{ijkl}x_{kl}\,,$ (45) $e_{ij} = \sum_{k=1}^{n}\sum_{l=1}^{n} b_{jkl}\,,$ (46) $b_{ijkl} = \begin{cases} f_{ik}c_{jl} + t_{ij} & i = k, j = 1 \\ f_{ik}c_{jl} & i \neq k \text{ or } j \neq l \end{cases}$ (47) $w_{ij} \geq 0, i = 1,2,\dots,n,$ (48) $x_{ij} \in \{0,1\}, i,j = 1,2,\dots,n.$ (49) x_{ij} = Same definition as in Table 3 x_{kl} = Same definition as in Table 3 c_{jl} = Same definition as in Table 3 f_{ik} = Same definition as in Table 3 t_{ij} = Same definition as in Table 3 b_{ijkl} = Same definition as in Table 3 n = Same definition as in Table 3

MIXED INTEGER PROGRAMMING PROBLEM (HERAGU & KUSIAK, 1987) (CONTINUED)

Assumptions	f_{ik} is independent of the locations of the departments c_{jl} is independent of the departments and that it is cheaper to transport patients directly from department i to department k than through a third location t_{ij} includes gross revenues minus cost of primary input but does not include the transportation cost of patients between departments
Inputs	Monetary term of locating department i at location j Flow of material from department i to department k Total number of departments Fixed cost of locating and operating department i at location j Flow of patients between department i and department k Cost of transporting one patient between location j and location l
Outputs	Minimised total cost Assign n departments to locations

A large MIPP was formulated by Ritzman, Bradford and Jacobs (1979) for finding the optimal arrangement of offices in a building. By developing a computer program they were able to evaluate the layout solutions generated against six objectives (Shouman, Nawara, Reyad & El-Darandaly, 2001).

A few years later Montreuil (1991) developed another MIPP formulation that defines binary decision variables for north-south and east-west relationships. The constraints of this formulation prevent that departments overlap, have a specific size and shape. A disadvantage of Montreuil's model (as with all the other FLP formulations) is the very limited problem size that can be solved optimally. Shouman *et al.* (2001) found that this model is limited to six departments. Meller *et al.* (2001) tightened Montreuil's model using valid inequalities and as a result managed to solve problems with up to eight departments. According to Konak, Kulturel-Konak, Norman and Smith (2006) Montreuil's model is a pioneering formulation for the MIP. Montreuil's model is not based on the traditional QAP formulation like the one in Table 9. The Linear Mixed Integer Model (LMIM) discussed later on in this section (Section 2.4.8) is a specialised case of Montreuil's model (Meller & Gau, 1996). The difference between these two models is that the LMIM formulation requires that the departments' lengths and widths need to be known a priori which improves the computation time when solving this model. Because these two models are very similar, only the LMIM is further discussed in this study.

Konak, Kulturel-Konak, Norman and Smith (2006) developed a MIPP formulation that is based on the Flexible Bay Structure (FBS). This formulation allows departments to be placed only in parallel. Each bay's width can vary which depends on the total area of the departments in that specific bay. The departments are restricted to only one bay and are bounded by straight aisles on either side. Consequently, the FBS restricts possible layout configurations and the complexity of the problem is reduced (Chang & Lin, 2012). An advantage of using this formulation is that optimal FBS layouts were found with up to fourteen departments. However, these restrictions imposed by FBS formulations may be useful in manufacturing cells or the arrangement of rooms, but large departments of a hospital are unlikely to be optimally arranged in parallel bays. In order to explore more layout configurations, this formulation is not further considered in this study.

2.4.6 GRAPH THEORETIC PROBLEM

The Graph Theoretic Problem (GTP) constructs a graph that maximises the weight on the adjacencies between pairs of departments. It was first formulated by Fould and Robinson (1976) who defined each department as a node inside a graph network. Initially, areas and shape of departments are ignored. Knowledge about the possible locations for the departments is not required in advance which makes the GTP suitable for solving layouts with unequal areas (Kim & Kim, 1995). This graph network relies on the desirable adjacency of each pair of departments. It is thus assumed that the desirability of locating each pair of departments adjacent to each other is known (Singh & Sharma, 2006). In this context, a graph is formed by connecting a set of nodes by arcs, termed vertices and edges respectively, and represented as $G = (V, E)$ whereby V pertains to the set of vertices and E pertains to the set of edges. The areas bounded by cycles of edges are referred to as the faces of the graph. The region outside the graph is also a face, but is considered an infinite face. Any two faces that have a common edge are defined as adjacent faces. A graph is weighted if its edges are assigned weights, that is, parameters such as cost or benefit. A graph is defined as planar when all its edges only intersect at the vertices. Furthermore, if a graph is fully connected, i.e. contains the maximum number of edges without losing planarity, then it is a Maximal Planar Graph (Hassan & Hogg, 1987). This formulation is shown in Table 10.

TABLE 10: GRAPH THEORETIC PROBLEM (HERAGU & KUSIAK, 1987)

Objectives	Maximise a closeness rating measure Assign n departments to locations
Notation	Maximise $$\sum_{i\in E}\sum_{j\in E} r_{ij} o_{ij} \quad (50)$$ Subject to $$o_{ij} = 1, \{i,j\} \in N, \quad (51)$$ $$o_{ij} = 0, \{i,j\} \in F. \quad (52)$$ $G = (V, E)$ = A weighted graph with V as a nonempty set of departments, E as a set of edges disjoint from V r_{ij} = The closeness rating indicating desirability of locating department i adjacent to department j V = Nonempty set of departments E = A set of edges disjoint from V N = The set of pairs of departments which must be adjacent in any feasible solution F = The set of pairs of departments which must not be adjacent in any feasible solution o_{ij} = Variable indicating assignment of departments. 1 if department i is adjacent to department j; 0 otherwise E' = $\{i,j\}: x_{ij} = 1, [i,j] \in E$

GRAPH THEORETIC PROBLEM (HERAGU & KUSIAK, 1987) (CONTINUED)

Assumptions	The desirability of locating each pair of departments adjacent to each other is known
Inputs	The closeness rating indicating desirability of locating department i adjacent to department j The set of pairs of departments which must be adjacent in any feasible solution The set of pairs of departments which must not be adjacent in any feasible solution The set of departments
Outputs	Maximised closeness Adjacency of departments

The Graph Theoretic approach usually follows three steps, namely (Kim & Kim, 1995; Meller & Gau, 1996):

- Developing a Maximal Planar Weighted Graph (MPWG) (Maximal Planar Graph with the maximum sum of edge weights) from department relationships to indicate which departments will be adjacent;
- Constructing the dual graph of the MPWG to represent departments as adjacent regions having specific boundaries; and
- Converting the dual graph into a block layout where departments have regular shapes with specific areas.

These steps of developing the MPWG and its dual correspond to the selection and placement steps of other existing facilities layout procedures (Kim & Kim, 1995). It is essentially a construction approach (modelling the FLP), but improved solutions have also been obtained using this approach.

The GTP has several advantages over other existing FLP approaches. Firstly, there is the question of the establishment of an upper bound on the optimal solution. Since the maximum number of adjacencies that can be achieved in a planar graph is $3n - 6$, summing the highest weight $3n - 6$ relationships provides the required bound (Heragu & Kusiak, 1987). Secondly, the value of the objective function obtained as the sum of weights of edges is in general better than those obtained by traditional computerised procedures such as ALDEP and CORELAP. Both of these computerised procedures achieve adjacencies by constructing planar weighted graphs from a spanning tree or maximum spanning tree while Graph Theory depends on constructing a MPWG and thus more relationships are likely to be satisfied resulting in an enhanced objective function value (Hassan & Hogg, 1987). Thirdly, Foulds and Giffen (1985) showed that it is possible to impose an alternative objective during the solving process.

Despite these advantages of the GTP, there are several limitations too. For one, the actual length of common boundaries of adjacent departments is not taken into consideration when constructing the block plan or calculating the objective function via the MPWG (Hassan & Hogg, 1987). While the approach has succeeded in finding good arrangements of departments, it has failed to find good configurations for them (arrangements in a particular form) (Kim & Kim, 1995).

2.4.7 LINEAR CONTINUOUS MODEL

The Linear Continuous Model (LCM) was developed by Heragy and Kusiak (1991). They formulated single-row as well as multi-row problems for both equal areas and unequal areas. Single-row and multi-row layout problems are also known as one-dimensional and two-dimensional space allocation problems respectively. Since multi-row is a better representation of real life problems only the multi-row layout problem will be discussed. Heragy and Kusiak (1991) found that the algorithms can be solved in a relatively low computation time with good quality sub-optimal solutions. According to their research the LCM is more useful in solving FLPs than other models promoted in literature.

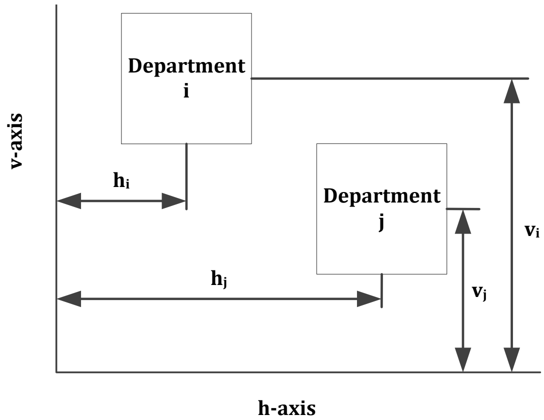


FIGURE 8: VARIABLES FOR EQUAL-SIZED LINEAR CONTINUOUS MODEL

Figure 8 shows the variables of the Equal-sized Linear Continuous Model formulation. Table 11 shows the formulation for a FLP with equal areas.

In order to transform the formulation to solve unequal areas, the following variables are defined in addition to those already defined in Table 11:

- l_i = the length of the horizontal side of department i; and
- b_i = the length of the vertical side of department i.

The variables for the unequal-sized LCM are described in Figure 9.

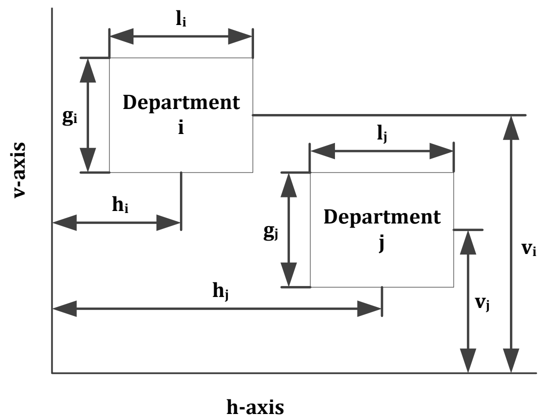


FIGURE 9: VARIABLES FOR UNEQUAL-SIZED LINEAR CONTINUOUS MODEL

TABLE 11: LINEAR CONTINUOUS MODEL FOR EQUAL-SIZED DEPARTMENTS (HERAGY & KUSIAK, 1991)

Objectives	Minimise the total cost Assign n departments to locations
Notation	Minimise $$\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} c_{ij}\alpha_{ij}\left(\left\|h_i - h_j\right\| + \left\|v_i - v_j\right\|\right) \quad (53)$$ Subject to $$\left\|h_i - h_j\right\| + \left\|v_i - v_j\right\| \geq 1,$$ $$i - 1, \dots, n-1; j = 1, \dots, n; x_i, y_i \ integer; i = 1, \dots, n, \quad (54)$$ $$\left\|h_i - h_j\right\| \leq h - 1, i = 1, \dots, n-1; j = i+1, \dots, n, \quad (55)$$ $$\left\|v_i - v_j\right\| \leq v - 1, i = 1, \dots, n-1; j = i+1, \dots, n. \quad (56)$$ n = Same definition as in Table 3 h_i = The horizontal distance between department i and the v-axis h_j = The horizontal distance between department j and the v-axis v_i = The vertical distance between department i and h-axis v_j = The vertical distance between department j and h-axis c_{ij} = Cost of transporting one patient between location j and location l α_{ij} = The frequency of trips required between department i and j v = Vertical dimensions of the floor plan h = Horizontal dimensions of the floor plan
Assumptions	The departments are arranged on a two dimensional plane as shown in Figure 8 The departments are oriented in only two given directions The shape of the departments is known in advance There is no restriction on the shape of the building in which the departments are to be located
Inputs	The horizontal distance between department i and the v-axis The horizontal distance between department j and the v-axis The vertical distance between department i and h-axis The vertical distance between department j and h-axis The cost per unit distance travelled between departments i and j The cost per unit distance travelled between departments i and j The number of trip to be made between departments i and j Vertical dimensions of the floor plan Horizontal dimensions of the floor plan
Outputs	Minimised total cost Assign n departments to locations

Heragy and Kusiak (1991) formulated another version of the LCM where constraints are added to ensure that departments do not overlap. The formulation of this model is shown in Table 12.

The difference between the model in Table 11 and the one in Table 12 is that the last model may lead to a layout solution with empty spaces between departments (Solimanpur & Jafari, 2008). The model is thus suitable for solving specific types of layout problems. The variable M, an arbitrarily large positive number, used in (58) and (59) ensures that no two departments in the layout overlap.

TABLE 12: LINEAR CONTINUOUS MODEL FOR UNEQUAL SIZED DEPARTMENTS (HERAGY & KUSIAK, 1991)

Objectives	Minimise transportation cost (material handling cost) Assign n departments to locations
Notation	Minimise $\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} c_{ij}\alpha_{ij}(\lvert x_i - x_j\rvert + \lvert y_i - y_j\rvert)$ (57) Subject to $\lvert x_i - x_j\rvert + Mz_{ij} \geq \frac{1}{2}(l_i + l_j) + k_{ij}, i = 1, \dots, n-1;$ $j = i+1, \dots, n,$ (58) $\lvert y_i - y_j\rvert + M(1 - z_{ij}) \geq \frac{1}{2}(g_i + g_j) + k_{ij}, i = 1, \dots, n-1;$ $j = i+1, \dots, n,$ (59) $z_{ij}(1 - z_{ij}) = 0, i = 1, \dots, n-1; j = i+1, \dots, n.$ (60) n = Same definition as in Table 3 h_i = The horizontal distance between department i and the v-axis h_j = The horizontal distance between department j and the v-axis v_i = The vertical distance between department i and h-axis v_j = The vertical distance between department j and h-axis c_{ij} = Cost of transporting one patient between location j and location l α_{ij} = The frequency of trips required between department i and j z_{ij} = Variable used to ensure that only one of the constraints hold so that the departments do not overlap M = An arbitrarily large positive number l_i = The distance between the extreme vertical sides of department i l_j = The distance between the extreme vertical sides of department j g_i = The distance between the extreme horizontal sides of department i g_j = The distance between the extreme horizontal sides of department j k_{ij} = Minimum distance by which departments i and j are to be separated
Assumptions	The departments are arranged on a two dimensional plane as shown in Figure 8 The departments are oriented in only two given directions The shape of the departments is known in advance The departments are square or rectangular in shape. There is no restriction on the shape of the building in which the departments are to be located
Inputs	Total number of departments Cost of transporting one patient between location j and location l The number of trips to be made between department i and j The distance between the extreme vertical sides of department i The distance between the extreme vertical sides of department j The distance between the extreme horizontal sides of department i The distance between the extreme horizontal sides of department j Minimum distance by which departments i and j are to be separated
Outputs	The horizontal distance between department i and the v-axis The horizontal distance between department j and the v-axis The vertical distance between department i and h-axis The vertical distance between department j and h-axis Minimised total cost Assign n departments to locations

2.4.8 LINEAR MIXED INTEGER MODEL

According to Heragy and Kusiak (1991) the Linear Mixed Integer Model (LMIM) has a lower number of integer variables than any other formulation of the FLP (with the exception of the LCM). Most LMIMs available in the literature have been obtained through linearizing the QAP, however the LMIM discussed in this section is not. The location of sites does not need to be known prior to solving the problem. Heragy and Kusiak (1991) also found that this formulation delivers high quality solutions in a relatively short time. This model takes time into consideration while the LCM focused on cost.

The variables for the unequal-sized LMIM problem are described in Figure 10.

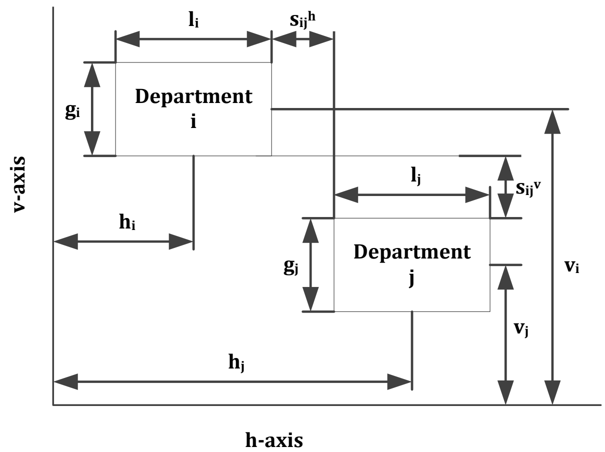


FIGURE 10: VARIABLES FOR UNEQUAL-SIZED LINEAR MIXED INTEGER MODEL

Table 13 shows the formulation for the LMIM:

TABLE 13: LINEAR MIXED INTEGER MODEL (HERAGY & KUSIAK, 1991)

Objectives	Minimise the total time involved in patients moving between departments Assign n departments to locations
Notation	Minimise $$\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} t_{ij}\alpha_{ij}\left(\left\|x_i^v - x_j^v\right\| + \left\|x_i^h - x_j^h\right\|\right) \quad (61)$$ Subject to $$\left\|x_i^v - x_j^v\right\| + My_{ij} \geq \frac{1}{2}(b_i + b_j) + c_{ij}^v, i = 1, \dots, n-1; j = i+1, \dots, n, \quad (62)$$ $$\left\|x_i^h - x_j^h\right\| + M(1 - y_{ij}) \geq \frac{1}{2}(l_i + l_j) + c_{ij}^h, i = 1, \dots, n-1; j = i+1, \dots, n, \quad (63)$$ $$z_{ij}(1 - z_{ij}) = 0, i = 1, \dots, n-1; j = i+1, \dots, n. \quad (64)$$ t_{ij} = The time required for a patient to move between departments i and j α_{ij} = Same definition as in Table 12 s_{ij}^v = Vertical clearance, i.e. the minimum distance by which departments i and j are to be separated if they are positioned in opposite rows in the layout

LINEAR MIXED INTEGER MODEL (HERAGY & KUSIAK, 1991) (CONTINUED)

Notation	s_{ij}^h = The horizontal clearance, i.e. the minimum distance by which departments i and j are to be separated if they are positioned in the same rows in the layout l_i = Same definition as in Table 12 l_j = Same definition as in Table 12 b_i = Same definition as in Table 12 b_j = Same definition as in Table 12 h_i = Same definition as in Table 12 h_j = Same definition as in Table 12 v_i = Same definition as in Table 12 v_j = Same definition as in Table 12 z_{ij} = Same definition as in Table 12
Assumptions	The departments are arranged on a two dimensional plane The departments are oriented in only two given directions The shape of the departments is known in advance There is no restriction on the shape of the building in which the departments are to be located
Inputs	The time required by a material handling carrier per trip between departments i and j The frequency of trips required between departments i and j The vertical clearance The horizontal clearance The distance between the extreme horizontal sides of department i The distance between the extreme vertical sides of department i Vertical distance between centre of department i and h-axis Horizontal distance between centre of department i and v-axis
Outputs	Minimised total time Departments assigned to locations

2.5 Solution methods

As mentioned in the introduction to FLP solution methods in Section 2.3.2, the layout models discussed in Section 2.4 can be particularly time-consuming to solve for real-word (i.e. large) problems. They can be optimally solved with exact methods such as the Branch and Bound Algorithm and the Cutting Plane Algorithm, but only if the problem size is small enough since the computation time significantly increases as the problem size increases. Typically a hospital layout will be too large to be solved with exact methods (Tompkins, White, Bozer & Tanchoco, 2010). Consequently, heuristics and metaheuristics have been developed so as to search for near optimal solutions of large FLPs. These methods are able to find good quality solutions within reasonable computation times which are sufficient for practical purposes. The Centre for Operational Research and Logistics (2015) of Portsmouth University in England found heuristic and metaheuristic techniques to be powerful and flexible search methodologies that have successfully tackled practical and difficult problems. Many heuristics have been developed to specifically solve large FLPs, such as: CRAFT, ALDEP, CORELAP, SPIRAL, and MULTIPLE. They are popular as layout software and are discussed in Section 2.6. The field of metaheuristics has enjoyed considerable popularity in the last few decades and these methods are currently being used to solve large FLPs (Blum, Roli & Sampels, 2008). Examples of metaheuristics used to solve FLPs are shown in Table 1 and the more popular metaheuristics were chosen to be analysed, namely: SA, TS, GA, ACO, and PSO. A description, history, algorithm outline, flow diagram, and the advantages and disadvantages of these methods are provided in this section. As mentioned in Section 2.3, hybrid metaheuristics, a new branch of metaheuristic research concerned with the hybridisation of metaheuristics with algorithmic components originating from other techniques, has also started to gain research attention. These methods are briefly discussed in Section 2.5.3. The chapter ends with a conclusion on the analysed methods.

2.5.1 EXACT METHODS

Exact methods are able to find the optimal solution of problems. There exist two categories of exact methods, namely Branch and Bound Algorithms and Cutting Plane Algorithms.

2.5.1.1 Branch and Bound Algorithms

Branch and Bound Algorithms can be utilised to find an optimal solution to the QAP, since the QAP has only binary variables. Literature reports optimal solutions only up to a problem size of 16 (Singh & Sharma, 2006). Beyond this problem size it becomes intractable for even a powerful computer to handle. The first Branch and Bound Algorithms were proposed separately by Gilmore (1962) and Lawler (1963). These two methods differ with regards to the computation of the lower bounds. Each of the methods implicitly evaluate all possible solutions. Land (1953) and Gavett and Plyter (1966) developed two more algorithms which involves the assignment of pairs of departments whereas the first algorithms assign one department to one location. In comparison to the original algorithms which assign one department to one location, these ones assign pairs of departments to pairs of locations (Charnsethikul, 1988).

All four algorithms operate by assigning departments to locations at each phase of the solving process. Each phase involves backtracking, excluding some assignments and resuming of the search process. Lavalle and Roucairol (1985) suggest that parallel Branch and Bound Algorithms can be used to solve the QAP optimally. The algorithms search in a parallel fashion through numerous parts of the decision tree. However, the authors found that high computation time is required for layouts with 12 or more departments (Drira, Pierreval & Hajri-Gabouj, 2007). Burkard proposed in 1973 that the QAP can be solved via reducing its square matrix. This implies that the matrix is changed into a matrix with non-negative elements, with at least one zero being present in every row and column. Furthermore, this reduction increases the influence of the linear term in the objective function and the quality of the bound via decreasing the magnitude of the quadratic term in the function. Bazaraa (1975) proposed another algorithm which suggests a partial layout at each phase of the solving process. Furthermore, it determines a lower bound on the cost on all potential layouts that can arrive from these partial layouts. If it is determined that the lower bound has a lower cost than the best found layout, the algorithm will continue to assign new departments. Otherwise, the search process along this path will be terminated and a new search path is then followed. The search process will continue until a whole layout is arrived at. Bazaraa and Elshafei (1979) developed a Branch and Bound Algorithm that assigns only one department to locations at each phase of the search process. Kaku and Thompson (1986) suggested another Branch and Bound Algorithm which performed better than the first developed algorithm (Heragu & Kusiak, 1987).

The problem with exact methods is that the optimal solution may be found early in the search process, but it is not accepted until a large number of solutions are computed (Burkard & Stratman, 1978; Bazaraa & Kirca, 1983). Exact methods thus require high memory as well as high computation time. Therefore in 1984, researchers developed a heuristic which terminates the search process early without verifying that the optimal solution is arrived at. The criteria for the termination process include time limits (stopping the search of a specified period of time), and quality of the upper bounds (after a predefined time limit the upper bound is decreased if there is no improvement in the solution) (Burkard, 1984).

2.5.1.2 Cutting Plane Algorithms

Cutting Plane Algorithms refine an objective function by means of linear inequalities (called cuts) (Mitchell, 1998). The Cutting Plane Algorithm gained popularity in 1980 when Bazaraa and Sherali (1980) established an algorithm that is built on Benders' partitioning scheme (which allows one to compute the solution of very large linear programming problems that have a special block structure) (Benders, 1962). Three years later Burkard and Bonninger (1983) established another Cutting Plane Algorithm to solve the QAP. The optimal Cutting Plane Algorithm has a high computation time and its storage is complex. Heragu and Kusiak (1987) found that the largest size FLP that can be optimally solved by a Cutting Plane Algorithm is one with only eight departments. These Cutting Plane Algorithms are known as traditional cutting planes. Another type is the so-called polyhedral cutting planes which are used in complex Branch and Cut Algorithms (involves combining the Branch and Bound and Cutting Plane Algorithm). According to Cela (2013) the experience of applying this method to the QAP is still very limited. This is due to the structural combinatorial properties of the QAP.

2.5.2 METAHEURISTICS

Metaheuristics have recently become very popular for solving optimisation problems (Bianchi, Dorigo, Gambardella & Gutjahr, 2009). They combine heuristics in a more general framework. However, they do not ensure that a globally optimum solution can be found. Many metaheuristics use some form of stochastic optimisation, so that the solution is dependent on a set of random variables generated.

According to Blum and Roli (2003), metaheuristics are:

> *...high level concepts for exploring search spaces by using different strategies. These strategies should be chosen in such a way that a dynamic balance is given between the exploitation of the accumulated search experience (which is commonly called intensification) and the exploration of the search space (which is commonly called diversification).*

Finding a balance between the 'intensification' and 'diversification' is necessary to quickly determine areas in the search space that exhibit high quality solutions while not wasting too much time in search space areas that are either already explored or provide low quality solutions (Blum & Roli, 2003).

The field of metaheuristics originated in 1983 with the development of SA which as the name implies, simulates the annealing process of metals (Kirkpatrick, Gelatt & Vecchi, 1983). Next, the Artificial Immune System was created by Farmer, Packard and Perelson (1986). After this Laguna, Barnes and Glover (1991) developed TS and pioneered the use of memory in metaheuristics whereby the search moves are recorded and avoided in further search steps. Ant Colony Optimisation (ACO) was introduced by Dorigo (1992) who was inspired by the swarm intelligence of social ants using pheromones as a chemical messenger. Koza (1992) published in the same year research on genetic programming. PSO was then developed through Kennedy and Eberhart (1995). The next year Storn and Price (1996) constructed the Differential Evolution, a vector based evolutionary algorithm. Geem, Kim and Loganathan (2001) came up with the Harmony Search Algorithm which was inspired by music. After this, Passino (2002) developed the Bacteria Foraging Algorithm. Nakrani and Tovey (2004) optimised internet hosting centres when they invented the Honey Bee Algorithm. This was further built upon by Karaboga (2005) with his design of the Artificial Bee Colony Algorithm, and later his Firefly Algorithm. Additionally, Yang and Deb (2014) developed the Cuckoo Search Algorithm.

Metaheuristics can be divided into single-solution based and population based searches (Talbi, 2009). Single-solution based metaheuristics are also called S-metaheuristics, as the name suggests that they seek to improve a single solution while solving optimisation problems. They can be seen as 'walks' through neighbourhoods or search trajectories through the solution space of the problem. These trajectories or walks are conducted through iterative search procedures that move from the current solution to other ones in the solution space (Blum & Li, 2008). With each iteration, generation and replacement procedures are applied to the current single solution. The generation procedures involve determining a set of candidate solutions from a current solution, 's'. The set of candidate solutions, C(s), are generated by local transformations of the current solution. The replacement procedures on the other hand involve selecting solutions from the candidate solutions in order to replace the current solution. The process will continue until a specified stopping criterion is reached. The generation and replacement phases may be memoryless. If this is the case, the generation and replacement are based only on the current population. Otherwise, history of the search stored in memory can be used in both the generation and replacement phases. Popular examples of S-metaheuristics include LS, SA, and TS. All three algorithms will be discussed in this section. On the other hand, population based metaheuristics, also called P-metaheuristics, can be viewed as an iterative improvement in a population of solutions (candidates) (Kennedy, Kennedy, Eberhart & Shi, 2001). The candidate solutions are improved by using population characteristics. The first step is to initialise the population. Next, a new population is generated in what is known as the generation phase. Finally, this new population is integrated into the current one through selection procedures called the replacement phase. The search process terminates when a given condition is satisfied, i.e. the stopping criterion. Similar to S-metaheuristics, the generation and the replacement phases can be memoryless. Examples of this class of metaheuristics include ACO, Artificial Immune Systems, Bee Colony, Evolutionary Algorithms, Estimation of Distribution Algorithms, Particle Swarm Optimisation (PSO), and Scatter Search.

There exists another category of metaheuristics which uses the behaviour of decentralised, self-organising optimisation called Swarm Intelligence. Swarm Intelligence can be described as algorithms inspired from the collective behaviour of species such as ants, bees, birds, fish, termites, and wasps (Blum & Mercle, 2008). It originated form the social behaviour of those species that compete for foods. (Talbi, 2009) states that "*the main characteristics of swarm intelligence-based algorithms are particles are simple and non-sophisticated agents, they cooperate by an indirect communication medium, and do movements in the decision space.*" Two very popular and successful swarm intelligence approaches include ACO and PSO.

Metaheuristics can be divided into two types of search strategies, one that is an improvement on simple LS algorithms, or one that has a learning component to the search. The improvement types include SA, TS, LS, variable neighbourhood search and GRASP. The learning component type on the other hand includes metaheuristics, such as ACO, evolutionary computation, and GAs (Blum & Roli, 2003).

For the purposes of this study it is sufficient to look into the following: the LS, SA, TS, GA, ACO, and PSO.

2.5.2.1 Local Search method

LS is one of the first popular improvement techniques developed and also one of the most basic iterative heuristic methods, which typically produces suboptimal solutions (Lourenço, Martin & Stützle, 2010). It is able to approximate solutions to large scale combinatorial optimisation problems in a short period of time. As it always moves from the current solution to the next better solution, it is called a greedy algorithm. When an algorithm is greedy it means that it follows the problem solving heuristic which entails making the locally optimal choice for each and every stage in the hopes of finding a global optimum as rapidly as possible.

The algorithm starts at an initial solution from which it iteratively tries to replace the current solution by moving to an improved solution in a specified neighbourhood of the current solution. This neighbourhood can be described as follows (Blum, Roli & Sampels, 2008):

> *...a neighbourhood structure is a function $N: S \rightarrow 2^S$ that assigns to every $s \in S$ a set of neighbours $N(s) \subseteq S$. $N(s)$ is called the neighbourhood of s. Often, neighbourhood structures are implicitly defined by specifying the changes that must be applied to a solution s in order to generate all its neighbours. The application of such an operator that produces a neighbour $s' \in N(s)$ of a solution s is commonly called a move.*

The topology of the search landscape is defined by the problem instance. One can view the search landscape as a labelled graph whereby the nodes represent solutions and the arcs represent the neighbourhood relations that exist between solutions. A solution $s* \in S$ is called a global minimum if for all $s \in S$ it holds that $f(s*) \leq f(s)$. The set of all global minimum is thus denoted by $S*$. The concept of local minimum can be defined as follows (Blum *et al.*, 2008) *"a local minimum with respect to a neighbourhood structure N is a solution $\hat{s}$ such that $\forall\, s \in N(\hat{s})$: $f(\hat{s}) \leq f(s)$. We call $\hat{s}$ a strict locally minimal solution if $f(\hat{s}) < f(s)\ \forall\, s\ (\hat{s})$."*

The iterative improvement search is the most basic search method and is shown below in Algorithm 2.1. Each consecutive move is performed only if the resulting solution is superior to the current solution. Once it has reached a local minimum, the algorithm terminates.

ALGORITHM 2.1: ITERATIVE IMPROVEMENT LOCAL SEARCH ALGORITHM ADAPTED FROM BLUM, ROLI AND SAMPELS (2008)

Iterative improvement local search
$s \leftarrow$ Generate initial solution
while $\exists\, s' \in N(s)$ such that $f(s') < f(s)$ **do**
$s \leftarrow$ Choose improving neighbour from $N(s)$
end while

There are also a few metaheuristics that are based on the LS such as Variable Neighbourhood Search, Guided LS, and Greedy Randomized Adaptive Search Procedure (Blum *et al.*, 2008).

2.5.2.2 Simulated Annealing

Simulated Annealing (SA) exhibits the ability to escape local optima, which significantly improves the prospects for finding the global optimum solution. The goal of SA is thus to find an acceptably good solution in a set amount of time (Dowsland & Thompson, 2012). SA is a popular direct search technique most commonly used to address discrete problems (as well as continuous optimisation problems, but to a lesser extent) (Pham & Karaboga, 2012). SA is applicable to unconstrained and bound-constrained optimisation problems with the ability to manage several variables. Direct search methods have a tendency to converge slower, but are also more tolerant to the presence of noise in the objective function and constraints. SA is a good solver for problems with general non-specific problem structures (Dowsland & Thompson, 2012).

The SA algorithm was inspired by the annealing process in metal work which involves heating and cooling a metal so as to alter its physical properties through changes in the internal molecular structure (Aarts, Korst & Michiels, 2014). Once cooled, the metal structure becomes fixed and this lower energy internal structure is then retained. If the cooling and annealing process is too quick, it will solidify into a sub-optimal configuration. Instead, if the metal cools slowly, the crystals within the metal will solidify optimally into a state of minimum energy. The temperature is the variable which simulates the heating and cooling process. Typically the temperature starts off high and slowly decreases due to cooling as the algorithm progresses. When the temperature is high, the algorithm allows more frequently for the accepted solutions to be worse off than the current solution so as to enable the algorithm to escape any local optima it finds itself in at the start of the execution. Escaping the local optima is facilitated by the algorithm allowing hill-climbing moves which lead to worse objective function values with the aim of finding the global optimum. As the temperature drops, so does the probability of worse solutions being accepted and thus the algorithm gradually focuses in on a search space area where there is a high chance of a close to optimum solution existing (Suman & Kumar, 2006). Due to gradual 'cooling', the algorithm is remarkably effective when solving large problems with numerous local optimums. The state of certain physical systems, as well as the objective function, are equivalent to the internal energy of the said system in the specified state. The goal of SA can therefore be seen as bringing the system from an arbitrary initial state to a state with the minimum possible level of energy (Aarts *et al*., 2014).

The following terminology will be used to describe the SA algorithm:

- x_i Design vector, i.e. design, architecture, configuration;
- E Objective function value, i.e. system energy;
- T Variable, i.e. system temperature;
- Δ Difference in system energy between two design vectors; and
- i Iteration number ($i = 1,2,3 \ldots$).

The Simulated Annealing Algorithm is as follows:

1. **Choose a random x_i, select the initial system temperature, and specify the cooling (i.e. annealing) schedule:** similar to the LS method, SA utilises multiple starting points and finds an optimum starting point from each of them. In order to improve optimisation, a temperature must be selected that will initially allow for almost any move away from the current solution to be acceptable. This allows the algorithm to better explore the whole search space prior to cooling whereby it will settle into a more confined region;
2. **Evaluate $E(x_i)$ using a simulation model:** the initial value of the objective function is found in order to provide a basis for comparison with neighbouring locations in the proceeding iterations;
3. **Perturb x_i to obtain a neighbouring design vector x_{i+1}:** for each iteration a new point is generated randomly. The distance between the new point and the current point (the extent of the search) is based on a probability distribution with a scale proportional to the temperature;
4. **Evaluate $E(x_{i+1})$ using a simulation model:** a new value of the objective function is found in order to determine if it is better or not;
5. **If $E(x_{i+1}) < E(x_i)$, then x_{i+1} is the new current solution:** the algorithm accepts all new points that lower the value of the objective function;

6. **If** $(x_{i+1}) > E(x_i)$ **, then accept** x_{i+1} **as the new current solution with an acceptance probability of** $e^{\frac{-\Delta E}{T}}$ **where** $\Delta = E(x_{i+1}) - E(x_i)$**:** points that increase the value of the objective function are accepted with a certain probability. Such points allow the algorithm to avoid being trapped in local minima which enables the algorithm to search globally for more possible solutions. The acceptance probability function $e^{\frac{-\Delta E}{T}}$ determines which solutions to accept. Once the neighbour solution has been found to be a worse solution, a couple of factors are regarded, namely: by how much is the neighbour solution worse, and; how high is the current temperature of the system. At a high temperature the system is more likely to accept solutions that are worse than the current one. Basically, the smaller the change in energy (the quality of the solution), and the higher the temperature, the higher are the changes for the algorithm to accept a worse solution;
7. **Reduce the system temperature according to the cooling schedule:** the annealing schedule systematically reduces the temperature as the algorithm proceeds. As the temperature drops, the algorithm reduces the extent of its search to converge to a minimum; and
8. **Terminate the algorithm:** once an optimal solution which satisfies the predefined criteria, or conversely when the maximum number of iterations is reached, the algorithm terminates and the optimal or near-optimal solution is arrived at.

The algorithm outline for SA is shown in Algorithm 2.2, and the strengths and weaknesses of SA are shown in Table 14.

TABLE 14: STRENGTHS AND WEAKNESSES OF SIMULATED ANNEALING ADAPTED FROM DOWSLAND AND THOMPSON (2012) AND VECCHI (1983)

Strengths
Able to deal with highly non-linear models, chaotic and noisy data and many constraints
Is a robust and a general technique
Its flexible nature and ability to approach global optimality are its main benefits over other LS methods
The algorithm is quite versatile since it does not rely on any restrictive properties of the model
Easily adapted to different problem contexts. The ability to fine-tune a given algorithm for use in more than one problem is very useful in industry
A 'weak' method which does not make use of gradient information and makes few assumptions
It can deal with highly non-linear problems and non-differentiable functions as well as functions with multiple local optima
Excellent at avoiding the problem of getting stuck in local optima and is much better on average at finding an approximate global optimum, whereas a hill climber algorithm will only accept neighbour solutions that are better than the current solution
Usually better than greedy algorithms, when it comes to problems that have numerous locally optimum solutions
Statistically guaranteed to converge in asymptotic time to an optimal solution.
Relatively easy to code, even for complex problems
Amenable to parallel implementation
Can deal with arbitrary systems and cost functions
Weaknesses
Since it is a metaheuristic, a lot of decisions are required to turn it into an actual algorithm
It is computation intensive
Tailoring work is required to account for different classes of constraints and to fine-tune the parameters of the algorithm can be rather delicate
Clear trade-off between the quality of the solutions and the time is required to compute them
Precision of the numbers used in implementation of SA can have a significant effect upon the quality of the outcome
Repeatedly annealing with a schedule is very slow, especially if the cost function is difficult to compute (which also probably makes it expensive)
Heuristic methods, which are problem-specific or take advantage of extra information about the system, will often be better than general metaheuristic methods, although SA is often comparable to heuristics
Computation time required in SA grows exponentially with respect to the size of the problem and this may end up in SA requiring more iterations than Exhaustive Search methods
Cannot tell whether it has found an optimal solution. Some other complimentary method (e.g. Branch and Bound Algorithm) is required to do this

ALGORITHM 2.2: SIMULATED ANNEALING ALGORITHM OUTLINE ADAPTED FROM BERTSEKAS (1999)

Simulated annealing algorithm outline

Generate initial feasible solution
while *System not solidified (i.e. T > 0)* **do**
  while *Thermodynamic equilibrium not reached* **do**
    Generate neighbouring solution (i.e. perturb current solution)
    Evaluate the change in energy ΔE resulting from the perturbation
    if $\Delta E < 0$ **then**
      Accept the move and make the neighbouring solution the current solution
    else
      Accept the move with probability $e^{\frac{-\Delta E}{T}}$
    end
  end
  Lower temperature according to the cooling schedule
end
Report incumbent solution

2.5.2.3 Tabu Search

Tabu Search (TS) incorporates non-improving moves in an improving search algorithm in the hopes of finding the global optimum. TS was proposed by Glover (1986) who then formalised it in 1989. The main idea behind TS is to act similar to LS when it gets close to a local optimum. The basic argument behind this algorithm is to pursue local search by allowing non-improving moves whenever the algorithm encounters a local optimum. LS methods have a tendency to become stuck in suboptimal regions. Cycling back to formerly visited solutions (i.e. being stuck in local minima) is disallowed by making use of a memory list, appropriately called the tabu list, which keeps a record of the recent search history (Gendreau, 2003). After each iteration of the algorithm, a group of moves that includes those which would return immediately to the previous point are added to the tabu list. No such move is allowed for a few iterations, but eventually all moves are removed from the tabu list and are made available once again.

The following definitions will be used to describe the TS algorithm:

- x Set of variables (solution set);
- $\hat{x}$ Incumbent solution;
- i Iteration number ($i = 1,2,3, \dots$);
- i_{max} Maximum iterations;
- T Tabu list; and
- $N(x)$ Neighbourhood set of a solution x.

The Tabu Search Algorithm is as follows:

1. **Choose a random feasible solution $x^{(o)}$, and an iteration limit i_{max}, and set the incumbent solution $\hat{x} \leftarrow x^{(o)}$ as well as the solution index $i \leftarrow 0$:** initialise the search by choosing a feasible solution and deciding on the number of iterations. No moves are listed as tabu yet. The search will now enter a loop in the hopes of finding a superior feasible solution;
2. **Stop the search process if no non-tabu move leads to a feasible neighbour of current solution or if the iteration limit is reached:** stop the search if no non-tabu move Δx in move set $N(x)$ leads to a

feasible neighbour of current solution $x^{(i)}$, or if $i = i_{max}$. Take note that incumbent solution $\hat{\boldsymbol{x}}$ is an approximate optimum;

3. **Choose a non-tabu feasible move:** select any non-tabu feasible move $\Delta x \in N$ as $\Delta x^{(i+1)}$;
4. **Update the solution set:** update $x^{(i+1)} \leftarrow x^{(i)} + \Delta x$;
5. **Update the incumbent solution if it is necessary:** if the objective function value of $x^{(i+1)}$ is superior to that of incumbent solution $\hat{x}$, replace $\hat{x}$ with $x^{(i+1)}$;
6. **Update the tabu list:** add a collection of moves that includes any returning immediately from $x^{(i+1)}$ to $x^{(i)}$. Remove from the tabu list any forbidden moves that have been on it for a sufficient number of iterations; and
7. **Increment the iteration number:** increment $i \leftarrow i + 1$ and return to step 2.

ALGORITHM 2.3: TABU SEARCH ALGORITHM OUTLINE ADAPTED FROM GENDREAU (2003)

Tabu Search algorithm outline

```
Generate initial feasible solution
Set tabu list T ← ∅
while Stopping criterion not met do
    Generate current solution neighbourhood N(x)
    Evaluate the performance of non-tabu solutions in N(x)
    Select best neighbour solution x̂
    Update incumbent solution (if necessary)
    Update tabu list T
    Set new current solution x ← x̂
end
Report incumbent solution
```

The algorithm outline for TS is shown in Algorithm 2.3, and the strengths and weaknesses of TS are shown in Table 15.

TABLE 15: STRENGTHS AND WEAKNESSES OF TABU SEARCH ADAPTED FROM HANAFI (2001) AND ABIDO (2002)

Strengths
Can be directly applied to virtually any kind of optimisation problem
Uses a flexible memory of search history to prevent cycling and to avoid entrapment in local optima
Can easily deal with non-convex, non-smooth, and non-differentiable objective functions
Has been theoretically proven that TS algorithm can yield global optimal solution with a probability of one
Able to avoid entrapment in local optimal solution and prevent cycling by using flexible memory of search history
Uses payoff (performance index or objective function) information to guide the search in the problem space. Therefore, it can easily deal with non-smooth, non-continuous, and non-differentiable objective functions that are the real-life optimisation problems. Additionally, this property relieves TS of assumptions and approximations, which often are required by traditional optimisation methods for many practical optimisation problems
Uses probabilistic transition rules to make decisions, not deterministic rules. Hence, TS is a kind of stochastic optimisation algorithm that can search a complicated and uncertain area to find the global optimum. This makes TS more flexible and robust than conventional methods
Robustness to the initial solution. Therefore, TS can be used to improve the solution quality obtained by other classical techniques
Allows non-improving solution to be accepted in order to escape from a local optimum
Can be applied to both discrete and continuous solution spaces
For larger and more difficult problems (scheduling, quadratic assignment, and vehicle routing), TS obtains solutions that rival and often surpass the best solutions previously found by other approaches
Weaknesses
Too many parameters to be determined
Number of iterations could be very large
Global optimum may not be found, depends on parameter settings

2.5.2.4 Genetic Algorithms

Genetic algorithms (GA) became popular through the work of Holland (1973) especially after publishing a book on GAs in 1975 (Rajeev & Krishnamoorthy, 1992). The algorithm combines Darwin's principle of survival of the fittest with structured information exchange using randomised operators to evolve an efficient search mechanism. GAs efficiently exploit useful information contained in a population of solutions to generate new solutions with an improved performance. Goldberg and Samtani (1986) applied the GA to optimise the design of a 10-bar truss and Deb (1991) applied GA to optimising the design of welded joints.

GAs are a related class of algorithms to the improvement procedures in that it begins with a set of possible solutions and attempts to improve it, but with using analogies to natural processes. It uses mutation and crossover techniques to evolve the existing solutions into better ones. Being based on the principal of survival of the fittest, it uses a selection scheme biased towards fitter individuals to make up the next generation. After a few generations the algorithm will converge with the best individual which represents hopefully the optimum. GAs have the following features:

- An initial population of solutions;
- A mechanism for generating new solutions by combining features from solutions in the existing population;
- A mechanism for generating a new solution by operating on a single previously known solution;
- A mechanism for selecting the set of solutions from the populations, giving preference to those with better objective function values; and
- A mechanism for removing solutions from the population.

The solutions generated during iterations can be selected to mutate or to reproduce. The selection process is biased towards choosing better solutions in the current population. The mutation that occurs for the FLP takes the form of some variant of the pair-wise exchange. Any activity assigned to the same location will occupy that location in the offspring. The activity assignments of the remaining locations are chosen randomly from one or the other parent. Next, the unassigned activities are matched with the remaining unassigned locations. As new offspring are created, the solutions with the poorest values of the objective are eliminated in order to keep the population size the same.

The following definitions will be used to describe the Genetic Algorithm:

- p Population size;
- x Feasible solution set;
- p_e Population elites;
- p_i Population immigrants;
- p_c Population crossovers;
- i Generation index ($i = 1,2,3 \ldots$); and
- i_{max} Maximum generation index.

The Genetic Algorithm is as follows:

1. **Choose any feasible solution, population size, generation limit, and population subdivisions:** initialise the search process by choosing population size p, a set of feasible solutions $x^{(1)}, \ldots, x^{(p)}$,

generation limit i_{max}, population size p_e, population immigrants p_i, and population crossovers p_c. Also set generation index $i \leftarrow 0$;

2. **Stop the search process if the specified generation limit is reached:** stop the search process if $i = i_{max}$ and report the best solution of the current population as an approximate optimum;
3. **Choose elite individuals of the population:** initialise the new generation $i + 1$ with copies of the p_e best solutions in the current generation. By doing this, the best genes are passed on to the next generation. The purpose of this is to improve the gene pool and thus the objective function value;
4. **Arbitrarily choose new immigrant feasible solutions:** randomly select p_i new immigrant feasible solutions and include them in the $i + 1$ population. This step allows new genes to enter into the population in the hopes of finding a superior solution;
5. **Execute crossovers and add them to the new generation:** choose $p_c/2$ non-overlapping pairs of solutions from the generation i population, and execute crossover on each pair at an independently chosen random cut point to complete the generation $i + 1$ population; and
6. **Increment the generation index:** increment $i \leftarrow i + 1$ and return to step 2.

ALGORITHM 2.4: GENETIC ALGORITHM OUTLINE ADAPTED FROM RAJEEV AND KRISHNAMOORTHY (1992)

Genetic algorithm outline

```
Generate initial population of individuals
Evaluate the fitness of each individual
while Stopping criterion not met do
    Select parent solutions for reproduction
    Generate offspring population
    Apply mutation operator to offspring solutions
    Evaluate fitness of offspring solutions
    Select individuals to be carried over to the next generation
    Update incumbent solution (if necessary)
end
Report incumbent solution
```

The algorithm outline for GA is shown in Algorithm 2.4, and the strengths and weaknesses of GA are shown in Table 16.

TABLE 16: STRENGTHS AND WEAKNESSES OF GENETIC ALGORITHMS ADAPTED FROM RAJEEV AND KRISHNAMOORTHY (1992) AND SIMPSON, DANDY AND MURPHY (1994)

Strengths
Not limited by restrictive assumptions about search space, such as continuity or existence of derivatives
Does not require problem-specific knowledge to carry out a search. For instance, calculus-based search algorithms use derivative information to carry out a search. In contrast to this, GAs are indifferent to problem-specific information
Works on coded design variables, which are finite length strings. These strings represent artificial chromosomes. Every character in the string is an artificial gene. GAs process successive populations of these artificial chromosomes in successive generations
Uses a population of points at a time in contrast to the single-point approach by the traditional optimisation methods. That means, at a given time, GAs process a number of designs
Uses randomized operators in place of the usual deterministic ones. The random operators improve the search process in an adaptive manner
Deals directly with a population of solutions at any one time. These are spread throughout the solution space, so the chance of reaching the global optimum is increased significantly
Each solution consists of a set of discrete sizes. One does not have to round diameters up or down to obtain the final solution
Identifies a set of solutions of network configurations that are close to the minimum cost solution. These configurations may correspond to quite different designs that can be then compared in terms of other important but non-quantifiable objectives

STRENGTHS AND WEAKNESSES OF GENETIC ALGORITHMS ADAPTED FROM RAJEEV AND KRISHNAMOORTHY (1992) AND SIMPSON, DANDY AND MURPHY (1994) (CONTINUED)

Uses objective function or fitness information only, compared with the more traditional methods that rely on existence and continuity of derivatives or other auxiliary information
Can solve every optimisation problem which can be described with the chromosome encoding
Solves problems with multiple solutions
Since the GA execution technique is not dependent on the error surface, one can solve multi-dimensional, non-differential, non-continuous, and even non-parametrical problems
Structural GA gives us the possibility to solve the solution structure and solution parameter problems at the same time by means of GA
Very easy to understand and it does not demand the knowledge of advanced mathematics
Easily transferred to existing simulations and models
Weaknesses
Certain optimisation problems (they are called variant problems) cannot be solved by means of GAs. This occurs due to poorly known fitness functions which generate bad chromosome blocks in spite of the fact that only good chromosome blocks cross-over
There is no absolute assurance that a GA will find a global optimum. It happens very often when the populations have a lot of subjects
Like other artificial intelligence techniques, the GA cannot assure constant optimisation response times. Even more, the difference between the shortest and the longest optimisation response time is much larger than with conventional gradient methods. This unfortunate GA property limits the GA's use in real time applications
GA applications in controls which are performed in real time are limited because of random solutions and convergence, in other words this means that the entire population is improving, but this could not be said for an individual within this population. Therefore, it is unreasonable to use GAs for on-line controls in real systems without testing them first on a simulation model

2.5.2.5 Ant Colony Optimisation

The first Ant Colony Optimisation (ACO) algorithm proposed was the Ant System (AS) by Dorigo in his doctoral dissertation (Dorigo, Maniezzo & Colorni, 1996). AS has been successfully applied to relatively small instances of the Travelling Salesman Problem (TSP), up to and including 75 cities. It exhibits an equal capacity to evolutionary approaches to compute the results for general-purpose heuristics. However, AS did not prove able in competing with state-of-the-art algorithms that were explicitly designed for large instances of the TSP. AS originally consisted of a set of three algorithms, namely ant-cycle, ant-density, and ant-quantity. For ant-density and ant quantity, ants update the pheromone directly after each move from a city to an adjacent city. In contrast to this, ant-cycle updates the pheromone only once all ants have constructed the trails, with the amount of pheromone deposited by each ant being set to be a function of the tour (path) quality. Since ant-cycle produced superior results over the other two variants, it was called Ant System and the other two algorithms were no longer studied. Dorigo's proposal stimulated a number of researchers to make extensions and improvements to its basic ideas. Dorigo and Di Caro worked together to develop the commonly accepted definition of the ACO (Di Caro & Dorigo, 1998). ACO has been applied to combinatorial problems and has proven effective in solving various problems, such as scheduling, routing, and assignment (Dorigo & Stützle, 2003).

The main principle behind ACO algorithms is to mimic the cooperative behaviour of real ants in order to solve optimisation problems (Dorigo, Di Caro & Gambardella, 1999). These algorithms can be seen as multi-agent systems wherein each and every agent is inspired by the behaviour of a real ant. The reason why a real ant's behaviour is of interest is that ants use collective behaviour to perform complex tasks, including food transportation and determining shortest paths to food sources. These ACO algorithms are built on the principle that a communication mechanism which is very simple can lead to finding the shortest path between points.

Figure 11 illustrates an experiment with a real colony of ants. Take note that the ants cannot see the obstacle very well. The colony moves along a path between the food source and the colony nest and during their trips they communicate indirectly with one another via ground trails of odorous volatile substances known as pheromones. The role of the trails is to guide the other ants toward the target point, i.e. food or nest. The larger the amount of pheromone on a certain path, the larger the probability that the ants will follow that path. According to Talbi (2009), "*for a given ant, the path is chosen according to the smelt quantity of pheromone.*" Furthermore, pheromone evaporates over time and the quantity left by one ant depends on the amount of food (reinforcement process). As Figure 11 illustrates, when an ant reaches an obstacle on its path, there exists an equal probability for each and every ant to choose to go left or to go right around it. Since the left trail is shorter than the right trail, it requires less travel time and thus the ant will end up leaving a higher level of pheromone. The more ants that take the left path, the higher the level of pheromone, and hence the shortest path emerges (Rardin, 1998).

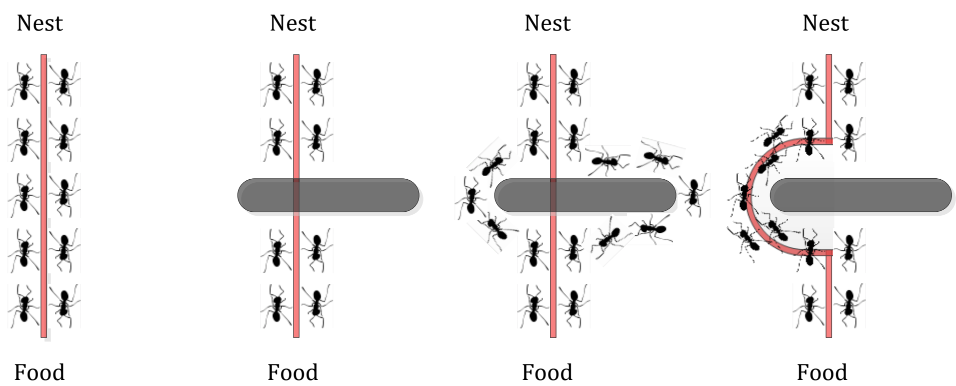


FIGURE 11: BEHAVIOUR OF ANTS SEARCHING FOR AN OPTIMAL PATH BETWEEN THE FOOD AND THEIR NEST ADAPTED FROM DORIGO, MANIEZZO AND COLORNI (1996)

The following definitions will be used to describe the ACO:

- E Trail intensity factor;
- i Iteration number ($i = 1,2,3, \dots i_{max}$);
- i_{max} Maximum iteration number;
- l Iteration number ($l = 1,2,3 \dots$);
- a Each ant in a set of ants;
- k Node;
- $G(V, E)$ Ant colony with set V of nodes and set E of edges inter-linking all pairs of nodes; and
- T_{ak} List of remaining nodes to be visited by ant a given that it is currently at node k.

The ACO algorithm is as follows:

1. **Choose a random set A of ants, and an iteration limit i_{max}, set the iteration number $i \leftarrow 0$, and assign an initial pheromone level to every edge in $G(V, E)$:** initialise the search process by choosing a set A of ants, deciding on the maximum number of iterations, and assigning pheromone levels to all the edges. The search process will now enter into an iteration loop in the hopes of generating an optimal solution;
2. **Stop the search process if the iteration limit is reached:** stop the search if $i = i_{max}$;
3. **Assign an initial random node $k * \in V$ to ant a and update the list of nodes to be visited $T_{ak} \leftarrow V \backslash \{k *\}$:** assign an initial random node $k * \in V$ to ant a ($a \in A$) and update T_{ak*}. Set an iteration number $l \leftarrow 0$;
4. **Choose node j and update pheromone concentration as well as the set of nodes to be visited:** continue with this step while $< |V|$. Choose $j \in T_{ak}$ according to the rule of displacement. Update the pheromone concentration on edge $(k *, j)$. Update the set of nodes to be visited $T_{ak} \leftarrow T_{ak*} \backslash \{j\}$. Set $k * \leftarrow j$ and increment the iteration number l;
5. **Update the incumbent solution if it is necessary:** perform global pheromone update on incumbent solution edges; and
6. **Increment the iteration number:** increment $i \leftarrow i + 1$ and return to step 2.

ALGORITHM 2.5: ANT COLONY OPTIMISATION ALGORITHM OUTLINE ADAPTED FROM DORIGO AND STÜTZLE (2003)

Ant colony optimisation algorithm outline

```
Assign every edge in G(V, E) an initial pheromone level
i ← 0
Generate a set A of ants
while i < i_max do
    for all a ∈ A do
        Assign an initial random node k ∗∈ V to ant a
        T_ak ← V\{k ∗}
        l ← 0
        while l < |V| do
            Choose a node j ∈ T_ak according to the rule of displacement
            Update the pheromone concentration on edge (k ∗, j)
            Update the set of nodes to be visited T_ak ← T_ak∗\{j}
            k ∗← j
            l ← l + 1
        end
    end
    Update incumbent solution
    Perform global pheromone update on incumbent solution edges
    i ← i + 1
end
Report incumbent solution
```

The algorithm outline for ACO is shown in Algorithm 2.5, and the strengths and weaknesses of ACO are shown in Table 17.

TABLE 17: STRENGTHS AND WEAKNESSES OF ANT COLONY OPTIMISATION ADAPTED FROM BOSWAL, PODDAR AND SHEKHAWAT (2009)

Strengths
Inherent parallelism
Positive Feedback accounts for rapid discovery of good solutions
Efficient for Traveling Salesman Problem and similar problems
Can be used in dynamic applications (e.g. adapts to changes such as new distances)
Fast, solutions of reasonable quality

STRENGTHS AND WEAKNESSES OF ANT COLONY OPTIMISATION ADAPTED FROM BOSWAL, PODDAR AND SHEKHAWAT (2009) (CONTINUED)

Weaknesses
Theoretical analysis is difficult
Sequences of random decisions (not independent)
Probability distribution changes by iteration
Research is experimental rather than theoretical
Time to convergence uncertain (but convergence is guaranteed)
Solution may be far from optimum
Generate only limited number of different solutions
Decisions made at early stages reduce a set of possible steps at latter stages

2.5.2.6 Particle Swarm Optimisation

The implicit rules that members of fish schools and bird flocks follow that result in them being able to move in a synchronised manner without colliding, and thus resulting in a perfect choreography, was studied by Reynolds in 1987 and Heppner and Grenander in 1990 (Mandal, Mukhopadhyay & Pal, 2016). Reynolds described the process in three simple behaviours, namely separation, alignment, and cohesion. According to Wilson (1975), the social behaviour of animals is governed by simple rules. In contrast to this, human social behaviour is more complex than a flock's movement. The core idea behind developing Particle Swarm Optimisation (PSO) is that numerous examples coming from nature enforce the view that social information sharing between individuals of a population may result in an evolutionary advantage (Eberhart *et al.*, 1996).

PSO is classified as a P-metaheuristics inspired from swarm intelligence. It mimics the social behaviour of natural organisms, e.g. birds flying in a flock migrating and fish swimming in a school searching for food (Talbi, 2009). In such swarms, individual behaviour is coordinated with the group using local movements without there being any form of central control. A particle swarm can be seen as a cellular automata, whereby individual cell (particles in PSO) updates are done in parallel. The reason for this is that each new cell value depends only on the old value of the cell and its neighbourhood, and all cells are updated using the same rules (Rardin, 1998). PSO combines self-experiences with social experiences. This means that each particle in the search space adjusts its 'flying' according to its own flying experience as well as the flying experiences of other particles. The particles move towards a promising area to get the global optimum. Each particle keeps track of its personal best solution (p_{best}) and the best value of any particle/global best (g_{best}). Thus, each particle modifies its position according to its p_{best}, g_{best}, current position and current velocity. Figure 12 shows a swarm of particles which move to the global optimum after a certain amount of PSO iterations. After three iterations it is clear that the particles are moving towards the local and global optimums which are shown by the darker colours. After seven iterations, all the particles reach the global optimum.

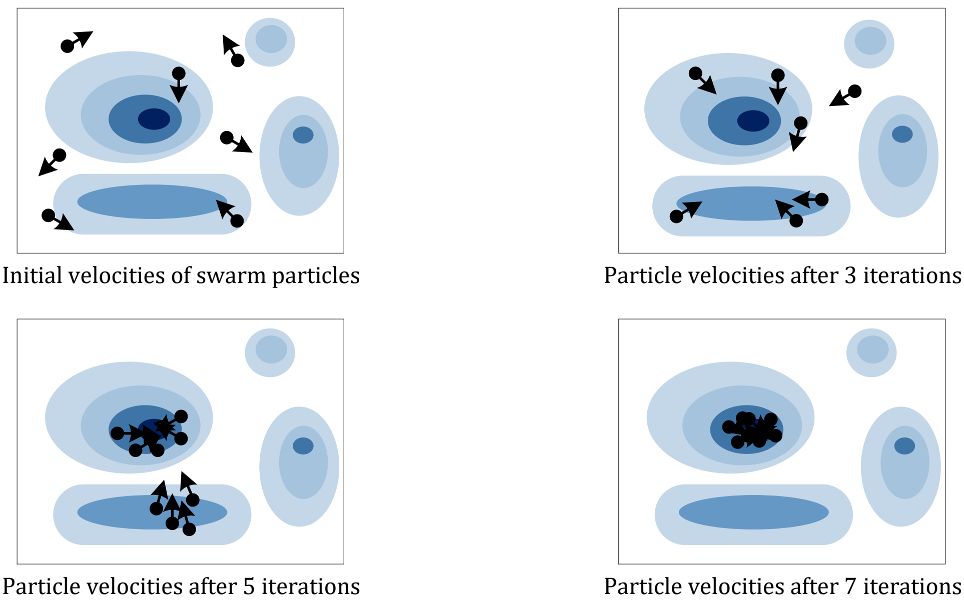


FIGURE 12: PARTICLE SWARM OPTIMISATION EXAMPLE ADAPTED FROM HEPPNER AND GRENANDER (1990)

A swarm is made up of N particles moving around in a D-dimensional search space. Each particle a_i is a solution candidate to the problem and is represented by the vector in the decision space. Each particle has its own unique position and velocity (flying direction and set of the particle). SPO involves taking advantage of the ability of the particles to cooperate, similar to birds in a flock or fish in a school. The success of certain particles influences the behaviour of other particles. Each particle's position is successively adjusted toward the global optimum by taking into account two factors, namely the best position visited by itself and the best position visited by swarm as a whole.

The following definitions will be used to describe the Particle Swarm algorithm:

- N The number of particles in the swarm, i.e. number of birds, fish, etc.;
- S Solution space;
- p_i Position of particle a_i in the solution space;
- v_i Velocity of particle's a_i;
- $v(a_i)$ Neighbourhood of particle at a_i (fixed);
- c_1 Weight of local information;
- c_2 Weight of global information;
- p_{best} Best position of the particle; and
- g_{best} Best position of the swarm.

The Particle Swarm algorithm is as follows:

1. **Choose an initial feasible swarm population with random locations and velocity vectors:** create a population (swarm) of particles uniformly distributed;
2. **Evaluate each particle's position according to the objective function:** evaluate each particle's current position;
3. **If a particle's current position is better than its previous best position, update it:** determine if the particle's current position is better than its previous position and move it to a new position;
4. **Determine the best particle (according to the particle's best previous positions):** determine the particle with the best position;

5. **Update particle's velocities:** update particle's velocities with the following equation $v_i^{t+1} = v_i^t + c_1 U_1^t \left(p_{best_i}^t - p_i^t\right) + c_2 U_2^t \left(g_{best}^t - p_i^t\right)$. The first term represents the particle's initial movement, the second represents the particle's personal influence and the third term social influence of other particles;
6. **Move particles to their new positions:** update the particles' positions using the following equation $p_i^{t+1} = p_i^t + v_i^{t+1}$; and
7. **Increment the iteration number:** increment $i \leftarrow i + 1$ and return to step 2 until the stopping criteria are satisfied.

ALGORITHM 2.6: PARTICLE SWARM ALGORITHM OUTLINE ADAPTED FROM RARDIN (1998) AND ROMERO, ZAMUDIO, BALTAZAR, MEZURA, SOTELO AND CALLAGHAN (2012)

Particle swarm optimisation algorithm outline

```
Generate initial feasible swarm population with random locations and velocity vectors
while Stopping criterion not met do
    for all p ∈ S do
        Evaluate the performance of the particle in objective space
        Update best location of the particle (if necessary)
        Update best location in the neighbourhood of the particle (if necessary)
        Update velocity vector of the particle
        Accelerate the particle toward a new location
    end
    Update incumbent solution (if necessary)
end
Report incumbent solution
```

The algorithm outline for PSO is shown in Algorithm 2.6, and the strengths and weaknesses of PSO are shown in Table 18.

TABLE 18: STRENGTHS AND WEAKNESSES OF PARTICLE SWARM OPTIMISATION ADAPTED FROM TALBI (2009) AND REYNOLDS (1987)

Strengths
Insensitive to scaling of design variables
Simple implementation
Easily parallelised for concurrent processing
Derivative free
Very few algorithm parameters
Very efficient global search algorithm
Weaknesses
Tendency to obtain a fast and premature convergence in mid optimum points
Slow convergence in refined search stage (weak LS ability)

2.5.3 HYBRID METAHEURISTICS

The concept of hybrid metaheuristics has been commonly accepted only in recent years, although the combination of different metaheuristics strategies dates back to the 1980s (Méndez, 2011). There exists a generalised consensus on the benefits of integrating various components of different search methods as well as the widespread use of hybrid techniques in fields of operations research and artificial intelligence (Blum & Roli, 2008). The main motivation behind hybridisation is to exploit the complementary character of different optimisation strategies. An adequate combination of complementary algorithmic concepts can be key for achieving top performance in solving hard optimisation problems. However, literature shows that it is nontrivial to generalise, i.e. a certain hybrid might work well for specific problems, but might perform poorly for others (Blum, Puchinger, Raidl & Roli, 2011). It is also a difficult task to develop an effective hybrid approach that requires expertise from different areas of optimisation.

There exists two categories of hybrid metaheuristics. The first consists of designing a solver including components from more than one metaheuristic and the second combines metaheuristics with other techniques. The second category typically works with fields such as artificial intelligence and operations research. Examples include the amalgamation of metaheuristics with constraint programming, data mining techniques, integer programming, and tree-based search methods (Gendreau & Potvin, 2010). Lim, Yuan and Omatu (2000) found that a hybrid of GA and LS produced solutions with average objective values within 0.8% of the best known solutions, for several QAP benchmarks. Tseng and Liang (2006) proposed a hybrid metaheuristic called ANGEL to solve the QAP which includes the combination of ACO, GA, and a LS method. They tested over a hundred instances of the QAP and found that ANGEL exhibited a success rate of 90% with respect to finding the optimal solution.

2.6 Layout software

Various layout software packages have been developed to solve large FLPs. This software uses computer-based algorithms such as CRAFT, ALDEP, MATCH, CORELAP, SPIRAL, MULTIPLE and COFA (Singh & Sharma, 2006), otherwise referred to as heuristics (Armour & Buffa, 1963). Computer-based algorithms can significantly advance the productivity of the layout planner as well as the value of the final solution through their ability to generate and numerically evaluate numerous layout alternatives in a very short period of time. Another advantage is that computerised layout algorithms are also highly effective with regards to performing rapid 'what if' analyses. This allows the user to vary input data or the layout itself, and thus find the most ideal and practical solution. However, although current computer-based algorithms are useful, they cannot yet replace human experience and judgement as they have great shortcomings in terms of their ability to address the qualitative characteristics/components of facility layouts (Tompkins *et al*., 2010).

Computer-based layout algorithms can be classified as distance based or adjacency algorithms. MATCH and SPIRAL are examples of adjacency based, while CRAFT, SHAPE, LOGIC, FLEX-BAY and MULTIPLE are distance based algorithms (Singh & Sharma, 2006). The difference between these two types of algorithms is seen in their objective functions. Adjacency based algorithms have the objective function shown in (65).

Maximise $$\sum_i \sum_j (r_{ij})\, x_{ij} \qquad (65)$$

In (65), x_{ij} is 1 if department i is adjacent to department j; else 0, and r_{ij} is the closeness rating of department i and j. The philosophy behind (65) is that material handling cost can be significantly reduced if the two departments in question have adjacent boundaries. Distance based algorithms have the objective function shown in (66).

$$\text{Minimise} \qquad (TC) = \frac{1}{2}\sum_{\substack{i=1\\ i\neq k}}^{n}\sum_{\substack{j=1\\ j\neq l}}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} C_{ik}\, D_{jl} X_{ij} X_{kl} \qquad (66)$$

In (66) C_{ik} is the material handling cost between department i and k; D_{jl} is the distance between department j and l; X_{ij} is 1 if department i is assigned to location j; else 0; and X_{kl} is 1 if department k is assigned to location l; else 0. The basic premise behind (66) is that the distance travelled increases the total traveling cost.

Layout software can also be classified into two main categories namely construction type and improvement type. Construction-type involves the development of a new layout from scratch whilst improvement-type generates layout alternatives based on a pre-existing layout (Tompkins *et al.*, 2010). There are also computerised algorithms that can be used as both construction and improvement algorithms such as BLOCPLAN and LOGIC. Table 19 shows the classification of a few computer-based algorithms.

TABLE 19: CLASSIFICATION OF COMPUTER-BASED ALGORITHMS ADAPTED FROM SCHIFFAUEROVA (2014)

Construction algorithms	Improvement algorithms
ALDEP	CRAFT
CORELAP	MCRAFT
PLANET	MULTIPLE
BLOCPLAN	
LOGIC	

Different computer-based algorithms are shown in Table 1 and Figure 6. A few of the more popular algorithms were chosen and will be discussed in this section. The algorithms are CRAFT, LOGIC, and MULTIPLE. In addition to these BLOCPLAN is also included in this discussion because of its unique properties.

2.6.1.1 CRAFT

CRAFT (Computerised Relative Allocation of Facilities Technique) was introduced by Armour and Buffa (1963). It is an example of an improvement-type method and a greedy algorithm (meaning it repeatedly selects the immediate best choice from a set of alternatives at each step of its execution). Since it is an improvement algorithm, it is natural that it departs from an initial layout which must be provided. Firstly, the centroids of the departments are determined for the initial layout. Next, it the rectilinear distance between pairs of department centroids is calculated and the values are stored in a distance matrix. An initial/rough layout cost can then be determined by multiplying each entry in the from-to matrix with its corresponding entry in the distance matrix and the unit cost matrix. The next step is to consider all conceivable two-way (or three-way) departmental exchanges and thereafter identify the best exchange, i.e. the one that produces the largest reduction in the layout costs. After it is identified, the layout is updated according to the best exchanges possible and then the new department centroids are computed in conjunction with the new layout cost. This completes the first iteration. The second iteration begins with CRAFT identifying the most ideal exchange by looking at all possible two-way (or three-way) exchanges in the layout. This iterative process continues until the layout costs cannot be further reduced (Tompkins *et al.*, 2010). One of the advantages of using CRAFT is that it can capture the initial layout with reasonable accuracy. This is rooted in CRAFT's ability to accommodate nonrectangular departments or obstacles located anywhere in a possibly nonrectangular building. However, one of CRAFT's weaknesses is that it will rarely generate department shapes that are straight, with uninterrupted aisles. It is also highly path dependent (Armour, Buffa & Vollman, 1964).

2.6.1.2 BLOCPLAN

BLOCPLAN was developed by Donaghey and Pire (1990). It arranges the departments in bands and uses a from-to chart and a relationship chart as input data for representing the flow. The cost associated with the layout is measured via the adjacency-based or distance-based objective. Each department in BLOCPLAN occupies exactly one band which are rectangular in shape. The number of bands are determined by the program and limited to three bands. However, the widths of the bands can vary. It may be used as a constructive or an improvement-type algorithm. One of the weaknesses of BLOCPLAN is that it may not be able to capture the initial layout accurately. It is also difficult to handle non-fixed departments that may have prescribed or fixed shapes.

2.6.1.3 LOGIC

LOGIC (Layout Optimisation with Guillotine Induced Cuts) was developed by Tam (1992). It can be used either as a construction or an improvement algorithm. LOGIC is based on dividing the layout into small portions by executing successive guillotine (straight lines that run from one end of the layout to the other). These cuts are executed in a series of horizontal or vertical cuts. With each cut, an appropriate subset of the departments is assigned to either the east-west or north-south side of the cut. LOGIC constructs a tree to systematically execute and keep tract of the departments. In comparison to CRAFT, it is generally not straightforward to model fixed departments or obstacles. However, LOGIC can be applied in non-rectangular buildings provided that the building shape is reasonable.

2.6.1.4 MULTIPLE

MULTIPLE (Multi-floor Plant Layout Evaluation) was developed by Bozer, Meller and Erlebacher (1994) for the purpose of developing multi-floor layouts. However, it can also be used in single-floor layouts by setting the number of floors to one and disregarding data requirements associated with lifts. MULTIPLE is similar to CRAFT in that a from-to chart is used as input data, and the objective function is identical. The departments are however not limited to rectangular shapes. Like CRAFT and MULTIPLE it is an improvement algorithm, and as such begins with an initial rough layout specified by the planner. Improvements are made at each iteration through two-way exchanges and the exchange that leads to the greatest reduction in layout cost is then selected. The main difference between CRAFT and MULTIPLE is that MULTIPLE can make exchanges whether the two departments are adjacent or not. BLOCPLAN can also make any exchange, but it is based on bands, and thus fixed departments may either shift or change shape. In essence, MULTIPLE maintains CRAFT's flexibility while relaxing CRAFT's constraint on departmental exchanges.

2.7 Analysis of methods

In this chapter various layout models, solution methods, and layout software were discussed. Seven popular models for FLPs were presented. Unfortunately, the layout models are very hard to solve for large problem instances. Exact methods, metaheuristics and hybrid metaheuristics are discussed as means to solve these layout models. The presented layout models and solution methods are now further analysed.

2.7.1 ANALYSIS OF LAYOUT MODELS

Table 20 shows the seven layout models with their corresponding variables and objectives. The QAP is frequently used to solve FLPs. However, instances with a problem size larger than 20, within reasonable limits, are difficult to manage since even a powerful computer by today's standards cannot handle these large instances of the problem. Many QAP formulations can only solve FLPs with equal-sized departments, which is difficult to justify in practical cases. It may be unrealistic to design a hospital with equal sized departments since the area of each department will most likely be different (these areas are determined in Chapter 4). If this is the case, the layout will include unutilised spaces and consequently incur unnecessary costs and inefficiency. The QAPs that are able to solve FLPs with unequal-sized departments divide the departments into numerous small grids each with equal areas, and effectively forbid the separation of said grids of the same department by assigning artificial flow between them. As a result of the rise in the number of departments with this approach, it makes solving even small problems with a few unequal-area departments impossible. Bozer *et al.* (1994) also proved that this approach is ineffective since it adds a constraint to the shape of the department. The optimal solution to the QAP formulation when there exist high artificial flows is therefore likely to be an inadequately poor FLP solution. Another weakness of the QAP is that if the distance between locations cannot be determined beforehand, the QAP model cannot be applied.

TABLE 20: ANALYSIS OF LAYOUT MODELS

Layout model	**Variables**							**Objectives**					
	Closeness rating	Distance between departments	Flow between departments	Frequency of trips	Travel time	Travel cost	Fixed cost	Minimise material handling cost	Minimise flow	Minimise travel time	Maximise a closeness rating measure	Minimise fixed cost	Minimise total cost
Quadratic Assignment Problem			x			x	x						x
Quadratic Set Covering Problem		x	x				x		x			x	
Linear Integer Programming Problem			x			x	x						x
Mixed Integer Problem			x			x	x						x
Graph Theoretic Problem	x										x		
Linear Continuous Model				x		x		x					
Linear Mixed Integer Model				x	x					x			

In contrast to this, the QSCP is able to solve FLPs with unequal-sized departments which are more scalable than the QAP. The drawbacks of this method are that the candidate locations for each centre have to be established beforehand and the specification of the centre shapes might not be practical in the sense that some centres have L-shapes, but the model assigns rectangular shapes to them. Therefore, the QSCP appears to be a better choice than the QAP for solving the FLP with unequal-sized departments.

The LIPP is shown to be equivalent to the QAP in terms of the variables and objective of the model. Furthermore, it was found that the model cannot be optimally solved for problems with nine or more facilities. This model also assumes that the costs of transportation are directly proportional to the weighted rectangular distances.

The MIPP combines continuous and discrete variables. Among the integer-programming formulations of the QAP, this model has a relatively small number of variables and constraints. Montreuil's MIPP model could be solved with eight departments. Konak, Kulturel-Konak, Norman and Smith (2006) developed a MIPP model which is based on the flexible bay structure and can be solved for FLPs with up to fourteen departments. However, possible layout configurations are restricted. According to Thai (2007), the MIPP model does have advantages over the QAP-based models. With the MIPP model, departments may have various shapes and sizes. Furthermore, the shape of the departments is controlled and irregular-shaped departments are not a problem. Irregular-shaped departments can be defined as departments which are very long, narrow, or non-rectangular.

The GTP relies on having a predefined desirable adjacency for each pair of departments. The areas and shape are ignored at the beginning. The model assumes that one knows the desirability of locating each pair of departments adjacent to each other. Firstly, the establishment of an upper bound on the optimal solution provides an advantage over other existing FLP approaches. Secondly, the value of the objective function obtained as the sum of weights of edges in the MPWG is generally better than those obtained by traditional computerised procedures, such as ALDEP and CORELAP. However, a limitation of this method is the fact that adjacent departments are not taken into consideration when the block plan is constructed, or when the objective function value is calculated. The approach has succeeded in finding good department arrangements, but it failed to find good configurations for them.

The LMIM has the least number of variables of any of the other formulations of the FLPs mentioned. Consequently, a relatively larger problem size (of 30) can be optimally solved which is almost double the limit of the other discussed layout models. The advantage of this method, as well as the LCM, is that site locations do not need to be known before it can be solved. However, the department dimensions are fixed. These two methods can also be used to solve FLPs with unequal areas. Both of these methods yield good quality sub-optimal solutions in a comparatively short time of computing. The LCM is similar to the MIPP which is also based on a continuous representation. According to Thai (2007), the MIPP formulation is more difficult to solve computationally. The LMIM and the LCM are relatively less studied than the other layout formulations. No improvements or notable discussions of both of these methods were found to date in literature. Thus, little research has been conducted on these two models.

In conclusion, the QSCP may be more practical for a hospital layout than the QAP formulations. With the MIPP, departments may have various shapes and sizes. The advantage of the GTP lies in the fact that adjacency of each pair of departments are taken into account. The QSCP, LIPP, and MIPP are QAP-based methods, while the LMIM, and LCM are not. The LMIM and LCM yield good quality solutions in a relatively short time, but require the dimensions of the departments to be known a priori. The layout models studied in this thesis can be divided into discrete based, and continuous based. The QAP and QSCP are discrete based while the MIPP, LCM, and LMIM are continuous based. The MIPP and LMIM formulations were found to be very similar. Both of these models are newer than the rest of the models and not much research has been conducted on these specific models so far.

In order to select the most appropriate layout model for designing a rural hospital layout, it is necessary to first fully comprehend the real world problem. For this reason, the layout model is only selected in Chapter 5 after discussing the context of a rural hospital (in (Chapter 4).

2.7.2 ANALYSIS OF SOLUTION METHODS

The two main approaches for solving the FLP were found to be exact methods and metaheuristics. Exact methods can further be sorted into Branch and Bound Algorithms and Cutting Plane Algorithms.

A few types of Branch and Bound algorithms were found, including a parallel Branch and Bound Algorithm which can solve layouts with 12 or more facilities. It was found that with Branch and Bound Algorithms the optimal solution is commonly found early on in the branch and bound process. It is not however verified until a significantly large number of solutions have been computed. All of algorithms discussed were found to have high memory and computation requirements. Optimal solutions can also only be determined up to a problem size of 16 at most.

Two main types of Cutting Plane Algorithms were found, namely traditional cutting planes and polyhedral cutting planes. It was found that the application of the Cutting Plane Algorithms to the FLP is still very limited. The optimal Cutting Plane Algorithm has a high computation time and its storage is complex. As a consequence, the largest size FLP that can be optimally solved by a Cutting Plane Algorithm is one with only eight facilities.

In conclusion, exact methods can be used to solve the layout model optimally and are therefore the best methods to use, if the problem size is small enough. Some layout models are also a bit more complex to solve than others. If the FLP cannot be solved using an exact method, the optimal solution should be approximated using metaheuristics. Six popular metaheuristics were analysed and are shown in Table 21. Since the most adequate layout model for modelling the FLP for this study is only selected in Chapter 5, the best suited solution method for solving the FLP can only be selected afterwards.

TABLE 21: METAHEURISTICS CLASSIFICATION

Metaheuristic	**S-metaheuristics**	**P-metaheuristics**	**Swarm Intelligence**
Local search method	x		
Simulated Annealing	x		
Tabu Search	x		
Genetic Algorithms		x	
Ant colony Optimisation		x	x
Particle Swarm Optimisation		x	x

The LS method is greedy and therefore not the best method to use for a problem with multiple local minima. For this reason, SA and TS are better methods to use to solve the FLP. The P-metaheuristics require the iterative improvement in a population of solutions, while the S-metaheuristics improve a single solution which makes the S-metaheuristics easier to use. The P-metaheuristics are not well suited for fine-tuning structures which are very close to optimal solutions. However, they are quick to locate the high performance regions of vast and complex search spaces. After a certain amount of time, the population becomes quite uniform and the solutions of the population no longer improve. The hybrid metaheuristics combine the strengths of both methods, but are not always the best options to use due to other factors such as time constraints and unnecessary complexity.

Another approach to modelling and solving the FLP is via computer-based algorithms. These algorithms are adjacency or distance based. BLOCKPLAN and LOGIC are classified as construction and improvement type algorithms. It was found that LOGIC is generally not as straightforward to model fixed departments and BLOCKPLAN may not be able to capture the initial layout accurately. CRAFT and MULTIPLE are both improvement algorithms that use from-to-charts. A disadvantage of CRAFT is that it is greedy. MULTIPLE was found to be similar to CRAFT with the exception that it can improve multi-floor layouts. The discussed computer-based algorithms were found to be effective for varying data input or the layout itself.

2.8 Conclusion

This chapter provides an introduction to operations research and the FLP in particular. Different quantitative methods to model and solve the FLP are analysed and compared. Computer-based algorithms are also discussed. The key findings are summarised in the paragraphs that follow.

The QAP, QSCP, LIPP, MIPP, GTP are found to be more popular approaches to modelling the FLP. A less studied LCM and LMIM formulations are also analysed. Both of these models reported optimal solutions for relatively larger problem sizes than the rest of the models. Most of these layout models aim to optimise the material handling cost and include variables such as distance, flow, transportation cost, and closeness ratings in the equations, with the exception of the GTP which aims to maximise a closeness rating measure. It was found that the QAP and the LIPP assume equal sized facilities which may be unrealistic for designing a hospital layout.

The layout models can be optimally solved using exact methods, e.g. Branch and Bound Algorithms, Cutting Plane Algorithms, only if the problem size is small enough. Otherwise metaheuristics can be used to approximate the optimal solution.

Computer-based algorithms were found very effective in rapidly performing 'what if' analyses based on varying the input data or the layout itself. However, the currently available computer-based algorithms generally do not consider the qualitative characteristics of a layout. Some of these algorithms are adjacency based while others are distance based. These algorithms can further be classified into construction type, improvement type, or methods that use both.

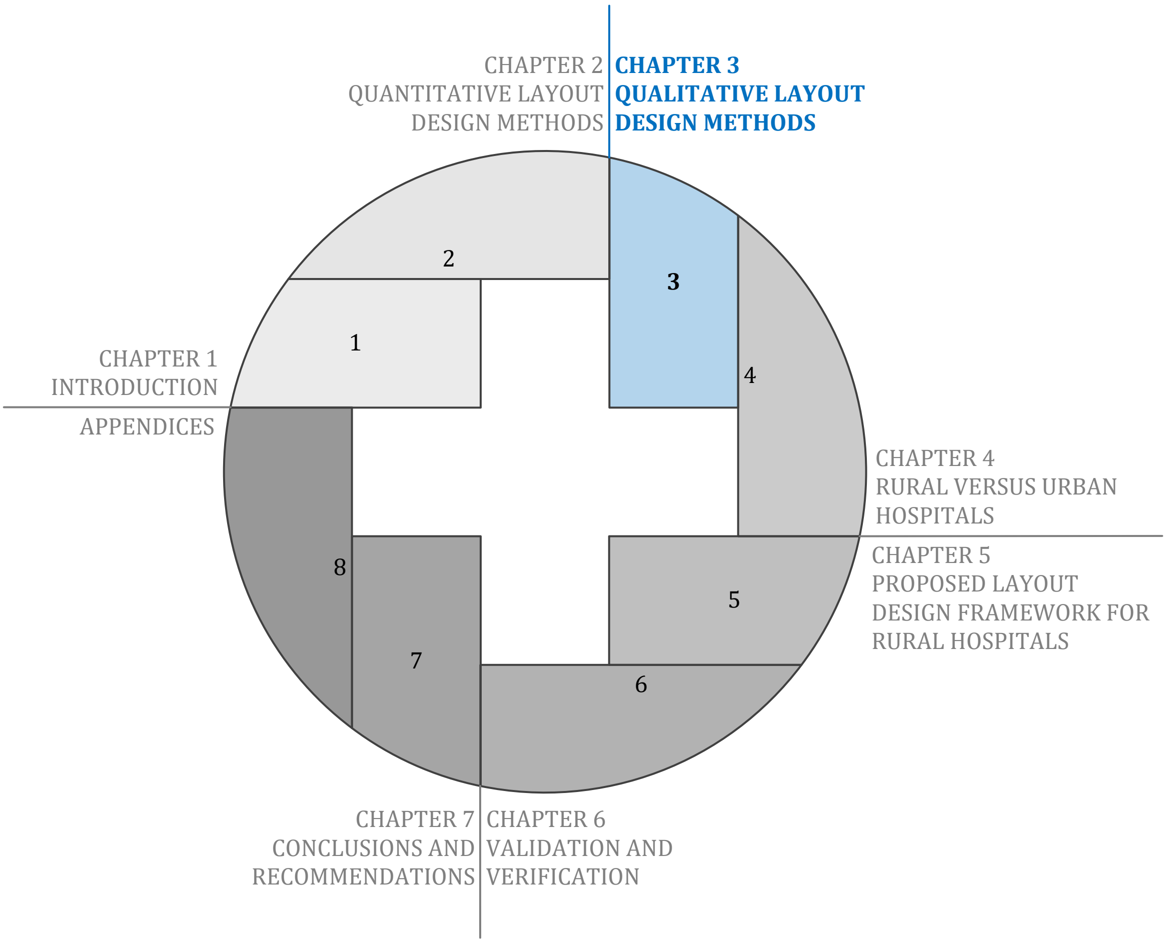
This concludes the literature study on quantitative research. The next chapter investigates qualitative methods and hospital design considerations that need to be taken into account when designing the layout of a hospital.

CHAPTER 3

QUALITATIVE LAYOUT DESIGN METHODS AND HOSPITAL DESIGN CONSIDERATIONS

"All research ultimately has a qualitative grounding."

Campbell (1994)



3.1 Introduction

In Chapter 2 the quantitative methods for designing the layout of a facility were analysed. The purpose of this chapter is to analyse qualitative layout design methods found in literature and to determine what hospital design considerations should be included when designing a hospital layout. In addition, the relationship between these hospital design considerations and the quantitative methods analysed in Chapter 2 is determined.

3.2 Layout types

A facility layout should be arranged according to everything needed for production or delivery of services (Drira, Pierreval & Hajri-Gabouj, 2007). Therefore layouts for a department, machine shop, manufacturing cell, warehouse, and work centre would logically be different. Designing the layout of a facility generally depends on the variety of products as well as the production volumes of the products (Hartl & Preusser, 2009). Thus, if one considers the FLP for a hospital from a production layout point of view one needs to take the layout requirements of a hospital into account and understand exactly what it entails. There are four main types of layouts, often defined according to the general pattern of work flow (Jacobs, Chase & Chase, 2010), namely: process layouts, product layouts, fixed-position layouts, and hybrid layouts.

Process layouts naturally group activities that are similar in nature together, in departments, typically according to the function which they perform. As such, they are occasionally called functional layouts. They are typically in facilities that produce customised low-volume products that may have the need for a flexible layout, having different sequences of operations and processing requirements when producing products (Groover, 2007). An example of this can be seen in a machine shop whereby all drills are typically located in one work centre, drilling machines in their own work centre, and lathes in yet another work centre. Process layouts are characteristic of job shops, service delivery, and other intermittent operations that need to serve different customers with different needs. The main advantage of such a layout is flexibility but this comes at the cost of the layout's efficiency (Jacobs *et al.*, 2010). Oftentimes, customers or jobs do not flow through the system in an orderly manner, movements between departments tend to take too much time, queues often develop, and backtracking is common. Operations may need to be set up in a unique manner for each and every customer, in a configuration that is suitable to their particular processing requirements. In a service facility, process layouts typically require large aisles so that customers may move between departments freely. The main concern for such a layout pertains to where exactly the departments should be located in relation to one another. Although each job or customer will follow a different route through the system, some paths are more common than others.

Product layouts are based largely on the sequence necessary for processing the part(s) being produced on the production line. Each and every product must have its own line specially designed to meet its unique requirements. Flow of work is commonly efficient and orderly, moving consecutively from one workstation to another all the way down the assembly line until completion of the product at the end of the line. When the demand is stable and the production volume is high, product layouts are ideal for activities of mass production that require repetitive operations (Nahmias & Cheng, 2009). The product or service targets the general market and not a particular customer per se. The main advantages of product layouts are efficiency and ease of use but this comes at the cost of flexibility on the production line.

Oftentimes the product is either too fragile or too heavy to move during a project, and this is when fixed-position layouts become ideal (Brandon-Jones, 2015). Examples of where it is useful include most aircraft assembly, housing, and shipbuilding projects. With the product remaining stationary for the entire manufacturing process, equipment, materials, and workers are brought back and forward to the site where production takes place. The utilisation of equipment is usually low due to the fact that it is oftentimes less costly to just leave equipment idle at the site where it is used intermittently (periodically) than to move it back and forth from one location to another. As a result, equipment is sometimes leased due to its limited use. Workers brought to the work site are typically highly skilled at performing the specific tasks they are assigned to (Russel & Taylor, 1999).

Hybrid layouts (also called combination layout) modify and/or combine some characteristics of the three basic layout types just discussed in order to try satisfy the requirements of a particular situation (Ali, 2015). An example of this can be seen when a firm may have a process layout for the majority of its process along with an assembly line off to the side. Conversely, a fixed-position layout may be used for assembling the final product, while the assembly lines are used to produce components (i.e. subassemblies) that add up to realise the final product (Advameg, 2015), e.g. manufacturing a commercial aircraft.

A hospital layout is classified as a hybrid layout since it combines process layout and fixed-layout characteristics (Ali, 2015; Advameg, 2015). Hospitals may have an overarching process layout, as the departments are logically grouped (e.g. intensive care, nursing units, administration) whilst at a department level there may be more of a fixed-position layout to the hospital (e.g. operation room). In an operation room, the patient will be stationary while nurses, doctors/specialists, and equipment are brought to the patient. Product layouts can also exist in the case of a cafeteria or lab. However, the main concern of this study pertains to the location of the departments in relation to each other, with the interior of the departments not being as important. Therefore, the process layout is considered further.

When hospitals are organised by function, isolated departments exist such as laboratories, radiology, and the intensive care unit, with each department behaving like a functional silo. Departments are seen as singular areas whereby equipment that is similar is co-located. The entire department specialises in similar processes and thus seeks to maximise their efficiency and utilisation (Karvonen, Korvenranta, Paatela & Seppala, 2007). Although each patient (job or customer) may follow an altogether different route through the system, some of the paths are more common than others, e.g. hospitals group together certain functions, for instance emergency medicine, intensive care, radiology, and surgery, even though they are in separate departments. This ideal arrangement would then allow a patient entering through the emergency room to be seen in radiology, possibly surgery, and then intensive care, and another to be admitted directly for elective surgery and then to intensive care. The strengths and weaknesses of a process layout are shown in Table 22. The functional silos cause complex patient flow routes and can lead to poor overall process control and thus a reduced quality of care. This can lead to long transfer distances that involve many multi-department visits and ultimately long patient throughput times. Scheduling is also not an easy task in such a layout.

TABLE 22: STRENGTHS AND WEAKNESSES OF A PROCESS LAYOUT ADAPTED FROM GROOVER (2007), KARVONEN *ET AL.* (2007), AND ALI (2015)

Strengths	Weaknesses
Ability to handle a variety of processing requirements Not particularly at risk to equipment failures Equipment used is less costly Possible to use individual incentive plans Requires lower initial capital investment High degree of machine utilisation Overhead costs are relatively low Breakdown of one machine does not disturb the production process Supervision can be more effective and specialised Greater flexibility of resources	In-process inventory costs can be high Challenging routing and scheduling Equipment utilisation rates are low Material handling slow and inefficient Complexities often reduce span of supervision Special attention for each product or customer Accounting, inventory control and purchasing are more involved Material handling costs are high due to backtracking More skilled labour is required resulting in higher cost Work in progress inventory is high needing greater storage space More frequent inspection is needed which results in costly supervision

In the next section layout procedures are discussed for designing layouts, including Muther's Systematic Layout Procedure which is a useful process layout tool. This method is applied in Section 3.4.

3.3 Layout Procedures

There exist three main traditional approaches to solving the FLP, namely: Apple's Plant Layout Procedure, Reed's Plant Layout Procedure, and Muther's Systematic Layout Planning Procedure (Mehrotra, Syal & Hastak, 2005). All three layout procedures provide an overall process to construct or improve a layout. However, these methods are very dependent on the opinion and spatial skills of the human designer (Tompkins *et al.*, 2010). There are also two older layout procedures in literature called Immer's Basic Steps developed in 1950 and Naddler's Ideal System Approach which was developed in 1961 (Bhatwadekar, Kulkarni & Thakur, 2015).

Some of the steps used in layout procedures are similar to variables used in the layout models discussed in Chapter 2. For example the variable f_{ik} (the flow of material between facility i at location k used in the QAP resembles the flow between activities used in Apple's Plant Layout Procedure as well as Muther's Systematic Layout Planning Procedure. Another example is the variable r_{ij} (the closeness rating indicating the desirability of locating facility i adjacent to facility j) used in the GTP which correlates to the activities relationship chart used in Apple's Plant Layout Procedure and Muther's Systematic Layout Planning Procedure. However, many of the steps of all three layout procedures are merely guidelines for the designer and it is unlikely that two designers will produce the same layout for a given application, even if they were using the same procedure. In contrast to this, the algorithmic approaches (layout models) will produce the same result if they are solved optimally.

3.3.1 APPLE'S PLANT LAYOUT PROCEDURE

Apple's Plant Layout Procedure consists of a system of 20 ordered steps as shown in Figure 13. This method suggests that no two layout procedures are the same and therefore neither are (nor should be) the procedures for designing them (Tompkins *et al.*, 2010). Furthermore, an understanding of the impact each of the steps has on each other is necessary before a holistic solution can be determined, requiring some jumping back and forth. It is an iterative process of continuous improvement.

1. Procure the basic data	2. Analyse the basic data	3. Design the productive process	4. Plan the material flow pattern	5. Consider the general material handling plan
6. Calculate equipment requirements	7. Plan individual workstations	8. Select specific material handling equipment	9. Coordinate groups of related operations	10. Design activity interrelationships
11. Determine storage requirements	12. Plan service auxiliary activities	13. Determine space requirements	14. Allocate activities to total space	15. Consider building types
16. Construct master layout	17. Evaluate, adjust, and check the layout with the appropriate persons	18. Obtain approvals	19. Install the layout	20. Follow up on implementation of the layout

FIGURE 13: APPLE'S PLANT LAYOUT PROCEDURE ADAPTED FROM TOMPKINS *ET AL.* (2010)

Take note of Steps 4, 10 and 13 shown in Figure 13. Step 4 refers to the flow of material. The analysis of activity interrelationships (Step 10) is a popular approach that is also used in Muther's Systematic Layout Planning Procedure. Step 13 is addressed in Section 4.2.2.

3.3.2 REED'S LAYOUT PROCEDURE

Reed's Plant Layout Procedure recommends a 10-step 'systematic plan of attack' for both the planning and preparing of the layout (Tompkins *et al.*, 2010). This is shown in Figure 14. The procedure uses a layout planning chart which Reed considers one of the most crucial phases in the layout process. This chart incorporates the addressing of standard times for each operation, machine selection and balance, manpower selection and balance, as well as material handling requirements.

1. Analyse the product(s) to be produced	2. Determine the process required to manufacture the product	3. Prepare layout planning charts	4. Determine workstations	5. Analyse storage area requirements
6. Establish minimum aisle widths	7. Establish office requirements	8. Consider personnel facilities and services	9. Survey plant services	10. Provide for future expansions

FIGURE 14: REED'S LAYOUT PROCEDURE ADAPTED FROM TOMPKINS *ET AL.* (2010)

The flow of material to create a product is once again analysed in Step 2. However, no other activity relationships are considered. Space requirements are investigated in Steps 5, 6, and 7.

3.3.3 MUTHER'S SYSTEMATIC LAYOUT PROCEDURE

Muther's Systematic Layout Planning (SLP) Procedure is a popular process layout tool (Section 3.1) that provides the foundation on which numerous layout design techniques and also software is developed (Welgama & Gibson, 1995). It is based primarily on an activity relationship chart which provides the input data, roles and relationships between activities, and material flow analysis (i.e. a from-to chart).

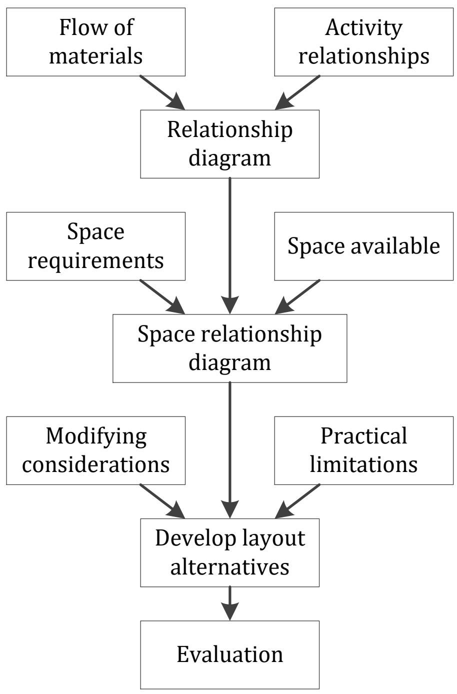


FIGURE 15: MUTHER'S SYSTEMATIC LAYOUT PROCEDURE ADAPTED FROM TOMPKINS *ET AL.* (2010)

The steps of this method are shown in Figure 15. The concepts of Muther's SLP Procedure are still very popular and prominent in textbooks. It is a very simple method and generating a layout solution is relatively easy (Tompkins *et al.*, 2010).

3.3.4 CONCLUSION: LAYOUT PROCEDURES

In conclusion, the layout procedures do not provide a formal process or algorithm for many of the crucial steps associated with developing a facility layout, unlike the layout models discussed in Chapter 2. These layout models are able to help the layout analyst develop or improve a layout, while simultaneously providing him or her with objective criteria to facilitate the evaluation of various layout alternatives that emerge in the process. Another disadvantage of layout procedures is that they will rarely give an optimal or near optimal solution since they are very much dependant on the designer's opinion and experience.

On the other hand, layout procedures are able to produce a layout with little effort within a short time. The comparison between layout procedures and layout models suggests that it may be possible to combine some of the steps of Muther's SLP Procedure with a layout model (for instance both methods analyse the flow between departments). It seems that the main advantage of using Muther's SLP Procedure is that it addresses the importance of placing some departments close to each other and separating certain ones (Steps 1, 2 and 3). This approach differs from the layout models discussed in Chapter 2 (with the exception of the GTP) which are based on the flow of material between departments. In the next section the first few steps of Muther's SLP Procedure are applied to the context of a hospital.

3.4 Department level analysis

A hospital consists of a wide range of services and functional units (i.e. departments). Functional units within a hospital oftentimes exhibit competing priorities and needs. Individual preferences and idealised scenarios must realistically be balanced against actual functional needs (flow and relationships to other departments), compulsory requirements, and the financial capabilities of the hospital (Carr, 2011). A good hospital design effectively integrates functional requirements with the human needs of its varied users (Philippi, 2012). In the context of a hospital the users include patients, visitors, staff, suppliers, and owners.

This section applies the first few steps of Muther's SLP Procedure, i.e. relationships between departments. In doing this, one would need to address which hospital departments should be placed in close proximity to each other and which ones should be placed apart.

First, existing relationship diagrams for hospitals were researched. The following key references were found:

- Pierdait (2006) developed a reference guide for hospitals (unpublished). Pierdair considered nine hospital departments and used a scale with three ratings, namely short and required connection, short and useful connection, and advised connection;
- Kobus (2008) developed a relationship diagram with 25 departments. The diagram includes less common units such as safety respiratory care, central processing, environmental services, maintenance,

public facilities, and oncology. In this diagram only a few relationships were indicated (less than one third). A scale of three ratings was used, namely essential, important, and desirable;

- Motaghi, Hamzenejad, Riahi and Soheili Kashani (2011) used heurists to design a block layout for the Shafa Hospital. They constructed a relationship chart for this specific hospital which has five floors. They used a total of 22 units in their relationship diagram. However, there are five separate units for wards. Installations, management, conference hall, and pavilion are also included. Furthermore, the operation rooms are divided into two separate units. A scale with seven ratings was used, namely absolutely necessary, special importance, important, normal, unimportant, undesirable, and quite undesirable; and
- Neufert and Neufert (2012) propose a relationship chart for 11 departments. They used a scale of three ratings, namely, very good connection required, good connection sensible, and connection is desirable.

Thus no generic relationship diagram for a district hospital was found and for this reason a new one is developed in this section. First, the function of each department of a district hospital was researched and its relationships with other departments were determined. Three of the references found used a scale with three ratings for relationships between departments. Motaghi *et al.* (2011) used the most comprehensive scale for relationships since their scale had seven ratings and included negative relationships. It was therefore decided to use this scale for rating the relationships between departments of a district hospital. In order to show these ratings more clearly, each rating is assigned to a numerical value between -10 and 10 as shown in Table 23.

TABLE 23: CLOSENESS RATING SCALE FOR DEPARTMENTAL RELATIONSHIPS

Departmental relationship	**Closeness rating**
Absolutely necessary	10
Especially important	7
Important	5
Desirable	3
Unimportant	0
Undesirable	-3
Important separation	-5
Absolutely necessary separation	-10

As mentioned in Section 1.7 different types of hospitals exist, namely district hospitals, regional hospitals, provincial tertiary hospitals, central hospitals, and specialised hospitals. According to Conradie and Steyn (2014) the service package for South African hospitals can be divided into outpatient services, inpatient services, clinical support services, administrative support services, and facilities management services. The departments in each field are shown in Figure 16.

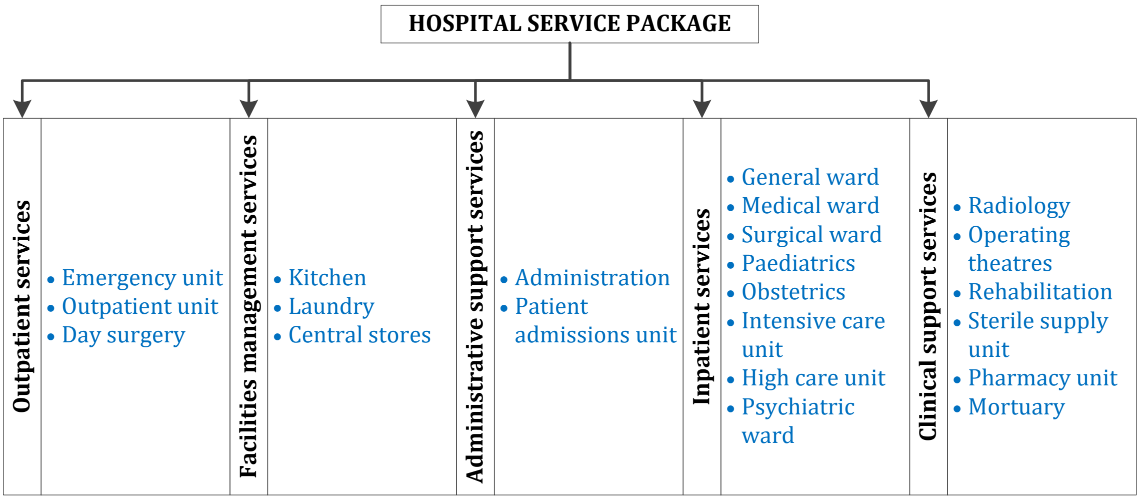


FIGURE 16: SOUTH AFRICAN HOSPITAL SERVICE PACKAGE

According to the Regulations Governing Private Hospitals and Unattached Operating Theatre Units (further discussed in Section 4.2.2) the following departments are relevant to district hospitals in South Africa, namely Administration (Admin), Obstetrics (Obst), Operating Suite (OS), Paediatric Unit (Paed), Laundry, Kitchen, Sterilisation and Disinfection Unit (S&DU), Pharmacy, Emergency and Casualty Unit (Emer), Acute Psychiatric Facility (Psych), Chronic Care Unit (CCU), Rehabilitation Unit (Rehab), Mortuary, Laboratory, Radiology, Neonatal Intensive Care Unit (NICU), Intensive Care Unit (ICU), and High Care Unit (HCU). All of these departments are now analysed in order to develop a generic relationship diagram for district hospitals.

3.4.1 ADMINISTRATION

The administration department is defined by Broekmann and Steyn (2014) as *"offices for administrative staff, clinicians, matrons, and other medical staff; board rooms, auditoria, conference rooms, chapel, library, staff rest rooms, ablutions and sanitary facilities; facilities for safekeeping of goods, stationery, stores, and cleaners' rooms."* The administration department manages daily operations of all departments in the hospital through planning, directing, co-ordinating, and supervising the delivery of healthcare. Functions of this unit include planning, implementing, and evaluating the following: departmental activities; facility utilisation studies; daily operation of patient admissions and clinical facilities; health information and medical records, and; maintenance and security of all patient records. This unit also implements health policies set by government as well as recruit, hire, and train medical, administrative, and other technical staff (Gupta, Gupta, Kant, Chandrashekhar & Satpathy, 2007).

The administration department should be orientated in a way that is easily accessible to the public, but that is at the same time private and secured with access control (Broekmann & Steyn, 2014). Offices for hospital management may be located in more private areas away from the entrance (Kunders, 2004). Financial areas that have a functional relationship with the public must be close to the entrance of the hospital, e.g. all outpatients come to the administration department to register and pay their account. It is therefore necessary to place the outpatient department in close proximity to the administration department. Outpatients refer to patients who seek diagnosis or treatment at a hospital, but are not admitted for an overnight stay while inpatients refer to patients who are admitted (Medical Dictionary for the Health Professions and Nursing, 2012).

The main entrance of the hospital (part of the administration department) typically leads into the central spine of a hospital. From here visitors are directed to the inpatient services, e.g. obstetrics, paediatrics, and patients are directed to clinical support services, e.g. radiology.

The department relationships with the administration department are therefore suggested to be as follows: Obst(3), OS(3), Paed(3), Out(10), Laundry(0), Kitchen(0), S&DU(3), Pharmacy(3), Emer(0), Psych(3), CCU(3), Rehab(3), Mortuary(0), Laboratory(0), Radiology(4), NICU(3), ICU(3), and HCU(3).

3.4.2 OBSTETRICS

Obstetrics deals with childbirth, but it is practically impossible to separate from pregnancy (maternity) related problems. General hospitals customarily combine obstetrical and gynaecological services. Gynaecology on the other hand, treats disturbances and diseases peculiar to women. The obstetric unit is responsible for providing safe and efficient care that ensures utmost safety and comfort for women and new-borns (Kunders, 2004). The nursing unit of this department provides prenatal care, observation, and comforting of the patients in labour, providing assistance in the delivery room, care of the mother after delivery and also care of the new-born (Department of Health, 2002).

The maternity care of a hospital typically spreads over two departments (Van der Schyf & Flemming, 2015). The antenatal services and postnatal services are usually provided in the outpatient department of a hospital while the antenatal ward, high-dependency unit, delivery unit, postnatal ward, well-baby nursery, kangaroo mother care, and obstetric theatres are located in the obstetrics department. For this reason, a close relationship with the outpatient department is required. The obstetrics department must be adjacent to the operating suite (unless it has a dedicated operating theatre) and the neonates' (new-borns) ward (Van der Schyf & Flemming, 2015). Therefore, high relationships ratings are assigned to the operating suite and the paediatrics department (since the neonates' ward is within this unit). Some hospitals design the delivery suite adjacent to the surgical suite. An advantage of such design is that the two departments require the same isolation, type of nursing service, cleaning, air-conditioning, and sterile supplies. However, a disadvantage of this design is inter-traffic and possible cross-contamination. Furthermore, close proximities to the HCUs and ICUs are preferable. Easy access to both the pharmacy and radiology is required.

The clinical section of this department should be located in a secluded area. Within the clinical facilities, the labour and delivery suites should be as remote as possible as well as easily accessible from the entrance to the department. Furthermore, the nursing unit has a close relationship with the pharmacy, laboratory, and the kitchen. This department is usually noisy and it is ideal to separate it from the rest of the hospital (Kunders, 2004).

The suggested department relationships with the obstetrics department are therefore as follows: Admin(0), OS(10), Paed(10), Laundry(3), Kitchen(3), S&DU(3), Pharmacy(7), Emer(3), Psych(-3), CCU(-3), Rehab(-3), Mortuary(1), Laboratory(3), Radiology(7), NICU(10), ICU(9), and HCU(9).

3.4.3 OPERATING SUITE

The operating suite department is defined by Van Reenen (2014) as "*a highly controlled environment for the operative and perioperative care of patients who are undergoing diagnostic and surgical procedures under anaesthesia*." The surgical facilities include the operating rooms, duty station, recover area, change rooms, storage, and setting up area. In a typical general hospital surgical patients represent 50 to 60 percent of the admissions, and a high percentage of them undergo surgery (Kunders, 2004). There are three types of surgical patients, namely inpatients, outpatients, and ambulatory surgery patients. Inpatients are those who are hospitalised for surgery. Outpatient surgery relates to usually minor surgical procedures that require local anaesthesia and the patients are admitted and discharged the same day (Kunders, 2004). About 55% of all surgical procedures are done on an outpatient basis (Wier, Steiner & Owens, 2015). The terms ambulatory surgery (also known as same-day surgery) and outpatient surgery are often incorrectly used interchangeably. Ambulatory surgery usually requires more extensive procedures, e.g. getting your wisdom teeth removed (Whitlock, 2015).

The best location for this department is one which allows efficient flow of patients, staff, and clean supplies (Kunders, 2004). Ideal adjacencies include emergency, radiology, laboratory, intensive care unit, sterilisation and disinfection department, and delivery suite (obstetrics). The sterilisation and disinfection department are responsible for preparing and autoclaving all surgical instrument, gloves, linen, syringes, and needles. This department may be adjacent, but it should not be placed adjacent to a theatre room in order to prevent cross-contamination (Van Reenen, 2014). A relatively lower rating is thus assigned to this relationship. Easy access from the emergency department and delivery suite are crucial. The ICU should be adjoined. It is also important to separate the operating suite from the rest of the hospital. Entry and exit into this department should be controlled. There should be no traffic through it and no interference from other departments. It is ideal to place this department away from the main traffic and other possible sources of noise, e.g. administration and outpatient departments. Lastly, it must also be accessible from wards.

The suggested department relationships with the operating suite are therefore as follows: Admin(-2), Obst(10), Paed(0), Out(-2), Laundry(0), Kitchen(0), S&DU(5), Pharmacy(0), Emer(10), Psych(3), CCU(3), Rehab(0), Mortuary(3), Laboratory(8), Radiology(8), NICU(7), ICU(10), and HCU(7).

3.4.4 PAEDIATRIC UNIT

The paediatric unit caters for children up to 12 years of age (neonates, infants, and children) (Flemming, 2014). The care includes preventative, promotive, curative (assessing, classifying and treating), and rehabilitative care (Department of Health, 2002). As much healthcare as possible is provided in the home, and children are admitted and kept in hospital only when this is essential. Up to 15 percent of beds in a general hospital may be required for paediatric patients (Kunders, 2004). An important design consideration is to acknowledge the psychological role that parents and friends play in the recovery and rehabilitation of the sick child. The Paediatric Unit is generally noisy and should therefore be located away from the main stream of hospital traffic. It is ideal to place this department close to the main entrance, but separate from the inpatient facilities (wards) in a way that children from the paediatric unit can go home without having contact with the other wards (Flemming, 2014). The neonatal nursery of the paediatric unit should be located close to obstetrics since that is where the maternity delivery unit is located and the postnatal wards. Similar to other nursing units, a close relationship with the operating suite, pharmacy, central stores, laboratory, and the dietary (kitchen) are required (Kunders, 2004).

The department relationships with the paediatric unit are therefore as follows: Admin(3), Obst(8), OS(5), Laundry(5), Kitchen(5), S&DU(3), Pharmacy(5), Emer(3), Psych(-5), CCU(-3), Rehab(-3), Mortuary(3), Laboratory(5), Radiology(3), NICU(10), ICU(-2), and HCU(-3).

3.4.5 OUTPATIENT UNIT

The outpatient department provides medical care that does not require an overnight stay in a hospital (known as ambulatory care) (Flemming, 2014). Ambulatory care involves preventative, promotive, curative, and rehabilitative services. Activities in the outpatient department include patient triage, consulting, counselling, examination, observation, diagnosis, treatment, and therapy. As mentioned earlier, the outpatient department provides antenatal and postnatal care for mothers and unborn/born child. Close proximity with obstetrics (and paediatrics) are therefore ideal.

It is important to place the outpatient department close to the main entrance (administration) since there are constant movement between these two units (Broekmann & Steyn, 2014). Another reason is that patients' medical records need to be readily accessible from the outpatient department. Furthermore, easy access to the rehabilitation unit and other wards are required.

It is essential that the pharmacy is close to the outpatient unit because many patients attend the hospital pharmacy to collect dispensed medicines after consultations or treatment (Flemming, 2014).

Good access to the radiology department is necessary since patients often attend the unit during the course of an outpatient session. This department is usually noisy since patients, staff, service staff, and escorts are constantly moving throughout the consulting rooms, to treatment rooms, service points, and other departments. It is useful to place this department away from relatively quiet units, e.g. the operating suite.

The department relationships with the outpatient unit are therefore as follows: Admin(10), Obst(10), OS(-2), Paed(8), Laun(3), Kitchen(0), S&DU(3), Pharmacy(10), Emer(3), Psych(3), CCU(5), Rehab(5), Mortuary(3), Laboratory(3), Radiology(5), NICU(3), ICU(3), and HCU(3).

3.4.6 LAUNDRY

The function of a hospital's laundry is to receive contaminated items for cleaning and providing an adequate, economic, continuous supply of clean, disinfected linen to all patient care units in a hospital (Fourie, Sheared & Steyn, 2014). The laundry services are one of the most important supportive services in a hospital, i.e. washing/cleaning of linen (Gupta *et al*., 2007). Depending on the hospital policy, it may be undertaken in-house or it may be outsourced. The main functions of a hospital laundry are to supply a clean and adequate amount of linen on a regular basis, and procedures must be taken to prevent cross infection (Natarajan, 2010). Positive relationship ratings are thus assigned to the wards, emergency department, operating suite and outpatient department. As a planning guide, the quantity of linen to clean per day may be approximated as 4kg per bed, where up to 20% is infected linen. In addition, 8kg of soiled linen for each surgical operation and delivery should be considered. The laundry typically has a separate entry and exit which helps to separate clean and soiled linen areas (Gupta *et al*., 2007). The hospital laundry should be located away from the main service and traffic of the hospital (Fourie, Sheared & Steyn, 2014).

The department relationships with the laundry are therefore as follows: Admin(0), Obst(4), OS(4), Paed(4), Out(3), Kitchen(0), S&DU(0), Pharmacy(0), Emer(4), Psych(4), CCU(4), Rehab(3), Mortuary(0), Laboratory(0), Radiology(0), NICU(4), ICU(4), and HCU(4).

3.4.7 KITCHEN

The food service department of a hospital is an important supportive service which provides inpatients their meals as per their dietary requirements, taking into consideration the nature, type of disease, nutritional requirements, and food habits of the patient. The food requirements of staff as well as visitors are catered for too. The department may be outsourced, depending on the hospital's policy (Gupta *et al*., 2007). It should be located centrally to supply patients' needs within the shortest time (Steyn & Boltman, 2014). Ideally, it should be placed close to wards, but it must be located so that heat and odours are not directed towards traffic areas. As a fire safety precaution they should also not be located under wards, especially those for ambulant patients (Kunders, 2004). It should be located away from normal hospital activities, but trucks should be able to easily deliver supplies such as meat, vegetables, and dairy products (Natarajan, 2010).

The department relationships with the kitchen are therefore as follows: Admin(-3), Obst(3), OS(-3), Paed(3), Out(0), Laundry(0), S&DU(-3), Pharmacy(-3), Emer(-3), Psych(3), CCU(3), Rehab(3), Mortuary(0), Laboratory(0), Radiology(0), NICU(3), ICU(3), and HCU(3).

3.4.8 STERILISATION AND DISINFECTION UNIT

The primary function of the sterilisation and disinfection unit is providing efficient, economic, quality supply of sterilised items to all patient-care points, and to receive contaminated items for cleaning (Steyn & Sheard, 2004). In some hospitals, this department also purchases, stocks, and distributes supplies. It is essential that sterilisation methods, procedures and process are carried out at a central department in order to maintain quality, standardisation, cost-effectiveness, control, and optimal utilisation (Gupta *et al.*, 2007). The sterilisation and disinfection unit should be centrally located with access to all service areas such as the ICU, wards, and emergency department (Manav, 2011). It should have direct access to the operating suite (Steyn & Sheard, 2004).

The department relationships with sterilisation and disinfection unit the are therefore as follows: Admin(0), Obst(7), OS(10), Paed(7), Out(3), Laundry(0), Kitchen(0), Pharmacy(0), Emer(7), Psych(3), CCU(7), Rehab(5), Mortuary(0), Laboratory(0), Radiology(0), NICU(7), ICU(7), and HCU(7).

3.4.9 PHARMACY

The hospital pharmacy supplies and dispenses necessary drugs and medical supplies. It purchases drugs from an identified supplier to maintain adequate quantities, as well as receives, records, and stores them (Department of Health, 2002). Traffic within this department should be flexible and economical. Provision must be made for securing dangerous drugs and bulk quantities should be kept elsewhere (Kunders, 2004).

It is important that the pharmacy is located in a way that it is accessible to the outpatient department, and convenient for dispensing whilst maintaining patients' privacy and dignity (Kunders, 2004). It is often the patient's last stop within any hospital establishment visit (thus a relationship with the administration department). Pharmaceuticals are also distributed to the inpatient areas under the supervision of the pharmacist. Delivery to the pharmacy should also be considered. The pharmacy should ideally be placed central to the core services near outpatients, inpatients, and the emergency department (Nice, 2014).

The department relationships with the pharmacy are therefore as follows: Admin(5), Obst(3), OS(3), Paed(3), Out(10), Laundry(0), Kitchen(0), S&DU(0), Emer(10), Psych(3), CCU(8), Rehab(3), Mortuary(0), Laboratory(0), Radiology(0), NICU(3), ICU(3), and HCU(3).

3.4.10 EMERGENCY AND CASUALTY UNIT

The emergency and casualty unit is defined by Fleming (2014) as "*the dedicated area in a health facility that is organised and administered to provide a high standard of emergency care to those in the community who are in need of acute or urgent care*." The emergency department is an essential unit of a hospital, and must be available to receive patients 24 hours a day. Its purpose is to manage patients with a wide variety of critical, urgent and semi-urgent condition. These patients are received, triaged, and stabilised (Haryana State Health Resource Centre, 2013).

When planning the emergency department, one should understand that the word 'emergency' is often misunderstood, and that patients often seek emergency care for a situations other than critical medical conditions since patient's perception of an emergency can vary (e.g. a person who is unable to contact a doctor at night to treat his constipation that has lasted a few days may feel like an emergency). Thus, the emergency department provides for a comprehensive range of services, from first aid and general outpatient services to sophisticated surgical and medical emergencies and full-scale trauma care, e.g. treatment and reporting of physical and psychological abuse (Department of Health, 2002). Therefore, it is important to incorporate flexibility in the design to handle a range of cases economically and efficiently (Kunders, 2004). In the case of a disaster in a region, the emergency unit should be able to manage patients who are victims (Haryana State Health Resource Centre, 2013; Department of Health, 2002).

It is vital that the emergency department has rapid access to the operating suite, and radiology department (over 40% of emergencies require X-rays and portable X-rays are usually not satisfactory) (Kunders, 2004). A separate entrance, away from the main hospital entrance, is required and should be easily accessible to ambulances and patients. Traffic control is critical since injured patients, victims, and their families can cause inefficient operation and consideration should be given to protection of privacy (Haryana State Health Resource Centre, 2013). The laboratory should be accessible from the emergency department since a sizable number of patients require laboratory tests (Kunders, 2004). Additionally, smooth access and proximity to the ICU and HCU in order to minimise the transfer times of critically ill patients (Fleming (2014). The emergency department should have 24-hour access to the hospital pharmacy. The mortuary should also be accessible. The emphasis of these relationships should be on rapid access.

The department relationships with the emergency and casualty unit are therefore as follows: Admin(-3), Obst(5), OS(10), Paed(3), Laundry(0), Kitchen(0), S&DU(3), Pharmacy(7), Psych(0), CCU(3), Rehab(-3), Mortuary(4), Laboratory(9), Radiology(10), NICU(5), ICU(5), and HCU(5).

3.4.11 ACUTE PSYCHIATRIC FACILITY

The Acute Psychiatric Facility provides medical and nursing support for patients in periods of acute psychiatric illness (National Health Service Confederation, 2012). The care provided involves a full range of disciplines, including psychologists, pharmacists, and occupational therapists. While some mental illnesses are treated at specialised mental hospitals, a large number of people receive psychiatric diagnosis and treatment of varying degrees at general hospitals. The care of these patients requires knowledge of their various behavioural patterns and how to best manage them (Kunders, 2004).

In order to provide care for acute psychiatric patients, laboratory tests (e.g. basic blood tests and HIV testing) or services for additional investigations are often required. Radiographic services are also often utilised, e.g. to exclude trauma (Department of Health, 2002). It is important that the psychiatric unit is protected and in a secure seclusion area which is under close permanent supervision of staff (Kunders, 2004). It should ideally be located away from the other hospital departments and have a separate entrance. In order to prevent self-harm, single-storey buildings are preferred. Another consideration is to create a therapeutic environment and give attention to noise levels, colour, natural light, and spaces that would promote a healing environment (Railoun & Van der Schyf, 2014). It is thus suggested to locate this department away from the main traffic areas (e.g. Admin), noisy departments (e.g. Paed, Emer) and critical units (e.g. ICU).

The department relationships with the acute psychiatric facility are therefore as follows: Admin(-3), Obst(-3), OS(-3), Paed(-3), Out (-3), Laundry(3), Kitchen(3), S&DU(0), Pharmacy(3), Emer(-3), CCU(0), Rehab(0), Mortuary(-4), Laboratory(6), Radiology(4), NICU(-3), ICU(-3), and HCU(-3).

3.4.12 CHRONIC CARE UNIT

The Chronic Care Unit (CCU) provides medical care for adults in all life stages with long term illnesses, as opposed to acute care which is concerned with emergency treatment and critical care (e.g. ICU or HCU) (Department of Health, 2002). The CCU combines patient bed space and clinical treatment space which allows the unit to provide an effective, economical, and therapeutic unit for patients (Van der Schyf & Fleming, 2014). This unit is complex in the sense that it may extend over a prolonged period of time and requires input from different health professionals, various medications, and possibly monitoring equipment. The support of family and friends usually plays a big role and should be considered in planning the department. It is important that noise is deduced, patient safety maximised, and the work environment aesthetically pleasing.

The CCU and other inpatient units (e.g. Paed, Obst) form the core of a hospital and have relationships with most departments, especially operating suite, pharmacy, central stores, and laboratory. The administration department should have a primary circulation route to the CCU. There should also be a reasonable relationship with the mortuary, laundry, and kitchen (Van der Schyf & Fleming, 2014).

The department relationships with the chronic care unit are therefore as follows: Admin(5), Obst(0), OS(5), Paed(0), Out(5), Laundry(5), Kitchen(5), S&DU(3), Pharmacy(5), Emer(5), Psych(0), Rehab(0), Mortuary(5), Laboratory(5), Radiology(3), NICU(0), ICU(5), and HCU(5).

3.4.13 REHABILITATION UNIT

The purpose of a rehabilitation unit is to manage acute and chronic disabling conditions, prepare the disabled person for reintegration into the community as well as to provide training, assisting and counselling activities on a daily basis. This includes tasks such as bathing, dressing, eating, and communicating (Amrpa, 2016). This unit also manage those problems related to disability that: cannot be managed in the community, support rehabilitation services in the community, and supply appropriate assistive devices to patients. Patients are also taught to service and maintain the assistive devices (Department of Health, 2002). Consideration should be given to the fact that many patients treated in these units use wheelchairs or walking aids. Types of patients typically include post-surgery recovery, multiple trauma, amputees, and neurological injuries and disease (Buhrs, 2013).

For the rehabilitation unit it is important that patients get enough sleep and rest. High noise levels or a sudden increase of noise can prevent patients getting restful sleep which may negatively impact their rehabilitation process due to the side effects of sleep deprivation, e.g. impaired memory, learning and well-being (Yelden, Duport, Kempny & Playford, 2015). For this reason, noisy departments such as obstetrics, the paediatric unit, and the emergency department should be located away from the rehabilitation unit. Another consideration is that family members form an integral part of the rehabilitation team and are encouraged to be present during treatments (Buhrs, 2013). Thus, promoting and accommodating visitors in this unit is of importance (relationship with Admin). Similar to other inpatient units, a reasonable relationship with the kitchen, pharmacy, and laundry is suggested.

The department relationships with the rehabilitation unit are therefore as follows: Admin(5), Obst(-5), OS(5), Paed(-5), Out(5), Laundry(5), Kitchen(5), S&DU(3), Pharmacy(5), Emer(-5), Psych(3), CCU(3), Mortuary(3), Laboratory(3), Radiology(3), NICU(3), ICU(3), and HCU(3).

3.4.14 MORTUARY

A hospital's mortuary holds dead bodies until burial can be arranged. It also provides a place where relatives and other people can view and identify bodies. The needs of visitors and patient dignity in handling bodies should thus be considered in the design (Reenen, 2014). Visitors should be provided with easy access to the mortuary upon arrival, without having to travel unnecessarily through other hospital departments. A separate entrance could thus be ideal. The mortuary should be located that it is easily accessible to mortuary staff and related service providers without presenting emotional or ethical problems for unrelated staff, visitors or patients (Kunders, 2004). When bodies are moved, they should not be moved through the main traffic areas. It is thus suggested to locate the mortuary away from Admin and Psych. Pathologists are sometimes required to investigate causes of death and make scientific investigations. Ideally, the mortuary should be located near the pathology department or laboratory. In order to move bodies to the mortuary it should be accessible from the wards (Paed, Obst, CCU, NICU, ICU, HCU), emergency department (and outpatients) and operating suite (Natarajan, 2010).

The department relationships with the mortuary are therefore as follows: Admin(-3), Obst(4), OS(4), Paed(4), Out(4), Laundry(0), Kitchen(0), S&DU(0), Pharmacy(0), Emer(4), Psych(-3), CCU(4), Rehab(2), Laboratory(5), Radiology(0), NICU(4), ICU(4), and HCU(4).

3.4.15 LABORATORY

A hospital laboratory performs tests in order to enable staff to make or confirm diagnoses as well as the treatment and prevention of diseases (Kunders, 2004). Laboratory tests are either specialised or routine, e.g. urine analysis and blood cell counts. The primary design objective of a laboratory should be to create environments in which laboratory activities can be conducted without compromising patient dignity, laboratory process or health and safety risks (Van Reenen, 2014). It should be located in a way that they cannot be used as thoroughfares for staff, patients or visitors. However, patients should have direct, suitable access and chemicals should easily be delivered and collected (Kunders, 2004). The laboratory serves the emergency, outpatient, and admitting departments. It should also be close to radiology and obstetrics. Since test specimens are transported from inpatient wards and clinical support services, reasonable relationships with these departments are expected.

The department relationships with the laboratory are therefore as follows: Admin(3), Obst(5), OS(5), Paed(5), Out(3), Laundry(0), Kitchen(0), S&DU(3), Pharmacy(0), Emer(9), Psych(6), CCU(5), Rehab(5), Mortuary(0), Radiology(4), NICU(5), ICU(5), and HCU(5).

3.4.16 RADIOLOGY

The main role of the radiology department is to assist in the diagnosis and treatment of diseases (Department of Health, 2002). In large hospitals, this service may be arranged into three departments, namely: diagnostic radiology, therapeutic radiology, and nuclear medicine. Usually medium and small-sized hospitals only have diagnostic radiology available. Its responsibilities include taking, developing, and interpreting X-rays. It also conducts research and participates in educational programs for nurses, technicians, and the community (Kunders, 2004).

It is crucial that the radiology department is easily accessible to the emergency department, outpatient department, and inpatient wards. The department should be placed central to these areas and take into consideration convenience, privacy, and traffic flow (Kunders, 2004). Other important relationships include the ICU and operating suite. It is possible to use potable radiographic equipment in selected instances for imaging of patients, e.g. ICU. It should also be noted that the devices in the radiology department are large and bulky and pose challenges to install. Access is not only important during construction, but also during maintenance, repair and replacement of these devices (Coetzer, 2013). A closer relationship to the entrance is thus suggested.

The department relationships with the radiology are therefore as follows: Admin(5), Obst(3), OS(5), Paed(3), Out(7), Laundry(0), Kitchen(0), S&DU(0), Pharmacy(0), Emer(10), Psych(4), CCU(3), Rehab(3), Mortuary(0), Laboratory(0), NICU(3), ICU(3), and HCU(3).

3.4.17 NEONATAL INTENSIVE CARE UNIT

The Neonatal Intensive Care Unit (NICU) specialises on the health of neonates who require constant nursing, difficult surgical procedures, continual respiratory support, or other interventions (Kunders, 2004). A neonate is defined as a child from birth to one month of age (or a two month old child weighing less than 2kg). Neonates are very vulnerable patients and consideration to the design of the wards is therefore essential. Quiet times in NICUs are very important since loud noise levels have an impact on neonates' ability to absorb oxygen. It is recommended that NICUs have a separate area in the hospital in order to minimise the transmission of diseases and maintaining privacy (De Jager, 2014). Yet, the unit should be well integrated with the other hospital departments for easy access (Bird, Bostic, Taylor & Zhou, 2011). It should also have ready access to the maternity unit (Obst), emergency unit, operating suite, and laboratory. Since the paediatric department accommodates more stable neonates, a close relationship with this department is suggested.

The department relationships with the NICU are therefore as follows: Admin(3), Obst(10), OS(8), Paed(10), Out(3) Laundry(3), Kitchen(0), S&DU(5), Pharmacy(5), Emer(5), Psych(0), CCU(0), Rehab(0), Mortuary(3), Laboratory(5), Radiology(3), ICU(0), and HCU(0).

3.4.18 INTENSIVE CARE UNIT

The Intensive Care Unit (ICU) can be defined as a "*highly specialised and technically sophisticated dedicated unit for the management and care of critically ill patients who are dependent on invasive life support, and intensive levels of medical and nursing care that requires complex treatment*" (Coetzer & Fleming, 2014). This care differs from other hospital units since ICU patients require a higher level of observation and monitoring and may have special equipment in their room, e.g. ventilators, heart monitors, respiratory monitors (Sutter Health, 2014).

The ICU should be located in a distinct area within the hospital preferably with controlled access. It should be centrally located with no thoroughfare through the unit. Supply and staff traffic should be separated from visitor traffic and no through traffic to other departments should occur. It is important that the unit is close to the emergency department, obstetrics (maternity unit), operating room (OS), radiology department, intermediate care units (e.g. HCU), recovery rooms, and respiratory therapy (Society of Critical Care Medicine, 1995). It also requires access to the hospital pharmacy and laboratory. The specialised cardiac team should be able to respond promptly to an ICU emergency call. Admissions to ICUs are through the emergency department or from the operating rooms after major surgery. It should also not be too far from the inpatient units since this will reduce the traveling distance and time to move patients between the two departments, especially in the case of an emergency to move a patient from a ward to the ICU (Kunders, 2004). Patients are typically moved to the HCU or inpatient wards, if the patient's condition improves.

The department relationships with the ICU are therefore as follows: Admin(3), Obst(9), OS(10), Paed(4), Out(3), Laundry(3), Kitchen(3), S&DU(5), Pharmacy(5), Emer(10), Psych(0), CCU(5), Rehab(3), Mortuary(5), Laboratory(5), Radiology(7), NICU(0), and HCU(9).

3.4.19 HIGH CARE UNIT

A High Care Units (HCU) is where patients are cared for more extensively than in a normal ward, but not to the point of ICUs (Coetzer & Fleming, 2014). The relationships with the HCU are thus rated between the ICU and CCU relationships. Patients in these units are not on life support systems. This unit is appropriate for patients after major surgery, for those with single-organ failure, patients who are at risk of requiring intensive care admission, or as a step-down between ICUs and ward-based care. It is usually located adjacent to the ICU (Intensive Care Society, 1997).

The department relationships with the HCU are therefore as follows: Admin(3), Obst(3), OS(7), Paed(5), Laundry(3), Kitchen(3), S&DU(5), Pharmacy(5), Emer(5), Psych(0), CCU(7), Rehab(3), Mortuary(4), Laboratory(5), Radiology(5), NICU(0), and ICU(10).

3.4.20 RESULTING DEPARTMENTAL RELATIONSHIPS AND FLOWS

The department relationships often have different ratings, e.g. on the one hand you want the paediatric unit (Paed) to be close to the ICU (4 assigned) in case a paediatric patient goes into a critical condition. But on the other hand, the paediatric department is usually noisy and may disturb critically ill patients from getting rest (-2 assigned). For cases like this, a score between the two values are used (2 assigned). The resulting relationship diagram is shown in Figure 17.

FIGURE 17: RELATIONSHIP DIAGRAM OF HOSPITAL DEPARTMENTS

The flow diagram shown in Figure 18 was generated based on the research of each department as well as consulting Carr (2011), Tarawneh (2014), and the World Health Organization (2000).

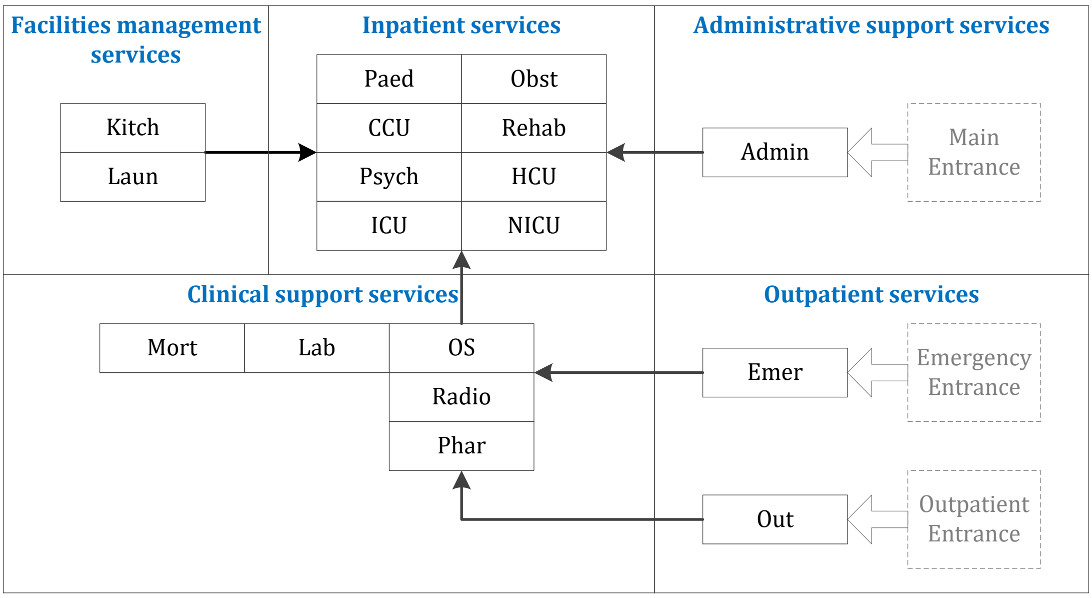


FIGURE 18: FLOW DIAGRAM OF HOSPITAL DEPARTMENTS

3.5 Hospital design considerations

Hospital planning has not historically incorporated designs that are aimed at improving quality of service and safety of patients, yet significant funds are invested in healthcare facilities annually (Hughes, Reiling & Murphy, 2008). Studies have mainly focused on the effects of light, colour, views, and noise, yet there are many more considerations that affect the quality of care in hospitals (Barach & Dickerman, 2007). Therefore, an investigation was conducted into the most important design considerations applicable to hospital layouts found in literature. The results involve considerations revolving around: patient-centeredness, efficiency, flexibility and expandability, sustainability, and therapeutic environments, as shown in Table 24.

TABLE 24: QUALITATIVE HOSPITAL DESIGN CONSIDERATIONS

Design objectives	**Description**	**References**
Patient-centeredness	Patients' need and wants are understood and addressed, including patient safety and infection prevention	Shrewsbury and Telford Hospital NHS Trust (2014) Life Healthcare (2014) Hughes *et al*. (2008) University Hospitals Institute (2013) Carr (2011)
Efficiency	Concerns the rate at which medical care is provided to patients, including: • Lean management • Occupant flows • Ergonomic factors	Hughes et al. (2008) University Hospitals Institute (2013) Carr (2011)
Flexibility and expandability	The ability to change infrastructure, technology, and management structure	Shrewsbury and Telford Hospital NHS Trust (2014) Life Healthcare (2014)
Sustainability	Endurance of the hospital over a lengthy period of time	Hughes *et al*. (2008) Carr (2011)
Therapeutic environment	Physical setting and organizational culture supporting patients and families, including: • Noise • Windows vs no windows • Sunny rooms • Multiple occupancy vs single patient rooms • Supportive design	Ferenc (2015) Barach and Dickerman (2007) Carr (2011)

Each of the design objectives is now further discussed.

3.5.1 PATIENT-CENTEREDNESS

Hospitals are built for the primary reason of providing medical care for patients. Patient-centeredness involves not only medical care but also non-medical needs and wants, such as patient safety (e.g. the protection against hospital acquired infections). The following design elements were found to promote patient-centeredness (Hughes *et al.*, 2008):

- Using variable-acuity rooms and single-bed rooms;

- Ensuring sufficient space to accommodate family members;
- Enabling access to healthcare information; and
- Having clearly marked signs to navigate the hospital.

Hospitals exhibit several particular safety concerns in addition to the general concerns of other buildings. These concerns involve the protection of hospital property and assets (including drugs), protection of patients (including incapacitated patients) and staff, prevention against the spread of infections, and safe control of violent or unstable patients (Carr, 2011). Designing for patient safety includes the following: choosing the correct materials for walls, ceilings, glass, and doors; using the correct hardware such as hinges, closers, and locksets; installing fire extinguishing systems; choosing the correct furniture (refer to Hunt and Sine (2013) for a lengthy discussion of each). These considerations are not included in the layout framework of this study since they are not within the study's scope.

There exist different ways in which to prevent the transmission of infections: using ventilation and filtration systems, choosing surfaces that can easily be decontaminated, and facilitating hand washing with the availability of sinks and alcohol hand rubs (Institute of Medicine, 2013). According to Zimring, Joseph and Choudhary (2004) hospital-acquired infections (caused by pathogens) are among the leading causes of death in the United States, resulting in the deaths of more people than AIDS, automobile accidents, or breast cancer. A research team identified more than 120 studies linking infection to the built environment of the hospital. Infections are transmitted through contact or are even airborne. The literature suggests that there is a clear relationship showing that infection rates are lower when there is higher air quality and patients are kept in single-bed as opposed to multi-bed rooms. Furthermore, several studies reveal that single-bed rooms also lessen the risk of infection due to contact, again promoting the advantage single-bed rooms (Barach & Dickerman, 2007). This is due to the fact that environmental surfaces and features are easily contaminated around infected patients via contact with both patients and/or staff. In comparison to single-bed rooms, multi-bed rooms are much more difficult to decontaminate properly once a patient is discharged, increasing the difficulties posed by multiple surfaces acting as infection reservoirs. Thus, it can confidently be said that single-bed rooms are superior to multi-bed rooms with regards to reducing transmission of infections through the air or via contact (Institute of Medicine, 2013).

3.5.2 EFFICIENCY

Efficiency in the context of a hospital relates to providing quality medical care with the least waste of time and effort. Eliminating waste through continuous improvement is termed lean management. This involves flowing the product at the pull of the customer (Bhuiyan & Baghel, 2005). The product in the context of a hospital is the cured, treated, and/or diagnosed patients. This flow through a hospital has a significant impact on the overall efficiency. Furthermore, a hospital's productivity can be significantly improved by taking ergonomic factors into account. Each of these areas will now be addressed.

3.5.2.1 Lean management

Lean management aims to increase the value of the customer with fewer resources and in order to achieve this, the focus shifts from optimising separate departments to optimising the flow of products and services that add value to these areas. The five main principles of lean are (Leaning Forward, 2005):

- Determine what creates value from the customers' perspective;
- Identify all the steps of the process chain;
- Ensure the flow of processes;
- Produce only according to the needs of customers; and
- Aim for perfection by continuously eliminating waste.

In the context of a hospital the patient is the main focus and all the processes that improve (add value to) the patient's health should be optimised. All processes that do not add any value to the patient's health is waste. Waste in the context of a hospital is defined as follows (Centre for Special Studies and Programs, 2010):

- **Overproduction:** when medication is given out early, treatments done in order to balance the utilisation of staff, and the duplication of tests;
- **Transportation and motion:** when the same patient, specimens, supplies, or workers are moved;
- **Waiting times:** include patients waiting for bed assignments, discharge, or testing results;
- **Processing:** includes the duplication of procedures, retesting, and unnecessary paperwork;
- **Inventory:** consists of specimens waiting for analysis, pharmacy stock and supplies; and
- **Defects:** includes medication errors, missing information, wrong procedure taken, or wrong patient treated.

All of these wastes increase costs and take unnecessary time from staff that could have been used to treat patients. Since healthcare needs to be affordable to all of society, it is important to minimise waste as far as possible. However, the quality of services should be maintained. Thus cost should be minimised while maintaining quality service, minimising errors, and reducing waiting times. The layout of the hospital determines how far the patients need to travel to get treated at the various hospital departments. Since transportation of patients does not add to the health of patients, it can be seen as a non-value adding activity. In fact, Huang and Irani (2013) found that transportation causes anxiety for patients, is a risk of injury to patients, and can lead to spreading of infection to or from the patient. When patients travel between hospital departments there is a delay in their treatment process. This delay could be life-threatening for patients in critical conditions. Queues can form in corridors, elevators, and transport between buildings, causing further delays. The total time taken to complete one patient's treatment thus increases. There can also be a cost involved regarding personnel hired to transport the patients. Karvonen, Korvenranta, Paatela and Seppala (2007) found that the transportation distance from a clinical unit to its internal provider has a negative relationship with the quality of care provided by the staff as well as a positive relationship with the duration the patient spends in the healthcare system (Soriano-Meier, Forrester, Markose & Arturo Garza-Reyes, 2011).

3.5.2.2 Occupant flow

There exist different types of occupant flows in a hospital such as patient flows, nurse flows, doctor flows, visitor flows, and supporting personnel flows. The effective flows of each can mean the difference between life and death for patients. The waiting times of patients are one of the six priority areas of the National Core Standards (discussed in Section 4.2.3 and Appendix B). The transportation of patients throughout the hospital can be seen as a non-value adding activity since it does not contribute to the end product, i.e. cured, treated, or diagnosed patient. Transportation involves travel delays between locations, increases total time taken to complete patient treatment, and the cost of personnel hired to transport. In addition to this, it causes anxiety for patients, increases the risk of injury to patients, and adds to the transmission of infections.

A general rule for designing a hospital is to separate patient, visitor, and staff flows. The use of dedicated resource corridors is particularly important in preventing congestion and delays (Rechel, Wright, Barlow & McKee, 2010). Flows of goods, patients, and work also need to be separated, so as to enable each to move according to the logic and pace most suitable for each. Focus should therefore be placed on similar processes rather than on similar clinical conditions. A good example is that of an emergency department in an Australian training hospital whereby patients were divided into two streams according to complexity rather than urgency, thus creating a fast-track patient stream for patients who can be treated and discharged very quickly which maximised throughput (Saghafian, Hopp, Van Oyen, Desmond & Kronick, 2012). This resulted in significant improvements in several other key performance indicators as well, including mean waiting time, and treatment time.

It is important to differentiate between continuous and batch processes since failing to distinguish can lead to seeing queuing as a lack of capacity (in terms of beds, diagnostics, doctors, facilities, or nurses). Investments aimed at increasing the capacity of a hospital often fail since they are not systematically directed at the most pertinent areas, i.e. the bottlenecks. There are often feedback loops, hidden bottlenecks, and lines moving at varying speeds, all of which negatively impact performance. Thus insufficient supply may well also be a problem, but it can only be understood as a function of how the service is (or rather should be) configured (Rechel *et al*., 2010). The emergency department, intensive care unit, and operating rooms as well as their related pre- and post-care areas are more often than not the most important bottlenecks to deal with, due to the fact that they are non-interchangeable resources.

3.5.2.3 Ergonomic factors

Ergonomic designs are aimed to promote efficiency and ease of use. Ergonomic factors include displays, layout of panels and machines, seating, thermal comfort, noise, and lighting (Konz & Johnson, 2004). Many of these topics are not within the scope of this study, yet the layout of a hospital can be designed to promote ergonomic efficiency by designing aisles with adequate widths for its purpose (e.g. an aisle may adhere to the minimum requirements for aisle widths but it might not be practical for patients and staff).

TABLE 25: NON-CRITICAL AND CRITICAL MINIMUM PASSING SPACES ADAPTED FROM THE ACCIDENT COMPENSATION CORPORATION (2011)

Minimum passing spaces	Non-critical passing (m)	Critical passing (m)
Patient beds	1,8	2,2
Large patient handling equipment	1,5	1,8
Wheelchair passing space	1,5	1,8
Patients assisted by carers	1,5	1,8

The main considerations for an aisle include where it is located, how frequently it is used by staff and patients, the equipment that is used, and whether the passing of people and equipment is critical or non-critical (Hall-Andersen & Broberg, 2014). Table 25 shows various considerations for corridors. Critical passing is where the unrestricted movement is important, and usually applies to emergency evacuation routes and corridors that have a high frequency of usage. On the other hand, non-critical passing is where immediate clear passage for patients are not critical, and usually applies to corridors with low-frequency use (Accident Compensation Corporation, 2011).

3.5.3 FLEXIBILITY AND EXPANDABILITY

Since medical needs and modes of treatment change continuously, it is important for hospitals layouts to design for flexibility and expandability (Life Healthcare, 2014). The layout should thus be treated as dynamic. Just like businesses are wise to have business strategies that are long-term, hospitals should ideally have a similar long-term master plan for how the layout may need to change to remain operating at an optimal level. This master plan must ideally be consistent with the hospital's business plan, and go as far as possible to anticipate future requirements in advance, making provisions for when it must adapt to changing hospital requirements (Shrewsbury and Telford Hospital NHS Trust, 2014). For these reasons, the following design considerations are proposed (Tompkins *et al.*, 2010):

- **Follow modular concepts** of space planning;
- **Use generic room sizes** as much as possible instead of highly specific ones;
- **Be open-ended**, with thoroughly planned directions for future expansion;
- **Minimise layout size** to avoid wasted time and motion of workers;
- **Eliminate centralized storage** and move storage to various departments; and

- **Minimise the amount of reorganisation** that will be made necessary by future growth and change.

In addition to the design considerations mentioned, technology and management structure should also be able to adapt to future requirements.

3.5.4 SUSTAINABILITY

Sustainability relates to the endurance of the hospital over a lengthy period of time (Hughes *et al.*, 2008). This involves using financial resources as efficiently and effectively as possible. Hospitals have a significant impact on both the economy and environment of the community surrounding them, being heavy users of energy and water, and generating relatively large quantities of waste. Because of these demands on community resources, sustainable design is a critical consideration. The benefits of sustainable design include reduced operational costs, and a better therapeutic environment (Carr, 2011). Examples of such designs would for instance maximise utilisation of natural daylight, optimise acoustic performance, and incorporate appropriate ventilation and moisture control (Carr, 2011).

3.5.5 THERAPEUTIC ENVIRONMENT

The importance of the environment for a patient's health and well-being dates back as far as 400BC with Hippocrates, and the 19th century with Florence Nightingale (Huisman, Morales, Van Hoof & Kort, 2012). Ulrich (2001) found scientific evidence that certain environments in a hospital can promote improved patient medical outcomes while others can worsen patient health. 80% of the most rigorous studies have positive links between environmental characteristics and patient health outcomes (Ulrich, 2001). Huisman *et al.* (2012) conducted a similar study on 798 papers and found that 50% of the papers provide strong evidence for this link, with 86% of them finding a link between the interactions of patients and their families with health outcomes. Furthermore, they found that the well-being of healthcare staff are also impacted by the nature of the environment, but evidence of staff outcomes is scarce and insufficiently substantiated. Environmental factors that have an effect on health outcomes of patients include noise levels, presence of windows, sunlit spaces, occupancy rate, and supportive design.

3.5.5.1 Noise levels

Noise levels in hospital are typically more than 15 to 20 dB higher than those recommended by WHO (Basner, Babisch, Davis, Brink, Clark, Janssen & Stansfeld, 2014). Thus, hospital noise may be a threat to patient rehabilitation and staff performance. Noises in hospitals, especially in intensive care units, are characterised by irregularly occurring noises from sources such as medical devices, telephones or pagers, conversations, door sounds, and nursing activities. High noise levels were found to negatively affect patients in the following ways (Basner *et al.*, 2014): decreased rate of wound healing; higher levels of disturbance and annoyance; decreased oxygen saturation, elevated blood pressure, increased heart and respiration rate; sleep disruption and awakening; higher incidence of rehospitalisation, and;

cognitive impairment (mainly in children). Similarly, noise levels have the following effects on staff (Joseph & Ulrich, 2007): increases their perceived work pressure, stress, and annoyance; increases fatigue; emotional exhaustion and burnout, and; difficulty in communication which potentially leads to making more errors.

The layout of a hospital can play a role in reducing noise levels by implementing the following designs (Herman Miller Inc., 2006; Joseph & Ulrich, 2007):

- Providing single-patient bedrooms: single rooms minimise noise caused by visitors, traffic, and that of care givers attending to other patients;
- Removing or reducing loud noise sources: such as washing and drying units, and other equipment and machinery that is used in caring for patients;
- Providing private rooms enclosed with walls that go up to the ceiling: the use of curtains alone is less than optimal for reducing noise transfer which is better effected through utilising solid walls;
- Enclosing examination and treatment areas with walls: similarly, noise cannot travel as well through solid walls;
- Providing private discussion areas in admitting areas as well as on the unit for private conferences with families and staff: this allows families to console one another and grieve without interrupting treatment of other patients or their recovery process;
- Increasing the distance between sound sources and people (sound intensity decreases by 6 dB every time this distance is doubled): location is key to effectively managing noise levels and must be considered prior to building a hospital; and
- Decentralising nurse stations: this disperses people which reduces the concentration of sound emanating from their activities.

3.5.5.2 Presence of windows

Studies on critical-care patients were conducted on rooms with and without windows and notable evidence of negative effects were found for the latter (Hughes *et al.*, 2008). Studies have linked the absence of windows with heightened rates of depression, anxiety, and delirium relative to rates for similar patients in rooms with windows (Joint Commission Resources, 2003). It was also found that the employees who work in rooms with nature viewing windows have less stress, better health status and higher job satisfaction.

3.5.5.3 Sunlit spaces

An investigation was conducted in a Canadian hospital with patients with severe depression and it was found that patients assigned to rooms overlooking sunny spaces had, on average, a shorter hospital stay than the patients assigned to rooms overlooking spaces in shadow/gloom (Zimring *et al.*, 2004). Another study found that the mortality numbers of patients with myocardial infarction decrease when they are assigned to rooms overlooking sunny spaces (Ulrich, 2001). A study that used questionnaires also shows that the employees prefer workplaces with window views of spaces illuminated by sunshine rather than shadows. However, rooms exposed to direct sunlight can create bright glare patches which affect patients and employees negatively.

3.5.5.4 Occupancy rate

The main argument for single rooms over multiple occupancy rooms is that the infection rates are lower (Chaudhury, Mahmood & Valente, 2004). However, the initial cost per bed for single-occupancy rooms is higher for acute care units. Some even found that multiple occupancy provide each of the patients with helpful social support (Ulrich, 2001). On the other hand, conflict among roommates can lead to costly room changes and patient moves may over the lifetime of the hospital exceed the initial construction cost advantages for multiple occupancy rooms (Calkins & Cassella, 2007). Several studies found that the presence of other patients in multiple-occupancy rooms can be a major source of stress, mainly due to a loss of privacy (Ulrich, 2001).

3.5.5.5 Supportive design

Supportive design refers to environmental characteristics that facilitate coping and restoration for the stress that accompanies illness and hospitalisation (Fischl, 2006). Supportive healthcare environments can foster gains in patient health outcomes. The following guidelines are proposed for creating supportive healthcare environments (Ulrich, 2001):

- **Foster control:** give patients a real/perceived sense that they are in control of their circumstances and determine what others do to them in order to help them deal better with stress and improve their health. Patients can feel more in control if they have, for example, sufficient information, and control over eating and sleeping times. The design of single rooms can promote this as well as improve patient safety (Hughes *et al.*, 2008). Other design approaches include providing privacy, gardens accessible to patients in wheelchairs, architectural design that promotes wayfinding in large hospitals, and privacy in imaging areas. Employees can feel a sense of control when they have comfortable break rooms and easily adjustable workstations since it allows them to briefly escape from workplace demands and stressors;
- **Foster social support:** encourage and support the presence of family and friends. This can be achieved by providing comfortable waiting areas, convenient access to rest rooms and food, attractive gardens with sitting areas that facilitate socialising with patients, and even convenient overnight accommodations; and
- **Provide access to nature and other positive distractions:** prolonged exposure to nature views can help calm patients as well as improve other health outcomes. One study found that a bedside window overlooking trees had more favourable recovery courses than patients overlooking a brick building wall. Another study found that patients have less anxiety and required fewer strong pain doses if they were exposed to a nature picture compared to no picture or an abstract picture (Kellert, Heerwagen & Mador, 2011).

3.5.6 LINKING DESIGN CONSIDERATIONS TO QUANTITATIVE METHODS

Thus far in this chapter, the qualitative design methods have been analysed, the manner in which they relate to the quantitative design methods analysed in Chapter 2 has been shown (Section 3.3), and a number of hospital design considerations have been discussed. The aim of this next section is to illustrate how the hospital design considerations relate to the quantitative methods presented in Chapter 2.

The five hospital design considerations with their corresponding measures as well as how they relate to the layout models, as discussed in Chapter 2, are shown in Table 26.

TABLE 26: LINKING HOSPITAL DESIGN MEASURES AND LAYOUT MODELS

Design objectives	**Design measures**	**Layout model**						
		Quadratic Assignment Problem	Quadratic Set Covering Problem	Linear Integer Programming Problem	Mixed Integer Programming Problem	Graph Theoretic Problem	Linear Continuous Model	Linear Mixed Integer Model
Efficiency	Optimise occupant flows	x	x	x	x		x	x
	Minimise transportation	x	x	x	x		x	x
	Minimise waiting times	x						x
	Minimise cost	x	x	x	x		x	
Flexibility and expandability	Minimise travel distances		x	x			x	x
Sustainability	Minimise costs	x	x	x	x		x	

Table 27 shows, some of the design considerations that are not part of the standard model formulations, but are included in the framework as constraints (Section 4.2.2) or can be included through additional constraints, e.g. a therapeutic environment can be promoted in a hospital by adding single rooms and private discussion areas in the layout design.

TABLE 27: INCORPORATION OF HOSPITAL DESIGN METHODS IN FRAMEWORK

Design objectives	**Design measures**	**Incorporated in framework as constraints**	Can be incorporated through additional constraints
Patient-centeredness	Variable-acuity rooms (private rooms)	x	
	Space for family members	x	
	Single occupancy rooms	x	
Efficiency	Separate patient, visitors and staff flows		x
	Design critical passing spaces		x
	Design dedicated resource corridors		x
Flexibility and expandability	Follow modular concepts		x
	Use generic room sizes	x	
	Minimise layout size	x	
	Decentralised storage	x	
Sustainability	Maximise daylighting		x

INCORPORATION OF HOSPITAL DESIGN METHODS IN FRAMEWORK (CONTINUED)

Therapeutic environment	Single occupancy rooms	x	
	Enclosed examination and treatment areas		x
	Provide private discussion areas	x	
	Design patient rooms with windows (adjacent to outside)		x
	Design patient rooms to overlook sunny spaces (correct orientation)	x	
	Multi occupancy rooms	x	
	Adjacent to gardens		x
	Staff break rooms	x	
	Provide waiting areas for family members with access to rest rooms and food	x	

3.6 Conclusion

Qualitative design methods and hospital design considerations were presented in this chapter. Links with the quantitative design methods of the previous chapter were also illustrated. Furthermore, the first steps of Muther's SLP Procedure were applied to a hospital context to generate a relationship diagram for a set of hospital departments. The key findings are summarised in the paragraphs that follow.

It was found that hospitals are classified as hybrid layouts, but the arrangement of its departments is seen as a process layout. In a process layout, organisations are organised by function and its units behave like functional silos.

Three main traditional approaches to solving the FLP were found and analysed, namely: Apple's Plant Layout Procedure, Reed's Plant Layout Procedure, and Muther's SLP Procedure. These layout procedures were found to be vague and rarely provide an optimal / near optimal solution since they are very much dependent on the designer's experience and opinion. However, it was suggested that some of the steps of Muther's SLP Procedure (a process layout tool) can be combined with a layout model analysed in Chapter 2.

An investigation was conducted into the most important design considerations applicable to hospital layouts found in literature. The results involve considerations revolving around: patient-centeredness, efficiency, flexibility and expandability, sustainability, and therapeutic environments. The way in which these considerations relate to the layout models presented in Chapter 2 is determined.

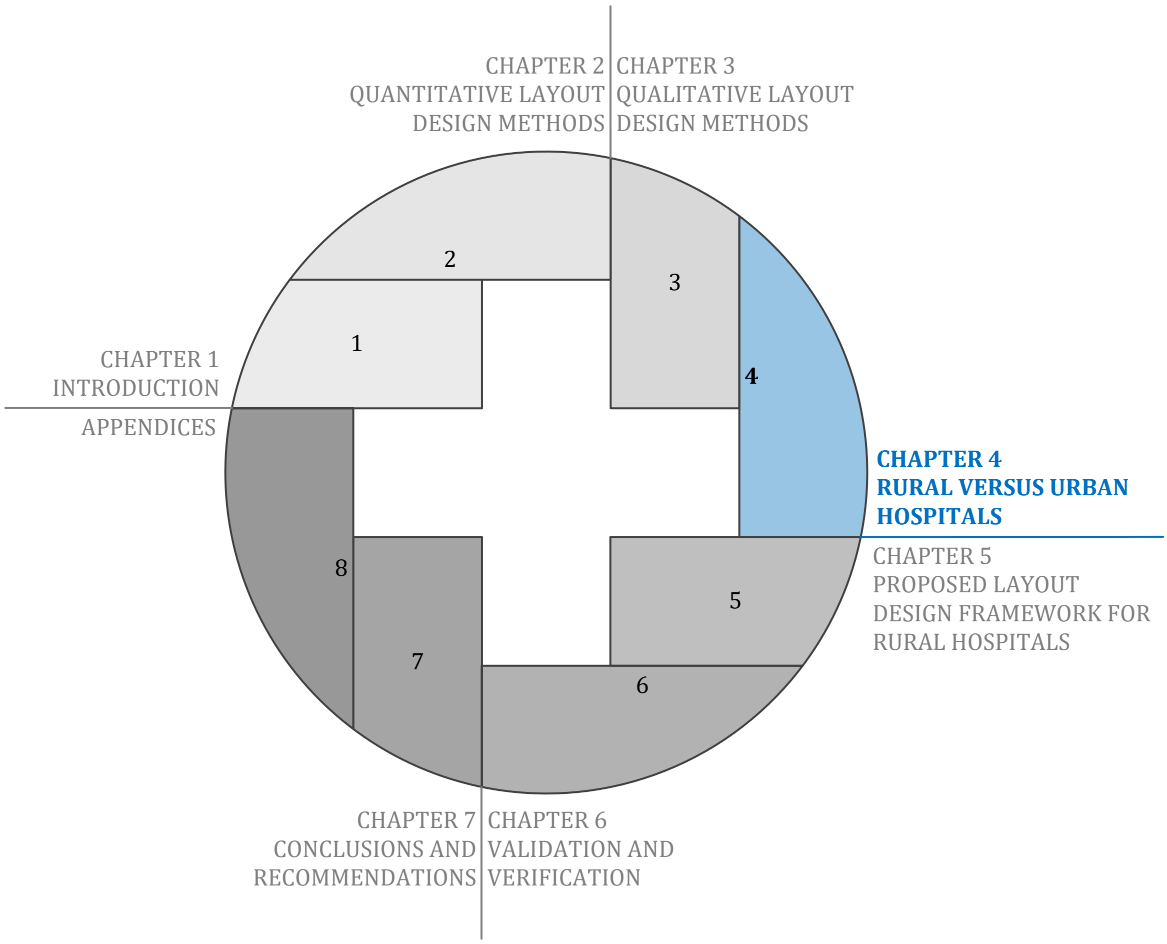
With a foundation in place regarding quantitative and qualitative layout design methods, it is now necessary to understand the context of a rural hospital. Thus, Chapter 4 investigates the differences and similarities between urban and rural hospitals, including the numerous constraints applicable to the various hospital rooms.

CHAPTER 4

RURAL VERSUS URBAN HOSPITALS

"The all-pervading disease of the modern world is the total imbalance between city and countryside, an imbalance in terms of wealth, power, culture, attraction and hope. The former has become over-extended and the latter has atrophied. The city has become the universal magnet, while rural life has lost its savour."

Schumacher (2000)



4.1 Introduction

In this chapter, the differences and similarities between rural and urban hospitals are investigated. Rural and urban communities differ from one another in certain aspects, for example: resource availability, access to medical care, and rural specific illnesses and attitudes towards health. The question is one of whether this influences the needs of a hospital layout for a rural community. To answer this question a comparison is made between the two types of hospital settings, and thereafter deductions are made regarding the implications for the floor layout. The main objectives of a rural hospital layout are identified.

In order to design a hospital that is suitable to serve a rural community, it is important to understand the health needs and challenges specific to rural areas whilst also drawing from the regulations and standards common to both urban and rural hospitals, as shown in the chapter structure of Figure 19.

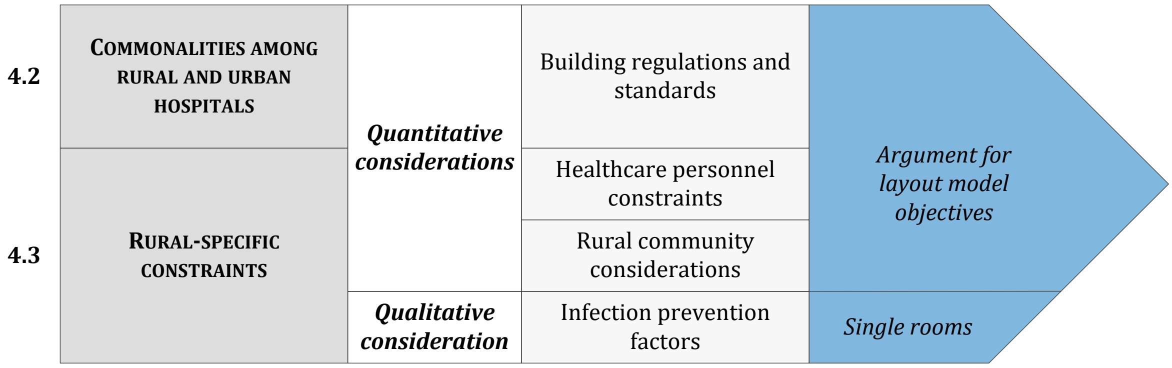


FIGURE 19 RURAL VERSUS URBAN COMPARISON STRUCTURE AND OBJECTIVES

Before investigating rural hospitals, it is necessary to discern what a rural hospital is. Alternative terms found in literature for a rural hospital are 'district hospital', 'community hospital,' and 'general hospital' (Jamison, Breman, Measham, Alleyne, Claeson, Evans, Mills & Musgrove, 2006). Hospitals can be divided into three levels, and rural hospitals fall under the first level, i.e. primary-level hospital care (discussed in Section 1.7). This means there are oftentimes only limited laboratory services available for pathological analysis, and few specialists, with the most typical ones providing internal medicine, obstetrics, paediatrics, and general surgery (Jamison *et al.*, 2006).

4.2 Commonalities among rural and urban hospitals

Rural hospitals and urban hospitals have many similarities regarding general building constraints, such as the National Building Standards Act of 1977, the South African National Standard 10400, Regulation 158 of the South African law, and hospital adherence rules which are governed by the National Core Standards. Each of these will be unpacked in the following sections, so as to better understand the basic premises on which buildings layouts (both rural and urban) are structured.

4.2.1 General building constraints

All buildings in South Africa are required to adhere to the National Building Standards Act 1977. According to Section s. AZ4, 1(b) of this act, all buildings also need to comply with the requirements of the relevant part of the South African National Standard 10400.

The National Buildings Standards Act 1977 s. C1, 1 requires that each room or space of any building should have dimensions that will ensure that said room or space is fit for the purpose for which it is intended. The minimum dimensions for each department and facility of a hospital are laid out in Regulation 158 and will be taken into account in the next section.

The National Buildings Act 1977 Section s. S1, 1 requires that facilities must accommodate persons with disabilities. This has an effect on the hospital layout in terms of necessary aisle widths and the design of bathroom facilities.

4.2.2 Hospital layout constraints

Hospitals have specific constraints that they need to adhere to, e.g. certain departments and rooms are compulsory. Each department and room also needs to be bigger than a certain size according to a set criterion. Therefore, this section examines the minimum area for each hospital room according to the size of the hospital (i.e. number of hospital beds) as well as determine which rooms and departments are optional. According to the Department of Health (2002), district hospitals usually have between 30 and 200 beds. The Department of Health is the custodian of healthcare in South Africa regarding care delivered at either public or private healthcare facilities. However, the responsibility is entrusted to the provincial departments.

According to De Jager (2011), the Regulations Governing Private Hospitals and Unattached Operating Theatre Units (otherwise known as Regulation 158, or more succinctly R158) are still in use for governing the design and operations of hospitals in South Africa, having been developed in 1980 and last updated in 1993. The Western Cape developed and gazetted their provincial regulations, R187 in 2001 and modified it in 2003. The Eastern Cape and Gauteng both prepared draft provincial regulations, but neither have been finalised or formally approved. According to Baloyi (2011) those developed by Gauteng appear to be the most comprehensive and it is proposed that these be accepted as a discussion document and put out for comment with a view to being developed for national use. Since the provincial standards are not accepted as the national standards yet, this study will focus on the requirements set out in R158.

Therefore, all the constraints of the R158 were analysed first. However, this document does not specify or recommend all the sizes of each room, for which reason additional regulations were incorporated, including constraints provided by the KwaZulu-Natal Department of Health (2010), as well as constraints that are clearly set out in other countries (e.g. Scotland and the United Arab Emirates).

Additionally, articles, books, and industrial norms were researched. Appendix A provides a detailed outline of this analysis. The minimum dimensions for each room are shown, as well as the relevant references and information regarding which rooms are optional. The following hospital departments were analysed: Administration, Obstetrics, Operating Suite, Paediatric Unit, Laundry, Kitchen, Sterilisation and Disinfection Unit, Pharmacy, Emergency and Casualty Unit, Acute Psychiatric Facility, Chronic Care Unit, Rehabilitation Unit, Mortuary, Laboratory, Radiology, Neonatal Intensive Care Unit, Intensive Care Unit, and High Care Unit.

4.2.3 ADHERENCE TO STANDARDS

National Department of Health developed the National Health Insurance (NHI) policy in order to improve health. The NHI aims to ensure that everyone has access to quality healthcare regardless of their socio-economic status. This will lead to changes in management systems, service delivery and administrative systems. In preparation for implementation of the NHI, service delivery in South African healthcare facilities needs improvement. Thus a national quality assurance program called the National Core Standards (NCS) was launched to drive facility improvements and serve as a benchmark for quality. All South African facilities, both in the private and public sectors, shall be required to comply with these standards in 2025 (National Department of Health, 2011:3b).

The NCS is divided into seven structured domains, namely: patient rights, patient safety and clinical governance, clinical support services, public health, leadership and corporate governance, operational management, and facilities and infrastructure. The seventh domain (facilities and infrastructure) of the NCS is relevant to this study and is included in Appendix B as well as its sub-domains and corresponding standards and criteria. This domain covers the requirements for clean, safe and secure physical infrastructure, hotel services and effective waste disposal. The remainder of the standards do not pertain to the construction of the hospital nor its layout, but rather the functioning of it.

Standard 7.1.3 requires that waiting areas are convenient and provide adequate shelter and seating for patients. The corresponding criterion 7.1.3.1 states that the waiting areas should be appropriately located and adequate for the number of patients using them. Therefore, for areas of the layout where queues will most likely form, waiting areas should be provided.

Standard 7.5.1 requires that waste management in the health establishment complies with legal requirements, national standards, and good practice. With regards to the hospital layout, waste management is taken into account in Section 4.1.2 by including waste room(s) in the layout. Other necessary rooms included are linen and laundry services of Standard 6.6.1 and food services of Standard 7.7.1.

4.3 Rural-specific constraints

Rural and urban lifestyles, health, and illnesses differ in many ways. According to Wainer and Chesters (2000), the negative factors associated with rural lifestyles include: social stresses, exacting behavioural norms expected within the community, limited modes of transportation and its low availability resulting in high travel costs, and limited work opportunities leading to unemployment and poverty. Furthermore, the rural environment is characterised by distance, specific occupational hazards, uncontrolled environments, sparse infrastructure, and risk taking attitudes towards health, illness and behaviour (Humphreys, 1998). Rural inhabitants are not protected against adverse conditions and circumstances (e.g. droughts, fires, floods, and recessions) as are urbanites (Wainer & Chesters, 2000). The aim of this section is thus to identify hospital layout design objectives that are specific to rural communities.

4.3.1 HEALTHCARE PERSONNEL CONSTRAINTS

One vital resource which affects the manner in which a hospital's departments must be arranged pertains to the number of healthcare personnel assigned to the hospital. Healthcare personnel scarcity in rural regions impacts the flow requirements of the establishment. Furthermore, due to rural communities typically being deep in poverty, their ability to pay for basic procedures, never mind advanced ones, determines to a large extent the types of facilities necessary, as some will quite simply never be used, thus having an impact on which rooms are necessary.

According to the National Department of Health (2011), 43.6% of South Africa's population live in rural areas. The latest provincial rural population percentage breakdown is given by Kok and Collison (2006) as shown in Table 28. The percentage medical scheme coverage of each province as estimated in 2011 by the South African Health Review (2013) is also shown in Table 28. It is clear that the majority of South Africans do not have a medical aid plan, regardless of whether they live in rural or urban areas. However, it is also evident that the more rural provinces (e.g. Limpopo) exhibit even lower coverage than more urban ones. The reason for these low statistics may be due to the average South African's lack of financial security.

TABLE 28: RURAL POPULATION SIZE AND THE CORRESPONDING MEDICAL SCHEME COVERAGE OF PROVINCES IN SOUTH AFRICA ADAPTED FROM NATIONAL DEPARTMENT OF HEALTH (2011)

Measurement	Eastern Cape	Free state	Gauteng	KwaZulu-Natal	Limpopo	Mpumalanga	Northern Cape	North West	Western Cape	South Africa
Rural population (%)	62	25	4	55	90	61	20	59	10	42
Medical scheme coverage (%)	10.5	14.4	27.3	12.1	7.9	15.9	16.6	15.4	24.7	16.9

According to Wits Centre for Rural Health Strategy (2008), the provinces with the highest percentage of rural inhabitants have the lowest number of medical practitioners per capita. This finding is supported by Table 29 which shows the public as well as private medical practitioner count per 100,000 people in 2011. Table 29 further indicates that the total number of healthcare personnel (i.e. human resources for health, or HRH) per 100,000 people in 2010 (with the exception of the North West) was substantially lower in the more rural provinces. The 2008 South African Democratic and Health Survey showed that this scarcity of nurses is more prominent in rural areas (Eygelaar & Stellenberg, 2012). This scarcity of healthcare personnel changes the dynamics of how best these personnel might be aided by the correct hospital layout, i.e. to maximize flow. According to the National Department of Health (2011), the rural population in South Africa (43.6% of the national population) is served by only 12% of the doctors and 19% of the nurses.

TABLE 29: HUMAN RESOURCES AND MEDICAL PRACTITIONERS PER PROVINCE IN SOUTH AFRICA ADAPTED FROM NATIONAL DEPARTMENT OF HEALTH (2011)

Measurement	Eastern Cape	Free state	Gauteng	KwaZulu-Natal	Limpopo	Mpumalanga	Northern Cape	North West	Western Cape	South Africa
Total human resources for health per 100,000 population per province in 2010	448	520	692	588	488	452	555	331	741	557
Public medical practitioners per 100,000 population in 2011	29.7	30.0	40.2	46.9	26.8	31.6	53.9	23.0	45.2	36.6
Private medical practitioners per 100,000 population in 2011	17.7	31.0	73.2	29.3	9.7	21.1	19.7	23.7	76.4	37.6

On average, about 1,200 medical students graduate each year in South Africa and less than 3% of these continue to work in rural areas in the long run. According to the National Department of Health (2011), the factors which affect the lack of healthcare professionals working in rural areas include the following: decreased funding, poor social infrastructure, fear of safety, lack of work opportunities for spouses of health workers, deficiencies in infrastructure, lack of opportunities for schooling children, and lack of commensurate compensation for dealing with these negative factors. Eygelaar and Stellenberg (2012) argue that the main barriers to receiving adequate medical care in rural areas are: the remoteness of such communities (distance to them), the high costs to access them, and problems with accessing, supporting, and relieving qualified hospital staff.

An additional problem is that some healthcare professionals do not report for their Community Service (CS). 'Community service' in this context refers to a requirement of health professionals to complete one year of practice in the public sector following their graduation. A survey by the National Department of Health (2009) reported that 17% of health professionals did not report for CS and a further 6.1% reported that they would emigrate after completing their CS. This amounts to roughly

23% of health professionals planning to leave South Africa. According to the NHI Policy Proposal (2009) the number of medical graduates entering into CS has decreased by 73.5% between 1999 and 2008 (from 1,112 to 295 per annum). This shortage of staff results in those who remain having even more arduous working conditions to deal with, as well as the accompanying stress of it all (Wits Centre for Rural Health Strategy, 2008). Several initiatives have been introduced to alleviate HRH shortages, such as the rural and scarce skills allowances, CS, and the Occupational Specific Dispensation. Therefore, it is of great importance that the design of a hospital layout is optimal, such that it enables efficient running and utilisation of its HRH resources.

This dwindling number of healthcare staff in rural hospitals results in a high workload and an extremely stressful work environment which subsequently leads to long patient queues and overworked staff. Therefore, optimal usage of the medical practitioners is critical and efficiency is thus an important design consideration. In other words, it is important to optimise objectives such as hospital flow and travel time within the hospital.

4.3.2 RURAL COMMUNITY CONSIDERATIONS

Rural-specific challenges include gaining access to medical care, dealing with rural-specific illnesses, and lax attitudes towards health. These are discussed in this section and are shown as a cause and effect diagram in Figure 20.

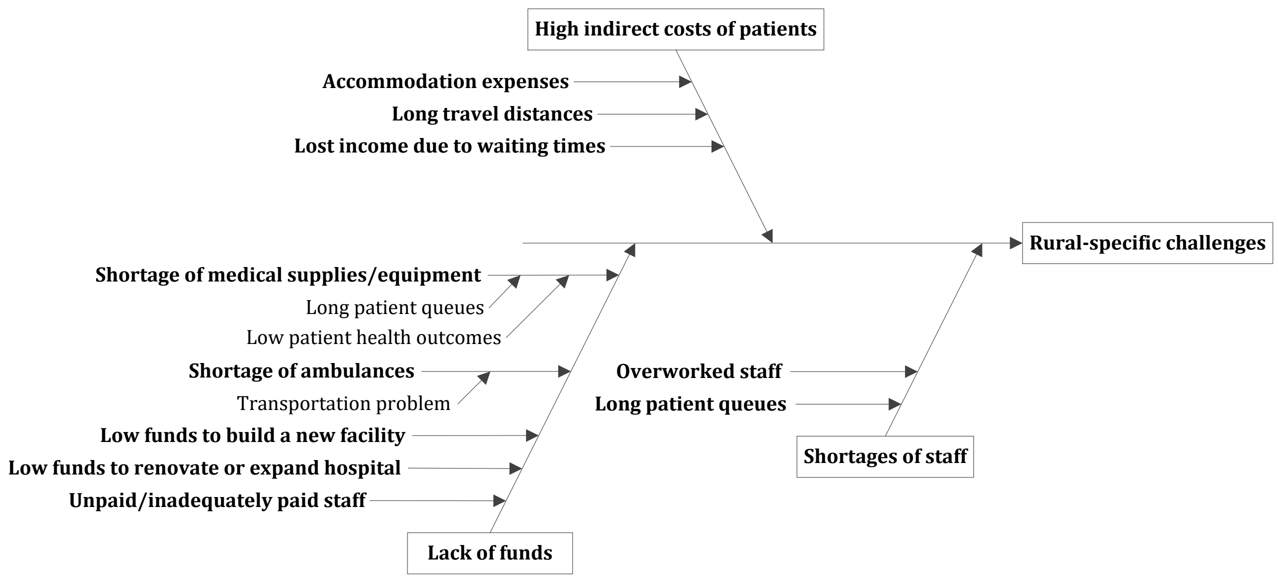


FIGURE 20: CAUSE AND EFFECT DIAGRAM OF RURAL-SPECIFIC CHALLENGES FACED BY RURAL COMMUNITIES

4.3.2.1 Access to medical care

According to the South African Constitution (1996), Section 27, "*every person has the right to access health services.*" More than 16.6% (5.2 million) people in South Africa experience difficulties in accessing healthcare and those most deprived are the rural communities (Shisana, 2007). Rural communities often do not make use of the nearest hospital and this could be due to the fact that access to healthcare is generally costly and inconvenient (National Department of Health, 2011). For example, the cost of traveling, paying for accommodation, time away from work and family, and operating hours of medical facilities play a role in this. This is exacerbated by the fact that due to limited healthcare personnel in rural areas the doctor is not always present when and if a patient makes their way to the hospital. The biggest of these challenges is that rural residents must travel greater distances in order to receive the necessary medical care which usually includes high indirect costs (e.g. bus tickets, accommodation). According to Goudge (2009), poor rural households in Limpopo spend up to 80% of their monthly income on health related costs. Although outside the scope of this study, giving consideration to choosing a hospital location which minimises the travelling distance for rural communities could make a significant impact on the health status of rural communities.

These challenges to accessing a healthcare facility often lead to healthcare needs being met by private alternatives. There is some evidence that suggests illegal health clinics often operate in townships and that people are prepared to pay for such services despite the obvious risks (Coetzer & Pascarel, 2012).

Hand in hand with higher levels of poverty come lower levels of health in rural communities when compared to urban communities (National Department of Health, 2011). According to the SAHRC (2007), poverty has long been recognized as a major cause of ill-health and acts as a barrier to accessing healthcare services. From Table 30 it can be seen that the three most rural provinces have the highest labour force unemployment rates (for those aged 15-64 years old). Jobs in rural settings are often physically strenuous in nature, e.g. farming, fishing, forestry, mining, and manufacturing (Strong & Elliot-Schmidt, 1997). Such professions are naturally linked to more severe health and safety hazards as a result of longer working hours, lack of enforcement of safety measures, and usage of makeshift tools. This results in a heightened frequency of work related injuries.

TABLE 30: UNEMPLOYMENT RATES AND CHILDREN LIVING IN POVERTY

Measurement	Eastern Cape	Free state	Gauteng	KwaZulu-Natal	Limpopo	Mpumalanga	Northern Cape	North West	Western Cape	South Africa
Unemployment rates for labour force aged 15-64 from Census 2011 (Statistics SA, 2013)	37%	33%	26%	33%	39%	32%	27%	32%	22%	30%
Number of children in millions under 18 (General Household Survey, 2011)	2.7	1.1	3.3	4.2	2.2	1.5	0.4	1.3	1.8	18.5
Percentage of children living in income poverty (General Household Survey, 2011)*	74%	59%	34%	67%	76%	57%	63%	64%	31%	58%
Percentage of children living in households without an employed adult (General Household Survey 2011)	51%	35%	16%	43%	50%	29%	42%	37%	14%	35%

*Income poverty: Households with a monthly income per capita less than R604 in 2011

Poverty also affects the ability of a healthcare facility to operate and deliver quality healthcare services. This lack of funds on the part of patients may in turn cause a shortage in medical supplies and equipment, a shortage of ambulances, low funds to maintain the infrastructure, and unpaid or inadequately paid healthcare staff.

According to Children's Gauge (2013), the percentage of young children (those under 16 years of age) living in rural areas is as high as 45% and as Table 30 shows, most of the children live in poverty stricken households, i.e. households that exhibit income poverty meaning they have an equivalent monthly income per capita of less than what R604 could buy in 2011. This high incidence of children influences the need for crèches and facilities to look after not only unhealthy children but also those that are too young to be left at home while a parent or guardian is confined to the hospital.

Another issue is that residents lose their income as a result of waiting in queues for many hours (sometimes even days) at healthcare facilities (Coetzer & Pascarel, 2012). In general, it appears that access to financial capital in general is a problem faced by the rural communities especially in the provinces with larger rural populations. In addition, the three most rural provinces have the highest unemployment rates as well as the highest percentages of young children to care for. For these reasons, lack of access to financial capital and high indirect costs are major concerns for rural communities.

4.3.2.2 Rural-specific illnesses

In the South African context, the burden of some chronic conditions such as diabetes is evenly distributed across socio-economic groups, whilst others such as HIV/AIDS, Tuberculosis, depression, STD, and diarrhoea have a substantially greater negative impact on lower income groups (Statistics SA, 2013).

Personal health choices such as diet and cleanliness impact the life expectancy of residents. Rural residents are less likely to have health problems related to poor air quality or crime. The Australian Institute of Health and Welfare (2005) found a significant difference in that residents outside major cities are more likely to have the following health problems: coronary heart disease and circulatory disease, chronic obstructive pulmonary disease, type 2 diabetes, asthma, infectious diseases, poor dental and oral health, disabilities, and prostate and colorectal cancer. Zithulele Hospital, a rural hospital in the Eastern Cape of South Africa, identified four priority areas that cause the majority of disease, suffering and even disability in the rural community (Jabulani Rural Health Foundation, 2014). As would be expected, the main areas are HIV/AIDS, Tuberculosis (TB), maternity related infections, and child sicknesses.

HIV/AIDS is a prominent health concern in South Africa which has the highest prevalence of HIV compared to any other country in the world with 5,6 million people living with HIV and 270,000 HIV related deaths recorded in 2011 alone (AIDS Foundation of South Africa, 2014). Districts with the highest rates of HIV infection have been shown to be rural ones yet again (The South African Health News Service, 2012).

TB and HIV/AIDS are very closely connected in that their relationship is often described as a co-epidemic (International Federation of Red Cross and Red Crescent Societies, 2015). At least one-third of the 3.8 million HIV-positive people in the world are also infected with TB (Rodriguez, 2009). Poverty and poor access to healthcare challenges the successful treatment of those affected by TB. TB is a highly contagious bacterial infection that is transmitted through the air. Therefore, it is of importance to adequately isolate or provide for the prevention of spreading this infection. Since TB is such a contagious disease and accounts for many deaths in rural communities, reducing the spread of the disease inside the hospital is an important consideration. Additionally, there exist many other infections that are spread inside hospitals. In Chapter 3 it was found that single rooms in a hospital can limit the transmission of infections to other patients and it would be wise to have at least enough single rooms to isolate these patients.

Infant mortality rates in South Africa are six times higher than that of other Organisation for Economic Co-operation and Development (OECD) countries. The infant mortality rate is 32.6 in urban areas compared to 52.6 on average in rural areas, whilst in some rural areas the infant mortality is as high as 70.1 (National Department of Health, 2011).

Additionally, rural communities typically have higher rates of mental health disorders too (Fact sheet rural health, 2013). They are prone to both social and economic disadvantages which are also seen as high risk factors for depression. High morbidity and mortality rates in poor rural communities also heighten risk factors for mental disorders such as anxiety and depression. Bad rural mental health is a handicap to rural development since it places a huge socio-economic burden on poor resource strapped communities. A leading cause of the neglect of mental health in rural areas is the difficulty associated with defining these mental disorders (unlike physical conditions) (Kanda, 2013). This is one of the reasons that the Psychiatry department is essential for district hospitals (refer to R158).

Therefore, it appears that rural areas have specific healthcare needs which differ from urban communities. For this reason, it is necessary to allow the designer of a hospital to change the hospital layout and rooms according to the healthcare needs, e.g. if TB is the most common illness in a community over a prolonged period of time, it may be beneficial to design the hospital in a way that accommodates many TB-patients.

4.3.2.3 Attitudes towards health

Attitudes to health and illness generally differ between urban and rural communities, according to Strong and Elliot-Schmidt (1997). The detrimental nature of illnesses and disabilities in urban communities is mainly attributed to discomfort from pain or negativity regarding loss of cosmetic attractiveness and ability to live a full life. However, for rural communities the response to disabilities or illnesses is often related to the degree with which the disability or illness impacts their productivity negatively.

According to Strong and Elliot-Schmidt (1997), rural inhabitants exhibit the perception that if their health diminishing condition is not life-threatening then visiting the hospital may as well be postponed until an appointment can be fit into his/her routine (which more often than not delays treatment indefinitely). These perspectives compound their health-negating behaviours. Rural communities value independence and self-reliance much more than their urban counterparts (Gessert, Waring, Bailey-Davis, Conway, Roberts & Van Wormer, 2015). Recently this has been supported by the high death toll in the Eastern Cape whereby young men during cultural initiation rituals enlisted unqualified traditional doctors to perform operations on them whereby infections resulted in their deaths (Bullock, 2015; Makinana, 2015).

In terms of the impact that rural communities attitudes have on hospital floor layouts, it only acts so as to reinforce the argument for facilities which allow multiple operations to be conducted in a short period of time. Therefore, the flow rate is again seen as a crucial factor in organising the floor layout.

4.4 Floor layout implications

In the previous section it was found that the main healthcare challenges faced by rural communities include a lack of funds, high indirect costs of patients, and shortages of healthcare staff. But the question is one of how this relates to the layout of a hospital.

When one considers the lack of funds available to operate or maintain a hospital, it would make sense to minimise costs. Therefore, minimising costs is identified as one of the hospital design objectives specific to rural hospitals. It is important to understand the different types of 'cost' involved in a hospital. Consider the variables used in Chapter 2 to design a hospital layout: γ_{ij}, c_{ij}, and b_{ijkl}. The variable γ_{ij} refers to the cost of locating and operating department i at location j. The variable b_{ijkl} is the monetary term of locating department i at location j. The variables γ_{ij} and b_{ijkl} are not dependent on the position of the department within the hospital, and therefore do not need to be optimised when designing the layout. The variable c_{ij} refers to the cost of transporting a patient between departments. In a factory setting, transportation using conveyor belts or pallet jacks will be relatively easy to identify and calculate. However, in a hospital setting this is not very straightforward. Patients are often accompanied when being transported between hospital departments by nurses or doctors which takes time away from their work, e.g. mechanically ventilated patients should be accompanied by a critical care nurse as well as a doctor. Therefore, transportation costs can possibly be determined as a segment of staff salary (Branson & Blakeman, 2013). However, this data is difficult to generate and it is only available after building the hospital which is not available when designing a hospital layout. Another approach is to calculate transportation costs is using the product of distance and flow between two departments (Bidyarthy, 2012). This appears to be the best explanation for transportation cost and will be used from this point onwards. The variable c_{ij} is thus dependent on the layout of the hospital.

On the other hand, high indirect costs incurred by patients due to accommodation expenses, long travel distances, and lost income due to waiting times in inter-hospital (external to the hospital) expenses, do not influence the sizes of hospital rooms or where each hospital department is located. Therefore, it cannot be one of the hospital design objectives. Nevertheless, this problem can be addressed by making public transport available for rural communities.

Shortages of staff as the result of long patient queues and overworked staff suggests that efficiency, i.e. patient flow, should be optimised. This forms the second hospital design objective specific to rural hospitals. Additionally, resources can be optimised by identifying the bottlenecks (usually identified as the doctors) in the system, and reducing them. This however is not in the scope of this study, but it is recommended to apply the popular industrial engineering concept of Theory of Constraints to remove such bottlenecks.

Lastly, it is clear that rural communities have different health needs to urban communities and for this reason it is important that the user of the framework developed in this study, is able to change the layout accordingly.

4.5 Conclusion

This chapter investigated the differences and similarities between urban and rural hospitals, including the numerous constraints applicable to the various hospital rooms. The key findings are summarised in the paragraphs that follow.

The most important standards and regulations associated with hospital design pertaining to the floor layout were found to be the National Core Standards and Regulations 158. Using these regulations and others found in literature, the minimum room sizes and departments of a district hospital were identified.

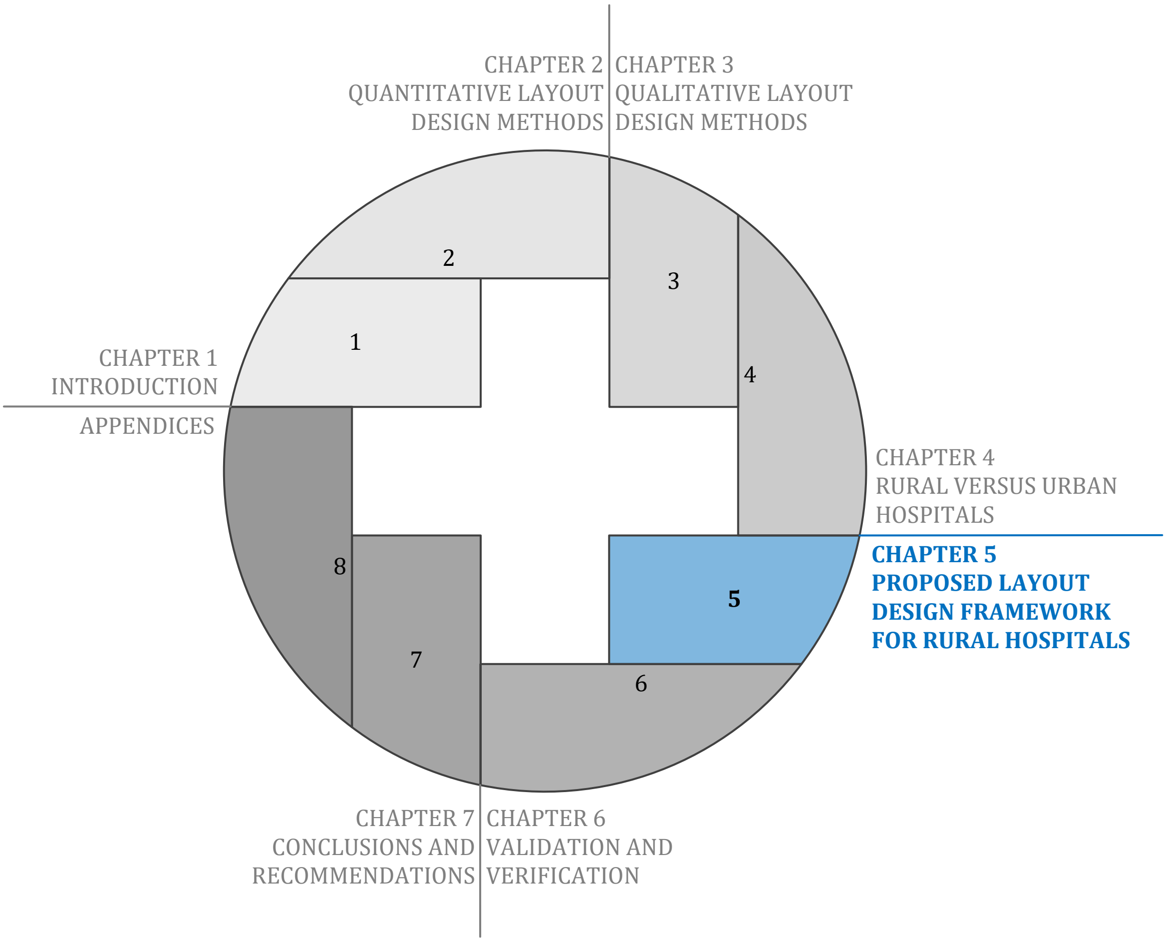
After this, the specific difficulties faced in rural settings were deliberated upon to arrive at what appears to be the most important considerations for the layouts of rural hospitals: minimise costs and patient flow through the hospital. Furthermore, it was found that infection prevention is an important consideration and single rooms should therefore be incorporated in the framework where possible.

Chapter 5 develops the layout design framework specifically tailored to rural hospitals.

CHAPTER 5

PROPOSED LAYOUT DESIGN FRAMEWORK FOR RURAL HOSPITALS

"Consequently, any discussion (including this one) can only be a partial description of possibilities, but a review of several major interpretive frameworks can provide a sense of options."



Creswell (2008)

5.1 Introduction

In Chapters 2 and 3, quantitative and qualitative methods for designing the layout of facilities and hospitals were discussed respectively. In this chapter these two methods are integrated. More specifically, a suitable layout model is chosen and adapted to accurately represent the real world problem while taking into consideration the needs and specific challenges of rural communities as discussed in Chapter 4. The assessment of model objectives, assumptions, inputs, and outputs as well as qualitative design considerations are used as criteria. Consequently, an adequate solution method to optimise the chosen model is selected. Lastly, the generic rural layout design framework is developed using Excel VBA, and RStudio.

5.2 Integration of quantitative and qualitative methods

As this study employs a mixed methods strategy, determining whether it is possible to integrate the quantitative and qualitative methods with one other, and how to do this, is necessary. The quantitative methods research in this study involves layout models, each exhibiting an objective function, a set of constraints, inputs, and outputs. The qualitative methods involve a relationship diagram illustrating the functional interaction of each hospital department. Furthermore, the main hospital design considerations were identified and linked to quantitative methods (see Section 3.4.6). These considerations will be incorporated as criteria for selecting the most adequate layout model (see Section 5.5.5).

A possible way to integrate the quantitative and qualitative methods is to use the results of the qualitative methods (resulting relationship diagram) as an input for the quantitative methods. This is a known mixed method phenomenon called embedding (otherwise known as a concurrent embedded strategy). Embedding has a primary method guiding the project and a secondary database that plays a supporting role in the procedures (Creswell & Clark, 2009). This typically means that the secondary method and primary method addresses different questions or seeks information at a different level of analysis. This type of research is ideal for the researcher to gain broader perspectives as a result of using different methods. In this study, the primarily qualitative data are used to aid the quantitative study and to represent the real world problem more accurately. The integration of these two methods is discussed in more detail in Section 5.5.7.

Since this research develops a conceptual framework, it forms part of concurrent transformative methodology. The transformative approach is guided by the researcher's use of a specific theoretical perspective based on ideologies such as a conceptual framework, critical theory, advocacy, or participatory research (Creswell, 2015). This perspective is reflected in the research objectives and aims discussed in Section 1.3. According to Clark and Ivankova (2015) the concurrent transformative model may take on the design features of an embedded approach. Therefore, this thesis follows a concurrent transformative research approach with embedded design features (embedding the data). This type of research has the advantage of positioning mixed methods research within a transformative framework (Creswell & Clark, 2009).

5.3 Theoretical framework definition

Theoretical or conceptual frameworks can be compared to maps (Dewey, 2013). Maps are problem-solving tools that help the user navigate through experiences. Maps represent an abstract form of reality and when accurate, they enable navigation within that reality (Shields & Tajalli, 2006). Dewey further points out that due to the fact that problems are constantly changing conceptual tools are required to be constantly refashioned so as to meet new demands.

Jabareen (2009) clearly defines a theoretical framework as "*a network, or 'a plane,' of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena. The concepts that constitute a conceptual framework support one another, articulate their respective phenomena, and establish a framework-specific philosophy.*"

It is worthwhile understanding the difference between models and frameworks. Ilott, Gerrish, Laker and Bray (2013:1) distinguish between the two by saying that frameworks "*are descriptive, showing relevant concepts and how they relate to each other*" whereas models tend to be more "*prescriptive, specific and with a narrow scope*."

Frameworks can be classified into five types (Shields & Tajalli, 2006; Shields, 1998):

- **Working hypothesis:** exploration or exploratory research;
- **Descriptive categories:** description or descriptive research;
- **Practical ideal type:** analysis (gauging);
- **Models of operations research:** decision making; and
- **Formal hypothesis:** explanation and prediction.

The purpose of the framework developed in this study is to guide or help a user (likely the architect or hospital planner) in making decisions regarding the layout of a rural hospital, e.g. where to place each department, how big each department should be, what the approximate cost of the design will be, etc. Therefore, it is clear that what needs to be developed is a decision making framework. To do this, 'models of operations research' are used to determine what the best layout for a rural hospital in a specific context is. The purpose is to guide the user in making decisions and not to replace him/her.

5.4 Real world problem

As discussed in Chapter 1, the real world problem involves designing the optimal layout of a rural hospital. Decisions need to be made about which departments to include, what size each department should be and where each department should be positioned. The proposed rural hospital design technique will integrate quantitative as well as qualitative design methods, and will be presented in the form of a block layout.

In Chapter 4, the needs and specific challenges of rural communities were discussed. It was found that the main problems regarding healthcare faced by these communities include a lack of funds, high indirect costs to patients, and shortages of healthcare staff. These problems form the objectives of the real world problem. However, the layout of a hospital cannot influence all of these problems as discussed in Section 5.4.1.

The real world problem also involves the following decisions:

- The floor space used for hospital corridors;
- The departments to include;
- The location of each department's centre;
- The number of beds in each department;
- The number of beds in the hospital;
- The rooms to include in each department;
- The size of each department;
- The size of each room within each department; and
- Which departments should and should not be placed in close proximity to each other.

5.5 Selection of layout model

A layout model is proposed that is most suited to represent the real world problem based on layout objectives, assumptions, inputs, outputs, and design considerations. Values of 1, 0, -1, and -M will be rewarded for each layout model's objective, assumption, input, and design consideration according to how well it represents the real world problem. A value of 1 indicates an accurate, valid representation, a value of 0 shows a neutral representation, -1 indicates an inaccurate representation, and –M (where M is a large positive number) shows that the model should not be chosen to represent the real world problem. In Section 5.5.6 all these awarded values are compared, surmised, and the most adequate model is selected. Lastly, necessary adjustments are made to this model.

5.5.1 ANALYSIS OF LAYOUT MODEL OBJECTIVES

This section analyses and compares the objectives of a rural hospital layout, and the objectives of the layout models discussed in Chapter 2.

5.5.1.1 Real world problem

The purpose of any hospital is clearly to optimise the health outcomes of the surrounding community, namely to deliver high quality services to as many people as possible. If one assumes that the quality of services stay constant, the aim should be to maximise the number of patients that go through the hospital over a certain period (known as throughput). Throughput is defined by Business Dictionary (2016) as *"the productivity of a machine, procedure, process, or system over a unit period."* In this case the number of patients that are either cured, referred, treated, or passed away minus the number of patients that enter the hospital seeking treatment measured over a specific period.

However, it is also important to differentiate between the objective(s) of a hospital as a whole and the objective(s) of a hospital layout**.** The hospital layout has a limited influence, e.g. it can influence the travelling time/distance of patients between departments, but not the operating costs or building costs of hospital departments (assuming that it is a single floor layout as discussed in Chapter 1). Building costs stay constant regardless of the position of a department relative to another. The travelling time/distance can be influenced by each department's position. Patients will always visit hospital departments in a certain order regardless of each department's location, as seen in Figure 19 of Chapter 3. Since the goal of this study is to maximise throughput, it is necessary to maximise the number of patients that pass through the hospital.

This point was confirmed in Chapter 4 by concluding that the objective of designing the layout of a district hospital is primarily to optimise flow or cost (product of distance and flow). However, patient flow is not a variable one can influence directly since it is an input to the layout models. But what can be controlled is the distance between departments and arrangement in which they are located. Varying corridor widths to improve flow is hardly ever a solution to improve flow since corridors are designed according to national regulations. Logically, when deciding upon the objective of a layout, one needs to link flow (flow rate) to the location of each department since a decision needs to be made as to where to locate each department. This can be accomplished by optimising the material handling costs as discussed in Chapter 2.

5.5.1.2 Layout model objectives

Some popular layout models found in literature for the FLP were discussed in Chapter 2. The main objective in each of these models is singular, as shown in Table 31. Some researchers have considered multi-objectives to solve the FLP. For example, Dweiri and Meier (1996) formulated a FLP that simultaneously minimises the material handling flow with the equipment flow and the information flow. Other authors combine different objectives into a single one by means of an Analytic Hierarchy Process methodology (Yang & Kuo, 2003), or by using a linear combination of the different objectives (Chen & Sha, 2005). The Analytic Hierarchy Process methodology is a very useful aid in decision making of problems involving multiple criteria. Since the objective of the real world problem is to optimise material handling cost, a single objective model will be chosen and multi-objective models will not be investigated.

TABLE 31: ANALYSIS OF LAYOUT MODELS' OBJECTIVES

Layout model	**Model objective**	**Variable(s) related to flow**	**Objective function**	**F**
Quadratic Assignment Problem	Minimise total cost	f_{ik}, c_{ij}	Flow x transportation cost	1
Quadratic Set Covering Problem	Minimise fixed cost and/or flow	f_{ik}, d_{jl}	Flow x distance	1
Linear Integer Programming Problem	Minimise total cost	f_{ik}	Flow x transportation cost	1
Mixed Integer Programming Problem	Minimise total cost	f_{ik}, c_{ij}	Flow x transportation cost	1
Graph Theoretic Problem	Maximise a closeness rating measure	-	Closeness ratings	1
Linear Continuous Model	Minimise transportation cost	α_{ij}, c_{ij}	Transportation cost x frequency x distance	1
Linear Mixed Integer Model	Minimise total traveling time	α_{ij}, t_{ij}	Time x frequency x distance	1

Six of the seven layout models as shown in Table 31 aim to optimise material handling costs which correspond to the objective of the real world problem. The GTP aims to optimise a closeness rating which is based on the desirable adjacency of each pair of facilities. This can theoretically also be based on material handling cost and is therefore also deemed an adequate model according to its objective.

The objective function of the QSCP consists of two terms that do not have the same units. The parameter theta is incorporated which may be varied in order to test different conversion rules.

5.5.2 ANALYSIS OF LAYOUT MODEL ASSUMPTIONS

The following assumptions regarding the real world problem were made (as discussed in Section 1.4):

- The hospital will be designed for a single floor layout; and
- The optimal positioning of the hospital departments will be determined and not the positioning of the rooms inside of each department.

The assumptions of the seven layout models were given in Chapter 2. Table 32 summarises this.

TABLE 32: ANALYSIS OF LAYOUT MODELS' ASSUMPTIONS

Assumption	**Layout models**							Value
	Quadratic Assignment Problem	Quadratic Set Covering Problem	Linear Integer Programming Problem	Mixed Integer Problem	Graph Theoretic Problem	Linear Continuous Model	Linear Mixed Integer Model	
The available space can be divided into blocks of equal size	x	x	x					-1
The candidate locations for each centre have to be established in advance (discrete layout)	x	x	x					
The number of departments is equal to the number of locations	x		x					0
Equal sized departments	x		x					-M
The departmental flow is independent of the departments' locations	x	x	x	x		x	x	1
The cost to transport one patient is independent of the departments(2)	x		x	x		x		
The desirability of locating each pair of departments adjacent to each other is known					x(1)			1
Area and shape does not influence solution					x			-1
The departments are oriented in only two given directions	x	x	x	x(2)		x	x	1
The shape of the departments is known in advance						x	x	-1
The departments are square or rectangular in shape	x		x	x		x	x	-1
There is no restriction on the shape of the building in which the facilities are to be located	x	x	x	x(3)	x	x	x	1
Total	1-M	2	1-M	2	1	1	1	

(1) Uses closeness graph which is independent of locations.

(2) Constraints can be added to ensure this.

(3) Square/rectangular shapes in the horizontal and vertical axis.

As mentioned in Chapter 2, the layout models can be classified as either discrete or continuous layouts based on the nature of centre locations of the departments. Discrete layout models limit the departments to be located at a number of discrete points while continuous layout models allow new departments to be located anywhere within the modelled space. The discrete layout models under consideration (QAP, QSCP, LIPP) divide the available space into smaller blocks. Thus, all of these models assume that the centres of departments can only be placed at the nodes of the network. Therefore a value of -1 is assigned to these layout models. This assumption is similar to the next one which assumes the candidate locations for each centre are established in advance (therefore a value of 0 is assigned). The MIPP, GTM, LCM, and LMIM allow departments to be placed anywhere in the modelled space.

In Chapter 4, the minimum area required for each department was determined. These areas differ to a great extent from one another. Thus, assuming equal-sized departments for a hospital is not a realistic assumption. Consequently, a value of –M is assigned to the QAP and LIPP (M being a very large positive number) in order to ensure the model is not chosen. The QSCP on the other hand is able to accommodate different centre sizes. Several candidate locations are made available for the location of each centre.

The assumptions of independent flow and transportation costs of the department's locations are valid assumptions since patients cannot decide which department they want to visit or in what order. They are sent to each department via administrative staff, doctors, or nurses. Therefore, patients will visit certain departments regardless of the department locations. The only choice patients have is through which door they will enter, namely the main entrance, emergency entrance, or outpatient entrance as seen in Figure 12 (Chapter 3). This however is not between departments and does not contradict the assumptions. These two assumptions are similar and a value of 1 is awarded to one or both of these assumptions. The Graph Theoretic Problem (GTP) does not use flow or cost variables, but it uses a closeness measure graph which can be defined as the departmental flow.

The assumption that departments are oriented in only two given directions is valid since many hospitals are only built in two directions. It is rare that any building is built in three or more directions. This simplifies the building process, furnishing of rooms, and flexibility of rooms. Assuming square or rectangular shaped departments imposes a restriction on the layout solution. In reality many departments have near square or rectangular shapes, L-shapes, or even U-shapes.

According to the layout model assumptions, it is clear that the QSCP, and Mixed Integer Problem are more suited to model the real world problem.

5.5.3 ANALYSIS OF LAYOUT MODEL INPUTS

The inputs used in the layout models were discussed in Chapter 2 and are summarised in Table 33.

TABLE 33: ANALYSIS OF LAYOUT MODEL'S INPUTS

Inputs	Layout models							Value
	Quadratic Assignment Problem	Quadratic Set Covering Problem	Linear Integer Programming Problem	Mixed Integer Problem	Graph Theoretic Problem	Linear Continuous Model	Linear Mixed Integer Model	
The fixed cost of locating and operating departments	x	x	x	x				0
The flow of patients between departments	x	x	x	x				1
The cost of transporting patients between departments	x		x	x		x		1
Distance between the centroids of candidate locations		x						1
Number of blocks into which the total area occupied by all departments is divided into	x	x	x					-1
Set of candidate locations for departments	x	x	x					
The closeness rating indicating the desirability of locating departments adjacent					x			1
The frequency of trips to be made between departments						x	x	1
The length and width of each department						x	x	-1
The minimum distance by which departments are to be separated						x		1
The time required for a patient to move between departments							x	1
Total	1	1	1	2	1	2	1	

The input of 'the fixed cost of locating and operating departments' is constant regardless of where a department is positioned. Therefore, a value of zero is assigned to this input. The flow of patients between departments is an essential input since it is the objective of the selected layout model. The inputs of distance between the centroids of candidate locations, and the cost of transporting patients between departments are significant since they correspond to the flow assumption. The number of blocks into which the total area occupied by all departments is divided affects the complexity of the problem as well as the accuracy of the solution. Candidate locations for departments, i.e. discrete points, restrict the solution space and are undesirable and therefore assigned -1. The closeness rating indicating the desirability of locating departments adjacent to one another is significant since it corresponds to the flow assumption. The frequency of trips to be made between departments is important and corresponds to the flow assumption. The length and width of each department restricts the solution space. The time required for a patient to move between departments is important and corresponds to the flow assumption.

5.5.4 ANALYSIS OF LAYOUT MODEL OUTPUTS

Table 34 shows an analysis of the seven layout models' outputs.

TABLE 34: ANALYSIS OF LAYOUT MODELS' OUTPUTS

Outputs	**Layout models**							Value
	Quadratic Assignment Problem	Quadratic Set Covering Problem	Linear Integer Programming Problem	Mixed Integer Problem	Graph Theoretic Problem	Linear Continuous Model	Linear Mixed Integer Model	
Block layout	x	x	x	x	x	x	x	1
Location of each department	x	x	x	x	x	x	x	1
Minimum total cost	x	x[1]	x	x		x[2]		1
Minimum closeness rating					x			1
Minimum total time							x	1
Minimum flow between departments		x						1
May have empty spaces between departments						x	x	-1
Total	3	3	3	3	3	2	2	

(1) Refers to fixed costs only.

(2) Refers to transportation costs only.

The Linear Mixed Integer model (LMIM) and the Linear Continuous Model (LCM) do not consider the shape and dimensions of the building and may produce a layout which contains empty spaces between the departments. This is not ideal and a negative value is awarded. The rest of the outputs accurately produce a layout and as such a value of 1 is awarded to each. Take note that the fixed cost of locating the department does not influence the position of the department within the layout, thus a value of 0 is assigned to it. A value of 1 is assigned to transportation costs.

5.5.5 ANALYSIS OF DESIGN CONSIDERATIONS

The qualitative methods in Chapter 3 were compared with the layout models. Table 35 summarises the design measures that each layout model addresses.

TABLE 35: ANALYSIS OF LAYOUT MODELS' DESIGN CONSIDERATIONS

Design objectives	**Design measures**	**Layout model**							
		Quadratic Assignment Problem	Quadratic Set Covering Problem	Linear Integer Programming Problem	Mixed Integer Programming Problem	Graph Theoretic Problem	Linear Continuous Model	Linear Mixed Integer Model	Value
Efficiency	Optimise occupant flows	x	x	x	x		x	x	1
	Minimise transportation	x	x	x	x		x	x	1
	Minimise waiting times	x						x	1
	Minimise cost	x	x	x	x		x		1
Flexibility and expandability	Minimise travel distances		x	x			x	x	1
Sustainability	Minimise costs	x	x	x	x		x		1
	Total	5	5	5	4	0	5	4	

5.5.6 SELECTION OF LAYOUT MODEL

From Table 36 it is evident that the QSCP and the Mixed Integer Problem are both equally the most suitable models to represent the real world problem.

TABLE 36: SELECTION OF THE BEST LAYOUT MODEL

Criteria	**Layout models**						
	Quadratic Assignment Problem	Quadratic Set Covering Problem	Linear Integer Programming Problem	Mixed Integer Problem	Graph Theoretic Problem	Linear Continuous Model	Linear Mixed Integer Model
Layout model objectives	1	1	1	1	1	1	1
Layout model assumptions	1-M	2	1-M	2	1	1	1
Layout model inputs	1	1	1	2	1	2	1
Layout model outputs	3	3	3	3	2	2	3
Design considerations	5	5	5	4	0	5	4
Total	11-M	**12**	11-M	**12**	5	11	10

An advantage of using the Mixed Integer Problem lies in that it is a continuous layout as opposed to a discreet layout used in the QSCP. This implies that the departments can be located at any point in the solution space. However, the solution space is considerably larger than in the case of a discreet layout making solving the model significantly harder. Furthermore, it was found in Chapter 3 that a minimum of 16 and a maximum of 19 departments are required for a rural hospital which makes it a very large problem to solve. Thus choosing a smaller solution space (QSCP) is beneficial. Furthermore, this study designs a block layout as opposed to a detailed layout and therefore the QSCP solution is sufficient. The QSCP also allows L-shape and U-shape departments in the final solution. For these reasons the QSCP is chosen to represent the real world problem.

5.5.7 ADJUSTMENTS TO LAYOUT MODEL

In Chapter 3 a relationship chart based on the activity requirements of each department was arrived at. The chosen layout model, the QSCP, uses patient flow as an input for the model and as a means of determining which departments to put relatively close and far from each other. If this is the case, departments which are seldom or never used by patients will most likely be placed on the outskirts of the layout, e.g. laundry. However, it makes logical sense to place the laundry department close to the wards since bed sheets need to be replaced every time an inpatient leaves the hospital. Clearly, patient flow is not the only important consideration, as flow in a hospital also includes medical staff flow, cleaning staff flow, specimen flow, test results flow, and waste flow.

Another way to explain this is to realise that some patients are in a more critical condition than others, e.g. requiring emergency treatment. There might not be many critical patients that are transported between two departments and the flow therefore is low, but it is essential to make the distance between such departments as short as possible. Consequently, using patient flow as a means to determine the relationships between hospital departments is not necessarily an accurate representation of the real world problem.

A possible solution is to use the relationship chart arrived at in Chapter 3 which is based on each department's activities as well as logical reasoning to replace the flow aspect of the model.

5.6 Selection of solution method

The solution method depends on the problem size, i.e. the number of departments. In Chapter 4 the number of required departments was determined as being 16, with two being optional. Two types of solution methods were identified, namely exact methods, and metaheuristics (discussed in Section 2.5). Branch and Bound Algorithm (an exact method) can find optimal solutions only up to a problem size of 16 while metaheuristics approximate the optimal solution for larger problems. Since the problem size ranges from 16 to 19, the Branch and Bound Algorithm will be used to solve smaller problems and a metaheuristic will be used to solve larger problems.

Metaheuristics can be classified into P-metaheuristics and S-metaheuristics (refer to Table 21). P-metaheuristics can improve a population of solutions (candidates) while S-metaheuristics seek to improve a single solution. Generating one solution is much quicker and easier than generating a population of solutions. For this reason an S-metaheuristic will be chosen.

The LS method is quick and greedy, but not accurate for solving problems with numerous locally optimum solutions. Therefore Simulated Annealing (SA) and Tabu Search (TS) are possible solution methods. TS generates a tabu list which complicates the solving process more than SA. For this reason SA is chosen.

5.7 Development of layout design framework

In order to guide the user to design a near-optimal hospital layout, two computer programs have to be developed. The first program should be able to capture input from a user and calculate the sizes of each hospital department accordingly, while the second is required to solve the layout using these inputs. In this section a few assumptions are outlined, followed by a discussion on the development of the framework via eight steps. In conclusion, a few examples of the outputs of this framework are then discussed.

5.7.1 ASSUMPTIONS

When developing a framework there are invariably assumptions which have to be made, and these include that:

1. The framework is developed for a single floor layout (see Section 1.7);
2. A district hospital layout is to be developed which implies a specific set of required and optional departments and rooms (see Section 1.7); and
3. The shape of each hospital department is independent of the arrangement of the rooms inside it which implies that the dimensions of each department can change without the need to analyse the arrangement of rooms within the department (see Section 1.7).

5.7.2 SELECTION OF PROGRAMS

Herein the two programs required to develop the layout design framework will be described. As mentioned, the first is required for capturing inputs from the user to calculate the sizes of each department, and the second is required to take these inputs and utilise them to optimise the arrangement of departments, thus creating as many iterations of the floor layout as are required.

The user input program must be capable of making various calculations and suggesting ballpark values to the user of the framework (e.g. number of beds, sizes of rooms). The user should then be able to change these values according to preferences and case-specific insights. These values should then be captured in the program and the total size and building cost of each hospital department should be calculated. Excel VBA was chosen for these purposes since it is a convenient software program for developing user-friendly interfaces and making the required calculations.

The layout construction program seeks the optimal (or near optimal arrangement) of the hospital departments specified in the first program. The QSCP (see Section 5.5) was chosen as the most adequate layout model for the framework, utilising the Branch and Bound Algorithm and SA as the solution methods (see Section 5.6). The Branch and Bound can optimally solve the QSCP with up to 16 departments and SA can approximate the optimal solution for larger problems. Thus, the second program has to solve the QSCP with SA or the Branch and Bound Algorithm while using the inputs generated in the first program. Lingo was selected as the programming language for the Branch and Bound Algorithm while RStudio was selected for programming SA.

5.7.3 FRAMEWORK STEPS

The development of the framework is discussed via eight steps, outlined in Figure 21, which indicates the calculations made in each of the programs (i.e. Excel VBA, Lingo, and RStudio). The first six steps are executed in Excel VBA. Each step (and sub-step) represents a window that is prompted to the user of the program. Each window recommends values to the user of the program and allows them to be changed by the user. The blue text in Figure 21 represents all the variables that can be edited by the user. The eight steps of the framework will now be discussed.

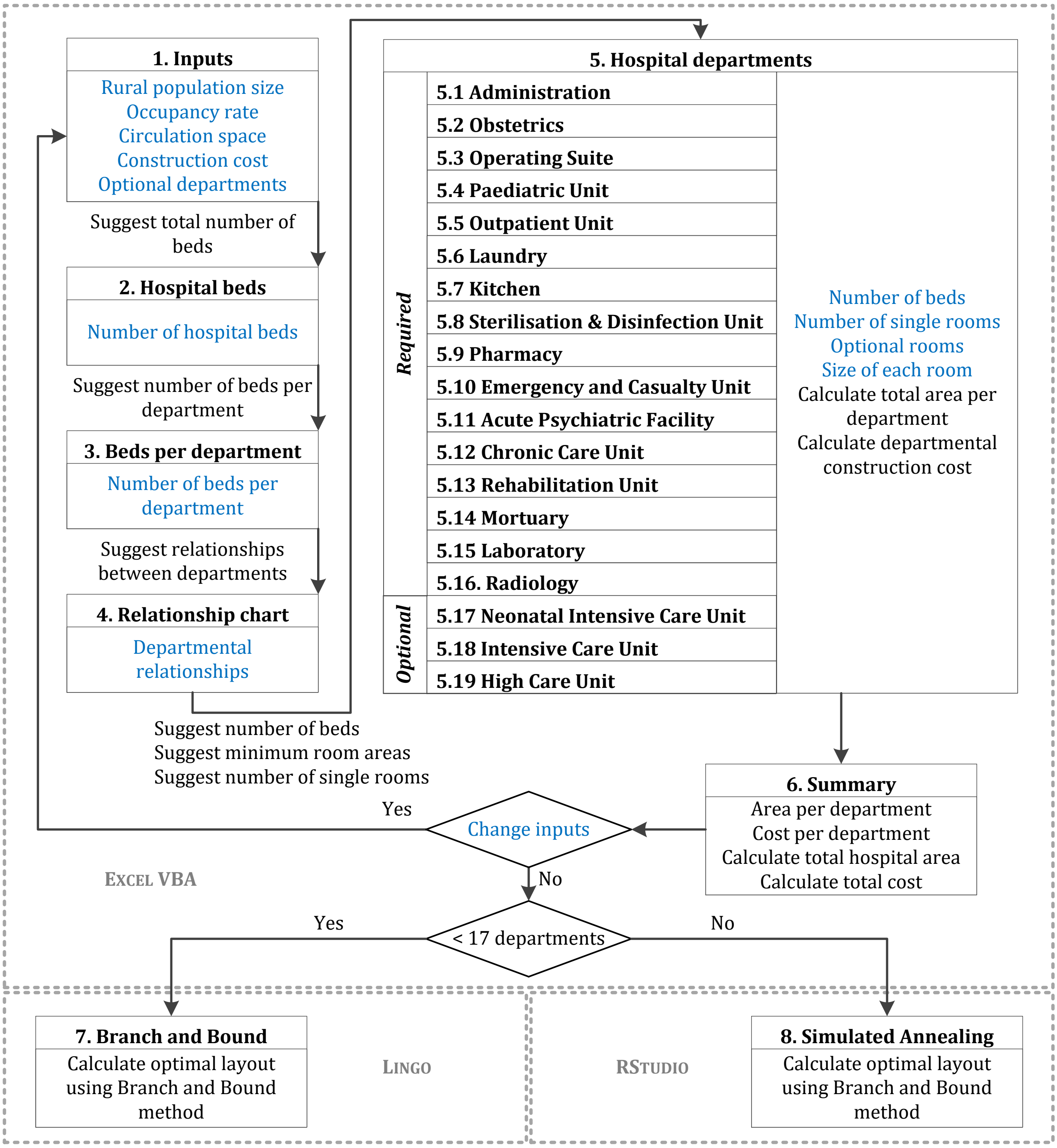


FIGURE 21: FRAMEWORK OUTLINE

5.7.3.1 Step 1 Inputs

The purpose of the first window is to define the characteristics of the hospital layout. In this window the user is prompted to enter the rural population size (this is the only variable for which a baseline value is not suggested to the user). The required hospital departments are shown and the user can select the optional departments by clicking on the checkboxes next to each listed department. The window also recommends the following variables that can be changed by the user: occupancy rate, circulation space, and construction cost. These variables will now be discussed further.

i. Occupancy rate

The occupancy rate is defined by Segen's Medical Dictionary (2011) as "*the proportion of beds in a hospital or ward which are in use at a particular time*." The Organisation for Economic Cooperation and Development (2005) (OECD) considers a rate of 85% as the limit of safe occupancy. Bagust, Place and Posnett, (1999) modelled the dynamics of the hospital system, using a discrete-event stochastic simulation model which reflects the relation between demand and available bed capacity and found that increased risks are apparent when average bed occupancy rates exceed approximately 85%, and furthermore that "*an acute hospital can expect regular bed shortages and periodic bed crises if average bed occupancy rises to 90% or more.*" An acute hospital is defined by Hirshon, Risko, Calvello, De Ramirez, Narayan, Theodosis, and O'Neill (2013) as "*a short-term hospital that has facilities, medical staff and all necessary personnel to provide diagnosis, care and treatment of a wide range of acute conditions, including injuries*." This 85% figure dates back to nearly 100 years ago when Erlang developed the queuing theory which argues that systems are most efficient when they operate at 85% capacity (Bain, Taylor, McDonnell & Georgiou, 2010). Another method to optimising the number of beds in a hospital is discussed by Goronescu, McClean and Millard (2002) who found that it depends on the relative value placed upon empty beds and blocked patients. It is therefore prudent to suggest an occupancy rate of 85% to the user of the framework, but also to allow the user to change this rate according to personal preferences depending on their hospital requirements (e.g. whether it is likely to provide more acute or more chronic care, and the cost of empty beds and inadequate space for patients).

ii. Circulation space

The importance of circulation space is often overlooked in the designing phase of buildings. Circulation space is defined by the National Centre for Education Statistics (2006) as "*the sum of all areas on all floors of a building required for physical access to some subdivision of space, whether physically bounded by partitions or not.*" Examples of these spaces include corridors, required exits, traffic aisles, escalators, stairways, elevator lobbies. These spaces are usually not indicated in block layout plans, yet careful planning of these areas is essential for an efficient layout (see Section 3.5.2 for the minimum dimensions required by the law). One way to plan for the necessary circulation space of a layout is to calculate it as the percentage of the total space. According to Karlen and Fleming (2016) 25% is recommended for general use of a building.

The United States' General Services Administration (2012) recommends a method to estimate and plan for circulation. The benefit of using this method is that the multiplier used in their calculations is dependent on the proportion of open to enclosed spaces in the layout which makes the estimate more accurate. They define the following terms:

- **Net Area (NA):** the area of each identified program space (i.e. department), including workspaces, dedicated support (e.g. supply rooms), shared support (e.g. staff break rooms), and special mission-critical support spaces (e.g. laboratories);
- **Circulation Area (CA):** primary circulation is the main circulation route connecting the building core and common spaces whilst secondary circulation relates to the aisles between individual and support spaces (e.g. offices, cubicles);
- **Usable Area (UA):** includes NA and CA, but excludes building common spaces such as elevators, exit stairs, and core toilets. Since this study focuses on a single floor layout, there is no need for elevators or stairs, and toilets are located within departments. Therefore, the UA is seen as being equal to the total area required for the hospital layout;
- **Circulation Multiplier (CM):** is applied to the NA to estimate the multiple of CA that should be included in the UA; and
- **Circulation Factor (CF):** the percentage of UA that makes up the CA.

The CA is a function of the open and enclosed spaces that exist in the layout. Typically, a floor plan with many open workstations will have a higher CA than a plan made up primarily of enclosed spaces. Open workstations require a larger area since they require proportionally greater circulation than enclosed spaces. Therefore, a unique CM should be chosen for each layout.

Take note of the difference between CA and CM: CM is applied to NA while CF is the percentage of US that makes up the CA. For example, a CM of 1.35 and a NA of 28,000m^2 results in a CA of 25.9% of the total UA. The CM should be selected based on the anticipated amount of CA that will needed for efficiency. The CM range is 1.4 to 1.6 and the average is 1.5, whereas the CF is between 28% and 38% with an average of 33%.

From Chapter 4, it is apparent that hospital departments contain mostly enclosed areas for the purpose of patient privacy. The United States' General Services Administration (2012) recommends a CM of 1.4 for a building with a greater portion of enclosed offices and support spaces. Thus, 1.4 (CF of 28.6%) will be used in the framework to calculate the total area needed for each hospital department.

iii. Construction cost

The construction cost of a hospital layout can be estimated by using the cost per square meter approach. The IUSS estimated this value for a single story Level 1 (district) hospital to be R14,250/m^2. This value was derived from research conducted on selected case studies where the cost of the hospital was divided by the construction area. All the case studies were escalated or de-escalated in order to provide the same base date and comparison of rates. This value excludes value-added tax, but includes the following costs:

- Theatre lights and examination lights;
- All fixed systems (e.g. nurse call, fire alarms);
- Built in shelves, counters, and nurses stations;

- All security systems (e.g. closed-circuit television);
- All human resource systems (e.g. clocking systems);
- IT and communications equipment (e.g. telephones);
- Kitchen equipment used in the main kitchen (e.g. fridges);
- Laundry equipment used in the main laundry (e.g. washers and dryers); and
- Pendants with gas and power connections in theatre and critical care areas.

Another estimation of the building cost of a district hospital in South Africa was proposed by the Africa Property and Construction Handbook (2013) which lists a cost of $1,110/m² (exchange rate of R13.45 for $1 on 3 September 2015). This is equivalent to R14,521/m², which is close to the IUSS recommendation. However, the route to determining this value is unclear and due to a fluctuating inflation rate it is a bit uncertain. Therefore, the value recommended by IUSS is used in this study.

Once all the values are entered into the provided spaces and the optional departments are selected (if desired) in the input window, the user can click the 'next' button and continue to the second step.

5.7.3.2 Step 2 Hospital beds

The purpose of the second window is to suggest the total number of hospital beds to the user and allow the user to change this value if desired.

Deciding upon the number of beds for a hospital is not a straightforward task. On the one hand there has to be enough beds available for patients so that under normal operating conditions no patients have to be refused treatment, and on the other hand empty beds equate to unnecessary costs. In addition, there is the concern of large variability in the number of occupied beds leading to higher costs. In order to account for this, some researchers focus on the arrival process of patients at a hospital and the length-of-stay distribution of patients (Kuijstermans, 2014). As this is not easily deduced for a rural hospital where these variables are extremely context dependent, another route should be followed.

Phillip, Mullner and Andes (1984) express the occupancy rate as a function of the hospital size, percentage of non-urgent beds, relative variation in the demand for hospital care faced by individual hospitals, and the number of hospitals serving an area. The number of beds serving a specific area would typically play a significant role when deciding upon the number of beds for an urban hospital, while this factor is inapplicable to rural communities due to the remote nature of rural areas.

Another way to decide upon the number of beds is to use the average number of beds per capita for the relevant country. The OECD (2013) provides these statistics of more than 36 countries. According to Econex (2010), South Africa has an average of 2.5 hospitals beds per 1000 population (including both public and private sectors). Some of these countries have an excessive hospital capacity while others are overcrowded. The number of beds required in a country depends on factors such as patterns of disease and the availability of alternative care settings (Green, 2002). The international Inter-Agency Standing Committee (IASC) (2010) gives a vague benchmark for the number of hospital beds per 1000 population, arguing that it should be greater than one. According to WHO (2010), the global average is 2.7 beds per 1000 population, where lower and middle income countries have 1.8 and 2.9 hospital beds per 1000 population respectively. They arbitrarily choose a benchmark of 3 hospital beds per 1000 population. However, these values usually include all types of hospitals which could be misleading. In 2014 the National Department of Health (2014) found that district hospitals in South Africa have on average 0.7 beds per 1000 population.

Thus, for the purposes of designing a new hospital layout, it is advantageous to express the number of hospital beds as a function of the community's population. In order to maintain the balance between overcrowding and vacant beds, the desired hospital occupancy rate should also be included in this calculation. The calculation used in developing the layout design framework will now be discussed by means of an example.

The average length of stay in South African public hospitals is 5.3 days (Ramjee, 2013) and the average inpatient admissions per 1000 population per year is 58.3 (Harris, Goudge, Ataguba, McIntyre, Nxumalo, Jikwana & Chersich, 2011). If the community's population is 200,000, then the average inpatient admissions per year are 11,660. The average admissions per day are thus 31.95. With an average length of stay being 5.3 days, 170 beds are needed if the desired occupancy rate is 100%. If the desired occupancy rate is 85% for the same number of admissions, 200 beds are required. This equates to 1 bed per 1000 population which falls within the guidelines provided by IASC. This is also slightly higher than the average number of hospital beds in South African district hospitals.

In conclusion to this step, a number of hospital beds are suggested to the user of the framework in the hospital beds window according to the specified population size, but the user can still decide to change this value. Once this is decided, the user can click 'next' and proceed to the third step.

5.7.3.3 Step 3 Beds per department

The purpose of the third window is to suggest the number of beds per department and allow the user to change these values if so desired.

The number of hospital beds in each department is another important design consideration. A few references suggest the percentage of beds in a few hospital departments, but no complete guide for estimating the beds distribution in a hospital was found. A way to estimate missing values is to use the process of benchmarking. Benchmarking is defined as "*a standard or point of reference against which things may be compared*" (Stevenson, 2015). This concept is used to estimate the distribution of beds in a new hospital using data from a few existing hospitals. Table 37 shows the number of beds of five South African hospitals and a few references that recommends the number of beds in departments.

The values that are not suggested by references are estimated using the average of the benchmark hospitals.

TABLE 37: BENCHMARKING HOSPITAL BED DISTRIBUTION ADAPTED FROM LIFE HEALTHCARE (2016)

	Benchmark hospitals					Other references					
Departments	Life Carstenhof Hospital	Life Kingsbury Hospital	Life Eugene Marais Hospital	Life Fourways Hospital	Life Glynnwood Hospital	Directorate General of Health Services (2012)	Directorate General of Health Services (2012)	Van Reenen (2014)	Kunders (2004)	De Jager (2014)	**Percentage of total beds**
Obstetrics	21	28	12	16	30	58	78	20%	-	-	20%
Operating Suite	6	12	14	10	10	-	-	-	2%	-	2%
Paediatric Unit	-	-	-	20	-	10	20	-	-	20%	20%
Emergency and Casualty Unit	-	-	-	-	-	10	10	-	-	-	5%
Acute Psychiatric Facility	-	-	-	-	-	10	10	-	-	-	10%
Chronic Care Unit	-	-	-	-	-	66	125	-	-	-	22%*
Rehabilitation Unit	-	-	-	-	80	5	10	-	-	-	4%
Neonatal Intensive Care Unit	12	12	6	5	5	-	-	-	-	-	4%
Intensive Care Unit	10	14	27	26	16	-	-	-	-	-	8%
High Care Unit	7	5	26	8	18	-	-	-	-	-	5%
Total number of beds	153	227	364	194	323	150	250	-	-	-	100%

(1) Adjusted to fill 100%.

The percentages of beds in each hospital department are used to calculate the number of beds in each department based on the total number of beds that the user selected in Step 2. These calculated beds per department are then suggested to the user. Once the user decides upon the number of beds in each department, the 'calculate' button will capture these values and use it in the next few steps. If the user does not specify a value, the suggested values will be used. If the user wishes to return to the previous step, the 'back' button can be clicked. Otherwise, the user can click 'next' and proceed to Step 4.

5.7.3.4 Step 4 Relationship chart

This fourth step specifies which departments should be placed together and which ones should be separated. Firstly, a matrix of the relationship between each hospital department (generated in Section 3.4 and discussed in Section 5.5.7) is suggested to the user. The user is able to change each of these values. This step plays an important role in finding the best arrangement of hospital departments. After amending the relationship matrix to meet their needs, the user can click 'next' and proceed to Step 5.

5.7.3.5 Step 5 Hospital departments

The purpose of Step 5 is to determine the size of each room, allow the user to choose which optional rooms to include in the layout, determine the total size of each department, and calculate the construction cost for each department.

In this step a window is shown for each hospital department and optional department (if selected by the user in Step 1). Each window shows a list of rooms that are required and optional for each hospital department. The user is able to then select which optional rooms to include in each department by clicking on a checkbox next to the relevant room. The user also has the option to include a few of the same rooms in each department (where applicable). The minimum floor space for each room as required by the South African law is also displayed. The user is able to enter a new area for each room if desired. Once this is done, the user can click on 'calculate' and the program will determine and show the total area and construction cost of the relevant department. If the user did not specify the area of a room or if the entered area is smaller than the minimum area, the area provided by law will be chosen to include in the layout. This will ensure that the layout conforms to the requirements of the law.

Furthermore, each box shows the number of beds chosen for the department and recommends the percentage of single rooms. The user is also able to change both of these variables. The following boxes are prompted to the user of the program (the last three optional departments will only be shown if selected by the user in Step 1):

- Administration;
- Obstetrics;
- Operating Suite;
- Paediatric Unit;
- Outpatient Unit;
- Laundry;
- Kitchen;
- Sterilisation and Disinfection Unit;
- Pharmacy;
- Emergency and Casualty Unit;
- Acute Psychiatric Facility;
- Chronic Care Unit;
- Rehabilitation Unit;
- Mortuary;
- Laboratory;
- Radiology;
- Neonatal Intensive Care Unit;
- Intensive Care Unit; and
- High Care Unit.

The estimation of the size of the Laundry, Kitchen, and Sterilisation and Disinfection Unit work a bit differently than the other departments. The reason for this is that these three departments do not contain many rooms and consequently the sum of the minimum areas of these rooms will not give an accurate estimation for the total size of the department. Therefore, the concept of benchmarking was used. The calculations used in each of these three departments will now be discussed.

TABLE 38: NUMBER OF BEDS AND APPROXIMATE SIZE OF LAUNDRY ADAPTED FROM FOURIE, SHEARED AND STEYN (2014)

Number of hospital beds	**Laundry size (in m^2)**
200	448
300	570
400	700
500	820
600	945

The main elements in hospital laundries are similar, but the main difference is one of scale. The Council for Scientific and Industrial Research (1995) (CSIR) compiled Table 38 which shows estimates for the size of a laundry according to the number of hospital beds. This data was derived from a number of existing hospitals in the Western Cape.

In order to incorporate the data from the CSIR, the linear graph shown in (67) was calculated to estimate the size per m^2 and this was then programmed into the Laundry box.

$$y = 1.24(beds) + 203 \tag{67}$$

The size of a hospital's kitchen is unique to that hospital, and depends on a variety of factors that include the number of patients and staff to receive meals, type of patient (e.g. age and culture), type of menu, and type of food preparation system (Steyn & Boltman, 2014). Table 39 shows the number of beds in eight South African hospitals along with the kitchen area of each hospital.

TABLE 39: NUMBER OF BEDS AND SIZE OF KITCHEN

Hospital	**Number of beds**	**Kitchen size (in m^2)**
Moses Kotane	183	292
Holy Cross	231	588
George	256	758
Worcester	269	276
Khayelitsha	277	625
Bertha Gxoba	300	565
Paarl	365	581
Natalspruit	752	1387

The data shown in Table 39 was used to generate a linear graph for the estimated size per m^2 shown in (68).

$$y = -0.0003(beds) + 1.9863 \quad (68)$$

Similar to a hospital's kitchen, the Sterilisation and Disinfection Unit is unique to the requirements of that hospital. Space determinants of this unit include the number of theatres, surgical procedures, distribution system, and processing needs (Steyn & Sheard, 2004). Table 40 shows data recommended by the Department of Health (2001).

TABLE 40: NUMBER OF BEDS AND SIZE OF STERILISATION AND DISINFECTION UNIT ADAPTED FROM STEYN AND SHEARD (2004)

Bed size	**Sterilisation and Disinfection Unit size (in m^2/bed)**
200	0.7
400	0.6
600	0.5
800	0.5
1000	0.5
1200	0.5

Since the data from Table 40 does not form a linear graph, it is decided to use a value of 0.7m^2/bed for estimating the size of the Sterilisation and Disinfection Unit of the framework as a district hospital typically has between 0 and 200 beds.

Once all boxes of the hospital departments are completed, the user can continue to the last step in Excel VBA.

5.7.3.6 Step 6 Summary

In this step a window is presented to the user with the total size of each hospital department as determined in Steps 1 to 5. The area of each department with the circulation space included is also shown. Using these values, a new construction cost per department is calculated. The total construction cost and size of the hospital is also shown. The user is also able to return to Step 1 and change values if so desired. The old entered values will still be shown so that the user does not have to redo the whole process.

TABLE 41: EXAMPLE OF EXCEL VBA OUTPUT

Departments	**Sum of room sizes (in m²)**	**Circulation space included (in m²)**
Administration	148	206
Obstetrics	435	604
Operating Suite	118	164
Paediatric Unit	230	319
Outpatient Unit	372	517
Laundry	148	206
Kitchen	167	232
Sterilisation and Disinfection Unit	106	147
Pharmacy	120	167
Emergency and Casualty Unit	439	610
Acute Psychiatric Facility	174	242
Chronic Care Unit	520	722
Rehabilitation Unit	233	324
Mortuary	76	106
Laboratory	88	122
Radiology	145	201
Neonatal Intensive Care Unit	48	67
Intensive Care Unit	91	126
High Care Unit	90	125
Total area of hospital rooms	3 748	-
Total size of hospital	-	5 206
Total construction cost	-	75 693 983

This step concludes the code in Excel VBA. An example of the output of the Excel VBA program is shown in Table 41. A circulation space of 28% was included in the layout.

In order to explain how the framework operates, four examples will be discussed. The output of Steps 1 to 6 will be used as input for Steps 7 and 8. These two steps use the QSCP formulation with the Branch and Bound Algorithm and SA respectively.

A hospital size of 5,206m² can be accommodated by a site space of 75 by 75 meters (5,625m²). It was decided to use these dimensions and divide the area into 3 by 3 meter blocks. This means that there are 576 potential locations where the centre of each hospital department can be placed. Consequently, the distance variable d_{jl} will be a matrix with 331,776 (576 x 576) entries. The relationship chart from Step 4 is used as an input f_{ik} to the framework. The layout problem will now be solved.

5.7.3.7 Step 7 Calculate the optimal layout using Branch and Bound Algorithm

Lingo is a convenient program for using the Branch and Bound Algorithm, and was therefore chosen. The Branch and Bound Algorithm is able to solve the FLP optimally, but only up to a problem size of 16. The QSCP was first coded in Lingo for a problem size of 6, but the program could not handle the amount of variables and constraints. The program has a limit of 150 constraints and 300 variables (373 constraints were found and 576 variables). The improved version of this program will also not be able to handle this problem having 250 constraints and 500 variables. Since Lingo cannot solve the problem of the framework, the optimal solution will be approximated using SA. This step was consequently removed from the framework. The updated framework is included in Appendix F.

5.7.3.8 Step 8 Approximate the optimal layout using Simulated Annealing

A suitable programming language for coding algorithms such as SA, is RStudio. This program has many packages to aid users. There is, for example, a package for SA called GenSA (Generalised Simulated Annealing). However, it was found that this package does not allow for binary constraints to be added in the solving process. Another solver called Optim was found that can approximate an optimal solution for a non-linear function using SA. The RStudio code is included in Appendix E. Two library tools are used in the code, namely PhonTools and Functional. A brief explanation of the functions written in RStudio is now provided.

- **Main function:** contains all the input variables, including the available space, number of departments, relationship diagram, distance matrix, and fixed cost matrix. Additionally, the dimensions and possible orientations of each department are stored in a vector called size_array_3D. The curry function in RStudio was used to change functions into new ones that depends on less variables;
- **VectorToMatrix and MatrixToVector functions:** are able to change vectors into matrices and matrices into vectors without losing any data. The reason for this is that the QSCP contains matrices as input variables;
- **BlockMatrixFull function:** tests different rotations of each department and returns false if no more rotations of departments are able to fit into the available space;
- **BlockMatrixImproved function:** ensures that the departments do not overlap and that they are all placed inside the available space;
- **PlaceDepartment function:** places a department with a specific width and height in the available space (called MatrixBlock) and returns false if it fails;
- **FunctionQSCP function:** the objective function of the QSCP is coded in this function;
- **ChangeDepartments function:** swaps two positions of departments around; and
- **GridPosition function:** makes finding the positions of departments easier for the user of the program.

The RStudio program will return the best set of parameters found and the objective function value that corresponds to this value.

5.7.4 EXAMPLES

Four examples of layouts generated by the framework developed in this study will now be discussed. In order to arrive at a useful solution, 10,000 iterations were run in RStudio for these examples. Example 1 has 19 hospital departments and ran for approximately 14 minutes. The other examples have only 16 departments and the computation time was reduced by nearly 10 seconds. The dimensions for each department were chosen to be the same for all four examples. This is also a variable that the user of the framework can decide upon in addition to the orientation of each department.

The first example includes 19 hospital departments in the layout and the relationships between these are shown in Table 42.

TABLE 42: EXAMPLE 1 RELATIONSHIPS

	Admin	Obst	OS	Paed	Out	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	3	10	0	-2	0	5	-3	-3	5	4	-3	4	5	3	3	3
Obst	0	0	10	10	10	5	3	5	5	5	-3	-2	-4	3	5	5	10	9	8
OS	0	0	0	4	-2	5	0	8	2	10	-2	4	3	4	7	7	8	10	7
Paed	0	0	0	0	8	5	3	5	4	3	-4	-2	-4	3	5	3	10	2	2
Out	0	0	0	0	0	3	0	3	10	3	0	5	5	3	3	5	3	3	3
Laun	0	0	0	0	0	0	0	0	0	0	3	5	4	0	0	0	4	4	4
Kitch	0	0	0	0	0	0	0	0	0	-3	3	4	4	0	0	0	2	3	3
S&DU	0	0	0	0	0	0	0	0	0	7	0	5	3	0	1	0	6	6	6
Phar	0	0	0	0	0	0	0	0	0	3	3	6	4	0	0	0	4	4	4
Emer	0	0	0	0	0	0	0	0	0	0	-3	4	-3	4	9	10	4	4	4
Psych	0	0	0	0	0	0	0	0	0	0	0	0	3	-3	6	4	-3	-2	-2
CCU	0	0	0	0	0	0	0	0	0	0	0	0	1	4	5	4	0	5	5
Rehab	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	1	3	3
Mort	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	4	4
Lab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	5	5
Radio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	5	5
NICU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ICU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
HCU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The output of Example 1 is shown in Figure 22. The blue lines indicate the highest positive relationships (assigned 10) and the red lines indicate the strongest negative relationships (assigned -4). It is clear that the departments with the highest relationships are placed in close proximity. The departments with the most negative relationships are separated with the exception of Rehab and Paed. There are two possible explanations for this placement. Firstly, there are not enough available blocks to place these two departments separate (investigated further in the third example). Secondly, the positive relationships between 4 and 10 are rated higher and took precedence.

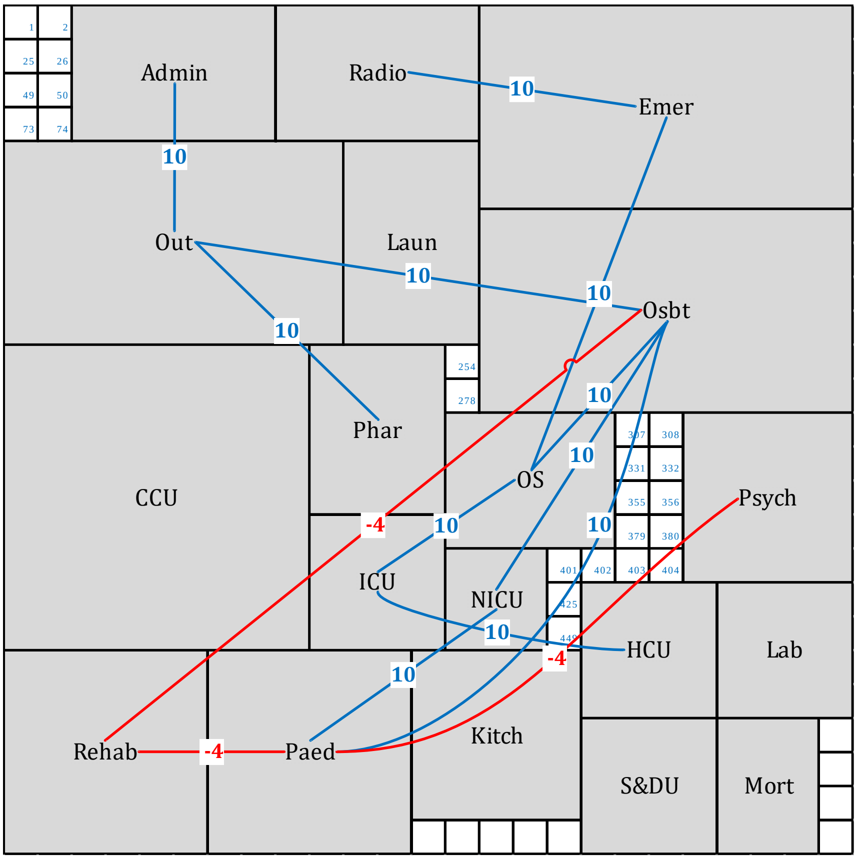


FIGURE 22: EXAMPLE 1 OUTPUT

The second example includes 16 hospital departments in the layout and the relationships between these are shown in Table 2. In this example only positive relationships were included in the input.

TABLE 43: EXAMPLE 2 RELATIONSHIPS

	Admin	Obst	OS	Paed	Out	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio
Admin	0	3	3	3	10	0	0	0	5	0	0	5	4	0	4	5
Obst	0	0	10	10	10	5	3	5	5	5	0	0	0	3	5	5
OS	0	0	0	4	0	5	0	8	2	10	0	4	3	4	7	7
Paed	0	0	0	0	8	5	3	5	4	3	0	0	0	3	5	3
Out	0	0	0	0	0	3	0	3	10	3	0	5	5	3	3	5
Laun	0	0	0	0	0	0	0	0	0	0	3	5	4	0	0	0
Kitch	0	0	0	0	0	0	0	0	0	0	3	4	4	0	0	0
S&DU	0	0	0	0	0	0	0	0	0	7	0	5	3	0	1	0
Phar	0	0	0	0	0	0	0	0	0	3	3	6	4	0	0	0
Emer	0	0	0	0	0	0	0	0	0	0	0	4	0	4	9	10
Psych	0	0	0	0	0	0	0	0	0	0	0	0	3	0	6	4
CCU	0	0	0	0	0	0	0	0	0	0	0	0	1	4	5	4
Rehab	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3
Mort	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
Lab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Radio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The output for Example 2 is provided in Figure 23. It can be seen that the departments with the highest relationships between them are placed in close proximity.

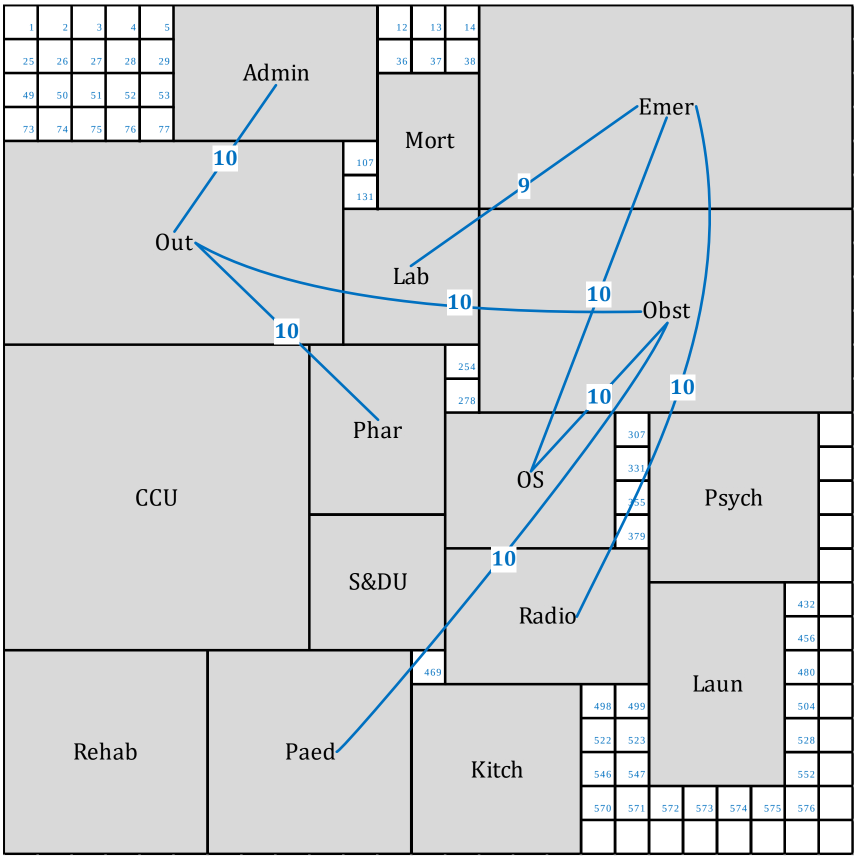


FIGURE 23: EXAMPLE 2 OUTPUT

The third example has 16 departments and the relationships between these departments are similar to the relationships in the first example, as shown in Table 44. Take note that the positive relationships are also similar to the second example, but negative relationships are now included.

TABLE 44: EXAMPLE 3 RELATIONSHIPS

	Admin	Obst	OS	Paed	Out	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio
Admin	0	3	3	3	10	0	-2	0	5	-3	-3	5	4	-3	4	5
Obst	0	0	10	10	10	5	3	5	5	5	-3	-2	-4	3	5	5
OS	0	0	0	4	-2	5	0	8	2	10	-2	4	3	4	7	7
Paed	0	0	0	0	8	5	3	5	4	3	-4	-2	-4	3	5	3
Out	0	0	0	0	0	3	0	3	10	3	0	5	5	3	3	5
Laun	0	0	0	0	0	0	0	0	0	0	3	5	4	0	0	0
Kitch	0	0	0	0	0	0	0	0	0	-3	3	4	4	0	0	0
S&DU	0	0	0	0	0	0	0	0	0	7	0	5	3	0	1	0
Phar	0	0	0	0	0	0	0	0	0	3	3	6	4	0	0	0
Emer	0	0	0	0	0	0	0	0	0	0	-3	4	-3	4	9	10
Psych	0	0	0	0	0	0	0	0	0	0	0	0	3	-3	6	4
CCU	0	0	0	0	0	0	0	0	0	0	0	0	1	4	5	4
Rehab	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3
Mort	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
Lab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Radio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The output of the third example is shown in Figure 24. In the second example, Rehab and Paed were placed adjacent but when assigned a negative relationship in example 3, they are placed apart. A similar occurrence happened with Admin and Mort. It is thus clear that the departments with negative relationships are placed further apart. Since Paed and Rehab are placed apart in the third example and not in the first, it can be concluded that a larger site will lead to improved solutions.

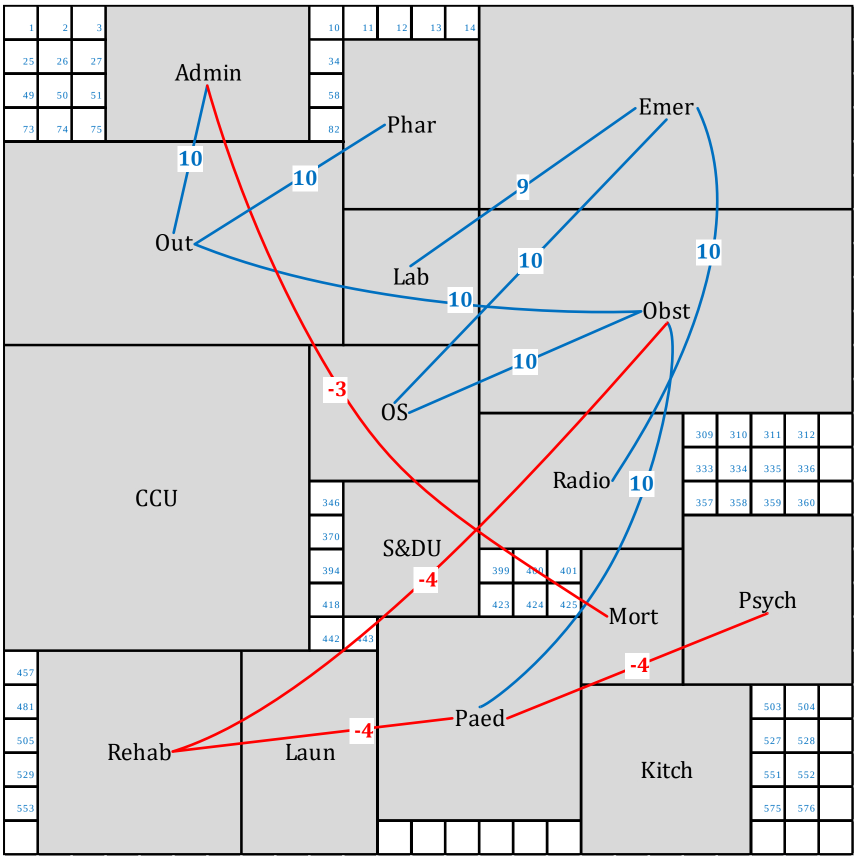


FIGURE 24: EXAMPLE 3 OUTPUT

The last example, investigates what happens when there is only one strong relationship (10 assigned) and the other relationships are rated relatively lower. The relationship diagram is shown in Table 45 and the relationship between Radio and Rehab is rated the highest.

TABLE 45: EXAMPLE 4 RELATIONSHIPS

	Admin	Obst	OS	Paed	Out	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio
Admin	0	1	1	1	3	0	0	0	2	0	0	2	1	0	1	2
Obst	0	0	3	3	3	2	1	2	2	2	0	0	0	1	2	2
OS	0	0	0	1	0	2	0	2	1	3	0	1	1	1	2	2
Paed	0	0	0	0	2	2	1	2	1	1	0	0	0	1	2	1
Out	0	0	0	0	0	1	0	1	3	1	0	2	2	1	1	2
Laun	0	0	0	0	0	0	0	0	0	0	1	2	1	0	0	0
Kitch	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
S&DU	0	0	0	0	0	0	0	0	0	2	0	2	1	0	1	0
Phar	0	0	0	0	0	0	0	0	0	1	1	2	1	0	0	0
Emer	0	0	0	0	0	0	0	0	0	0	0	1	0	1	3	3
Psych	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	1
CCU	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	1
Rehab	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	10
Mort	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Lab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Radio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The output of the fourth example is shown in Figure 25. It can be seen that Rehab and Radio are placed adjacent. In examples one to three these two departments were placed far apart. Thus, the user of the framework is able to place two specific departments adjacent when a significantly higher relationship is assigned.

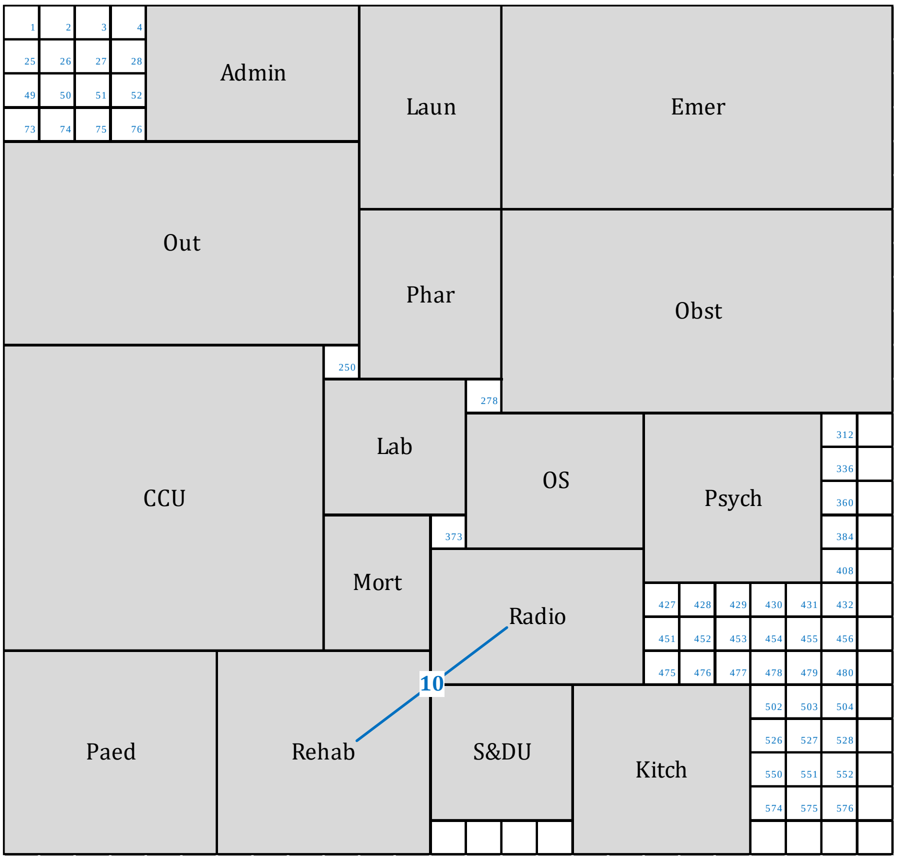


FIGURE 25: EXAMPLE 4 OUTPUT

5.8 Conclusion

In this chapter, the quantitative and qualitative layout design methods are integrated via embedding. It was consequently found that this study follows a concurrent transformative research approach with embedded design features.

The QSCP was chosen and adapted to model the problem of designing a rural hospital layout. The selection was based on its objectives, assumptions, inputs, and outputs as well as qualitative design considerations. SA was chosen as an adequate solution method for the QSCP.

Lastly, the generic rural layout design framework was developed using Excel VBA, and RStudio. A program in Excel VBA was developed to capture inputs, estimate values, and ultimately provide the areas and building cost of each hospital department. This program guides the user to adhere to the requirements of the law. A program developed in RStudio is able to approximate the optimal solution for the Excel VBA outputs using SA. The user is able to change variables of the Excel VBA and RStudio program according to preferences. The framework is adjustable to suit the needs of the user with regards to:

- Size of the site and ability to change shape in a rectangular fashion;
- Accuracy, i.e. the number of blocks the site is divided into;
- Total number of hospital beds;
- Target occupancy rate;
- Which optional departments are included in the layout;
- Number of beds in each department;
- Size of each department;
- Orientation and dimensions of each department;
- Circulation space in each department;
- Relationship between departments, i.e. degree to which departments should be placed in close proximity to each other and which ones should be separated;
- Size of each room within departments;
- Which optional rooms are included in each department; and
- Construction cost per square meter.

The framework calculates and recommends the following:

- Total number of beds, dependent on the community's population size and the occupancy rate;
- Number of beds per department, according to benchmarking of five South African hospitals;
- Total building cost of each department;
- Circulation space;
- Size of each room, according to the South African law requirements; and
- Relationship between departments, according to literature research on hospitals.

Four examples of the output of this framework are also discussed. It is found that the output of each example clearly models the specifications of the layout (i.e. input variables).

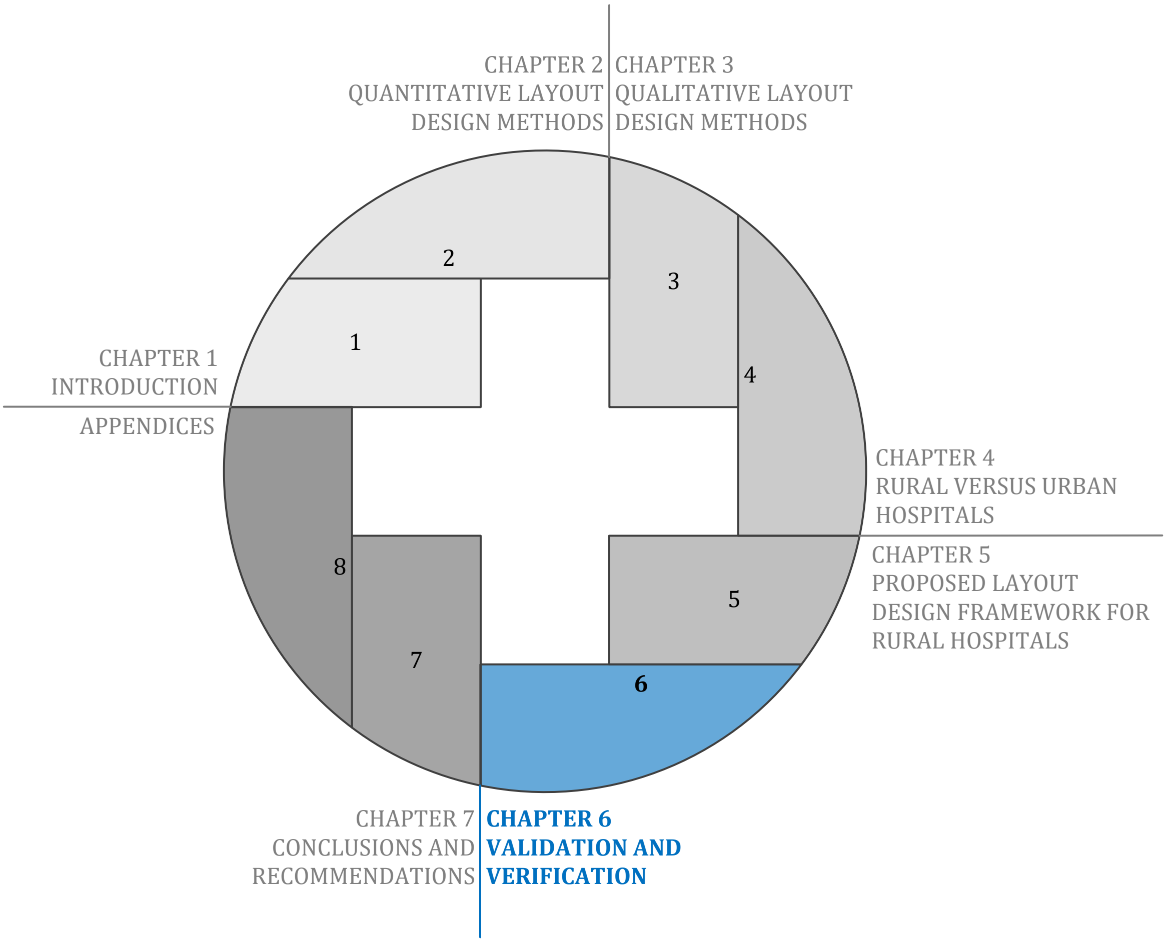
The next chapter aims to verify and validate the developed layout design framework.

CHAPTER 6

VALIDATION AND VERIFICATION

"Validation can be expressed by the query 'Are you building the right thing?' and verification by 'Are you building it right?'"

Boehm (1981)



6.1 Introduction

In order to prove the accuracy of the developed framework, as well as its adequacy, the findings and the framework must be verified and validated. Expert analysis is used to make the necessary adjustments to the framework before applying it to a case study on Semonkong Hospital.

6.2 Verification

After conducting research, it is important to make a judgement of the research findings, i.e. evaluation (Claesson, 2006). However, evaluation procedures are not always applicable depending on the nature of the reality studied and the theories used (Svensson, 2003). Two important dimensions of evaluation are verification and validation. Verification is concerned with the truth or accuracy and the predictive power of theories, models, and methods whereas validation deals with their relevance and meaningfulness (Warell, 2001). Truth in this context refers to the assessment of the ability of the theoretical and practical result to be used to explain a real world problem.

Verification of this study is done in three ways. Firstly, the layout design questions in Section 1.2.1 are considered. Table 73 of Appendix C explains how and where each question is addressed in this study. Secondly, the research objectives of this study are examined. Table 74 of Appendix C explains how and where each objective is addressed in this study. Thirdly, the outputs of the developed framework are checked in order to make sure that the program functions as it was intended to and that the results are as expected. This is clarified in detail in Table 75 of Appendix C.

6.3 Various routes to validation

There exist three commonly utilised routes to validating claims made by researchers, including interviews with experts, application to case studies, and implementation (Mouton, 2011). Each exhibits its own set of strengths and weaknesses.

Interviews are basically meetings in which information is obtained from the interviewee so as to disprove or confirm the claims made by a researcher. The four forms of interviews described by Mouton (2011) include structured self-administered questionnaires, structured telephone interviewing, semi-structured focus group interviewing, and free attitude interviewing methods.

The second route to validating the framework is through conducting case studies. By applying the framework to chosen case studies, the framework can be shown to be useful in real world problems/scenarios.

The third and final route to validating the framework is through implementation. Although it is the truest test of the workability of a concept, it requires the hospital to be built and evaluated which will take a few years, and many resources so as to be proven applicable. As already established in Section 1.7, the time constraint on this study makes it infeasible to test the framework practically through implementation.

For the purposes of this study, it is therefore sufficient to perform expert analysis together with a case study. Each of these are now addressed in turn.

6.4 Subject-matter expert analysis

The aim of this section is to validate the research, determine its shortcomings, and to make necessary improvements to the framework before applying it to a case study. Furthermore, potential for future research is identified.

6.4.1 THE PROCESS FOR VALIDATION VIA INTERVIEWS

Expert analysis in the context of this study takes the form of an interview based assessment in which each interviewee (expert) gives his perspective as to the rationality of the findings and their applicability to providing an answer to the problem situation, as well as to gain key insights into what their motivations and recommendations are for each point in consideration.

When validating a hospital design framework the following aspects need to covered:

- **Accuracy:** the calculations must be correct;
- **Adherence:** all the applicable laws must be adhered to;
- **Realism of costs:** the costs must be realistic;
- **Inclusiveness:** the correct departments must be included;
- **Correctness:** the correct rooms must be considered;
- **Realism of areas:** the calculated areas for rooms must be realistic; and
- **Realism of solution:** the final layout must be realistic.

These aspects form the basis of the validation questionnaire.

6.4.2 INTERVIEWEE PROFILE

This study focuses on three main areas/domains, namely layout design, construction planning, and healthcare. Experts were chosen according to their areas of expertise, in the hopes that each will provide key insights into the validity of the different aspects of this study. It is of course possible for experts to exhibit expertise in more than one field, which is beneficial. The roles of each are now laid out.

6.4.2.1 Healthcare architect

An architect is a person who "*designs buildings and in many cases also supervises their construction*" (Stevenson, 2015). This person is able to provide input on the following:

- Whether the proposed layout is realistic;
- Whether the applicable laws and regulations are adhered to in the recommended layout; and
- Whether the summary of the details of the laws and regulations that are applicable to each department are sufficient to provide guidance to the designer.

6.4.2.2 Quantity surveyor

A quantity surveyor is a person who "*calculates the amount of materials needed for building work, and how much they will cost*" (Stevenson, 2015). This person is able to determine the following:

- Whether the cost estimate is realistic; and
- Whether the calculations that underpin this estimate are correct.

6.4.2.3 Healthcare expert or manager

A healthcare expert or manager will be able to evaluate the framework from a medical viewpoint. A healthcare manager is a person who "*provides leadership and direction to organisations that deliver personal health services, and to divisions, departments, units, or services within those organisations*" (Buchbinder & Thompson, 2010). This person is able to determine the following:

- Whether the layout is practical in the context of a hospital;
- Whether the flow-relationship diagram is realistic;
- Whether the necessary departments are included; and
- Whether the necessary rooms are included.

In order to get unbiased results, more than one expert from each area of expertise was interviewed.

6.4.3 INTERVIEWEE SUMMARY

A total of six subject matter experts (SMEs) were interviewed for the purpose of validating the framework via interviews. The majority of the SMEs are employed by the Western Cape provincial government in either the Department of Health or the Infrastructure and Technical Management Chief Directorate.

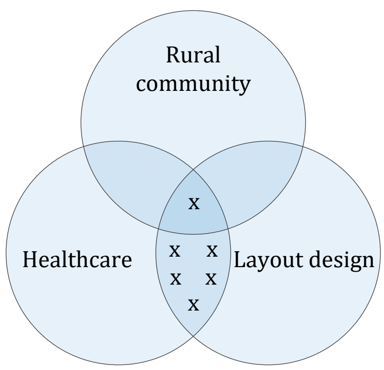


FIGURE 26: THE INTERVIEWEES' AREAS OF EXPERTISE

Figure 26 shows the three areas of focus of this study along with the expertise of each interviewee. Interviewees with expertise in more than one area are positioned where these areas overlap. It is clear that the areas of healthcare and layout design are thoroughly covered by the validators. The rural community area will be further validated in the application of the framework to a case study of a rural hospital to make up for the deficiency in rural community expert interviewees.

6.4.4 VALIDATION QUESTIONS

By interviewing a number of experts, a varied perspective can be achieved. The questions in Table 46 were posed to each interviewee.

TABLE 46: VALIDATION QUESTIONS

Area		**Validation questions**
Healthcare	1	Do you agree with the choice of departments included in the framework for designing a district hospital?
	2	Do you agree with the rooms included in each department?
	3	Do you think the relationship diagram is realistic? And do you think this is a useful way to decide upon the placement of each hospital department relative to another?
	4	Do you think the generated layout is practical from a healthcare point of view?
Rural community	5	Do you think the generated layout will be able to support the healthcare needs of the community or changed accordingly?
Construction	6	Do you think the framework can be useful for estimating the initial costs for a hospital that you are considering building?
	7	Do you think it can be useful for estimating the initial size of the hospital and its departments?
	8	Do you think the cost estimation is accurate enough to use during the initial planning phase of developing a new hospital?
	9	Do you think the methods used and calculations are appropriate for designing a hospital layout?
Laws and regulations	10	Do you think the framework shows an accurate summary of the applicable laws and standards?
	11	Do you think the summary of these guidelines can be deemed useful for a person who needs to design a hospital?
General	12	Do you think the framework is useful for generating an initial concept layout that architects and other members of the design team can use as input for the design process?
	13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?
	14	Are there any changes or additions to the framework that you think would be useful?

6.4.5 SUMMARY OF FEEDBACK FROM EXPERTS

After interviewing the experts, a document was sent to each one of them in order to gather their opinions, general comments, and recommendations for improvement. A copy of this document can be found in Appendix D.

6.4.5.1 Summary of validation question answers

Table 47 provides a short account of the feedback gained from the interviews with the experts.

TABLE 47 INTERVIEWEE FEEDBACK SUMMARY

Question	**Answer summary**
1	All the interviewees agreed with the choice of departments for designing a rural hospital layout included in the framework.
2	With the exception one interviewee, all the interviewees agreed with the rooms included in each department. One interviewee recommends that the new IUSS data should be used to determine which rooms to include in the layout.
3	Four interviewees agreed that the relationship diagram is realistic and that it is a useful way to decide upon the placement of each hospital department relative to another. One interviewee did not answer this question and another stressed that it is only useful for the initial stages of design.
4	Four out of six interviewees think that it is practical from a healthcare point of view. One interviewee mentioned that it would be helpful to consider the influence of IT in the design. Another stressed the importance of experience and precedent studies to support the initial inputs.
5	All the interviewees agreed that the generated layout will be able to support the healthcare needs of the community or changed accordingly.
6	Five of the interviewees agreed that the framework is useful for the estimation of the initial costs of the hospital. One interviewee recommends comparing the results with the IUSS's OOM estimator.
7	Four out of six interviewees agreed that it can be useful for estimating the initial size of the hospital and its departments.
8	All the interviewees agreed that the cost estimation is accurate enough to use during the initial planning phase of developing a new hospital.
9	All the interviewees agreed that that the methods used and calculations are appropriate for designing a hospital layout.
10	Four out of six interviewees agreed that the framework shows an accurate summary of the applicable laws and standards. One interviewee recommends that the new IUSS data would be useful to include in the summary.
11	All the interviewees find these guidelines useful for designing a hospital.
12	Four of the interviewees think that the framework is useful for generating an initial concept layout that architects and other members of the design team can use as input for the design process. One interviewee comments that the concept layout should be informed by broader issues such as size, location and form of the site, and the re-use of facilities.
13	All the interviewees are prepared to use this framework as an aid in the design phase of a rural hospital.
14	This question pertains to recommendations for the framework. Three interviewees agree that no changes are necessary. One interviewee recommends including the impact of information communication technology and hospital business processes. Another interviewee finds the framework useful, but recommends that it should be tested before using it. Another interviewee comments that it will be useful if it is fast to generate a layout, but recommends comparing the outputs to other similar trusted methods.

In conclusion, each of the validation questions was answered positively, with a few minor considerations for improvement. These will be addressed shortly before applying the framework to a case study.

6.4.5.2 Adjustments to framework

Based on the answers to the validation questions, the following areas of improvement were deemed necessary by the validators:

- **Usage of the Infrastructure Unit Support Systems (IUSS) guidelines:** The IUSS guidelines were up until recently not formally approved by the government of South Africa and for this reason it was not originally included in the framework. Some of these guidelines are still in the process of being approved (gazetted). The IUSS refers to voluntary standards or guidance documents that have been prepared as guidelines by the National Department of Health for the benefit of all South Africans. They are for the use of public as well as private healthcare providers. These guidelines were developed from a range of sources including local and international literature, expert opinion, practice, and expert group workshops. This was then compiled into a discussion document which was afterwards released for public comment. This feedback was consolidated into a new document which was again released for comment and review. Further feedback was incorporated into a proposal document and submitted to the National Department of Health. Once the government signs the document off, the documents have been approved or gazetted. Since the IUSS guidelines are new and based on years of research, it will be valuable to incorporate these guidelines into the framework. Consequently, these guidelines were analysed and the necessary sizes and rooms were updated in Appendix A as well as the Excel VBA program. This should make the estimation of the initial size and cost of the hospital more realistic and ultimately make the layout more practical;
- **Analysis of information communication technology (ICT)**: Information communication technology may play a significant role in the design of rooms within a department. However, the role of ICT on a department level is significantly less. Since the analysis of rooms within departments falls outside the scope of this study (as discussed in Section 1.7), the influence of ICT on the framework is considered insignificant;
- **IUSS's OOM (Order of Magnitude) estimator:** The purpose of this estimator is to enable the South African Department of Health to determine an order of magnitude budget for the medium term expenditure framework over the financial years during which the project will be planned and constructed (Steyn, 2014). Consequently, the framework includes not only the construction cost, but also professional fees, health technology cost, and commissioning cost. It was found that the OOM also uses a construction cost of R14,250/m^2 to estimate the construction cost of a district hospital. However, the size of a new district hospital is estimated to be 90m^2 per bed. This value will vary from hospital to hospital since the sizes of rooms and departments included in the layout are different. Therefore, it can be argued that the developed framework is a better estimation for the initial size of a hospital layout; and
- **Testing the framework:** The framework is applied in the next section to a case study.

The framework has therefore been adjusted in line with the recommendations made by SMEs during the interview based validation. The developed framework is now applied to a case study which forms the second part of the validation process.

6.5 Case study

In order to show that the developed framework is useful in real world problems, it is now applied to the case study of the Semonkong Hospital Project (SHP). Firstly, a background on the SHP is provided.

Secondly, the framework is applied and the results are discussed. Lastly, feedback from the architects involved with the SHP is given.

6.5.1 THE SEMONKONG HOSPITAL PROJECT

This section provides background on the SHP and focuses specifically on the rational for a new hospital, governance of the new hospital, the role of the new hospital, applicable laws and standards, and construction and site planning.

6.5.1.1 Rationale for a new hospital

Within the Semonkong region of Lesotho there is currently a need for an optimally designed hospital plan adequate to serve the general community. If there is an emergency, residents from this community will have to travel approximately 115 kilometres to the nearest hospital which is located in Maseru. The ability to do so is further restricted by the availability of ambulances (Semonkong Hospital Project, 2014). The SHP was initiated by a few medical students from the University of the Free State. These students found the remains of an abandoned hospital in the mountains of Semonkong during July of 2005. As a result they have since decided to build a new hospital to serve the rural community of Semonkong and call it the Jehovah Shammah Hospital (which can be translated to City of the Lord). The fact that there is no such hospital anywhere near the proposed site which has the required capacity further motivates the need for this hospital. The problem of designing the layout of this hospital fits the criteria of the developed framework of this study, namely a new district hospital that aims to serve the surrounding rural community.

6.5.1.2 Governance of a new hospital

The SHP is governed by a number of stakeholders, including members of the International Mission Hospital Trust, members of the Semonkong Hospital Trust, nursing professionals of the local healthcare clinics, project architects, members from the local community, and the advisory board of the Trusts. The architects involved with the SHP are selected as the ideal validators for the developed framework of this study.

The new hospital will function as a private hospital funded by the Trust and is financially independent from the Government of Lesotho. A Memorandum of Understanding between the Ministry of Health (Lesotho) and the Trust was signed in May of 2014. This grants the Trust permission to develop the hospital and establish the parameters of cooperation between the Ministry and the Trust.

6.5.1.3 The role of the Jehovah Shammah Hospital

The main purpose of the Jehovah Shammah Hospital is to provide effective, affordable health care services to the Semonkong community. These services are not intended to duplicate the services of the current clinics, but rather to complement the health activities of the community by providing support for patient referral as well as various administrative, educational, and technical activities. It is therefore essential that training facilities and appropriate accommodation are provided for visiting medical specialists, general practitioners, nurses, allied healthcare workers, and international students.

6.5.1.4 Applicable laws and standards

The Jehovah Shammah Hospital must be constructed and operated in accordance with all the applicable Lesotho laws and standards. However, Lesotho has no formal building regulations. An architect of the Queen Mamohato Memorial Hospital in Maseru recommended the use of South African building regulations along with consultations with the Lesotho authorities during the design phase.

The SHP identified the following documents and references for building regulations:

- South African National Building Regulations SANS10400;
- South African Occupational Health and Safely Act Regulations; and
- South African Regulations Governing Private Hospitals and Unattached Operating Theatre Units (R158).

The South African Occupational Health and Safely Act Regulations are relevant to the detailed design of a hospital but insignificant to the block layout design. The other two regulations are however applicable to the block layout design and as such, both of these were included in the framework in Section 4.2.

In conclusion, the relevant regulations are included in the framework as well as the new IUSS guidelines which were deemed a valuable contributor in designing a hospital layout.

6.5.1.5 Construction considerations

The SHP identified the following design considerations for Jehovah Shammah Hospital:

- High-performance solutions, but low-technical design solutions where possible;
- Ease of use should be target of design;
- Placement of elements and departments should result in an optimal interrelationship among departments;
- Creation of unity, an interflow and interaction of people working together; and
- Economical in space use.

Additional to a new hospital, a veterinary facility, and staff accommodation are also included in the construction plan of the SHP. The available site for these three facilities is shown in Figure 27.

FIGURE 27: THE SEMONKONG HOSPITAL PROJECT'S SITE SPACE

6.5.2 APPLICATION OF THE FRAMEWORK TO THE CASE STUDY

In this section the seven steps of the developed framework are applied to the Jehovah Shammah Hospital.

6.5.2.1 Step 1 Inputs

The first step defines the characteristics of the hospital layout. The following factors are addressed in this step: rural population size, occupancy rate, circulation space, construction cost, and optional departments.

The SHP estimated the population size of Semonkong as 89,717 (Graham, 2016). This value was entered into the program. The suggested values for the occupancy rate, circulation space, and construction cost were selected (85%, 28%, and R14,250/m^2 respectively). Lastly, no optional departments were selected.

6.5.2.2 Step 2 Hospital beds

Since the developed framework's calculations are based on South African population data, the relevant values are changed to suit the population of Lesotho. Lesotho has a population of 1,741,000 (Lesotho Bureau of Statistics, 2015). The following data relevant to Lesotho was found, namely the average length of stay in Lesotho being 4.99 days, and the admissions per year being 47,865 (Graham, 2016). Consequently, the admission rate per year is 1 in every 36.35 of the population (equal to 6.76 admissions per day). With these new values and the population size of Semonkong taken as being 89,717, the framework suggests 40 beds for the Jehovah Shammah Hospital. However, the SHP predicts an increase in hospital admissions and population growth and plans to build a long term hospital for 120 beds. This value was therefore selected for the next steps.

6.5.2.3 Step 3 Beds per department

This step recommends the number of hospital beds to the user and allows the user to select the number of beds. The suggested number of beds, and selected number of beds for the Jehovah Shammah Hospital are shown in Table 48.

TABLE 48: SUGGESTED AND SELECTED NUMBER OF BEDS FOR THE JEHOVAH SHAMMAH HOSPITAL

Department	**Suggested number of beds**	**Selected number of beds**
Administration	0	0
Obstetrics	24	20
Operating Suite	2	0
Paediatric Unit	24	26
Outpatient Unit	20	10
Laundry	0	0
Kitchen	0	0
Sterilisation and Disinfection Unit	0	0
Pharmacy	0	0
Emergency and Casualty Unit	7	16
Surgical Unit	12	10
Chronic Care Unit	26	30
Rehabilitation Unit	5	8
Mortuary	0	0
Laboratory	0	0
Radiology	0	0
Total number of beds	120	120

The SHP decided not to include an Acute Psychiatric Unit in their layout. They plan to use single rooms in the hospital for psychiatric patients. Additionally, they plan to include a separate unit for a surgical ward away from the other wards. This unit is further discussed in the next step.

6.5.2.4 Step 4 Relationship chart

This step determines which departments should be placed close together and which ones should be separated. The SHP plans to include a surgical ward. This unit is different from the CCU in that it has a very close relationship with the operating suite, ICU, and HCU (Van der Schyf & Fleming, 2014). A new relationship diagram is suggested which was also selected for the Jehovah Shammah Hospital. This is shown in Figure 28.

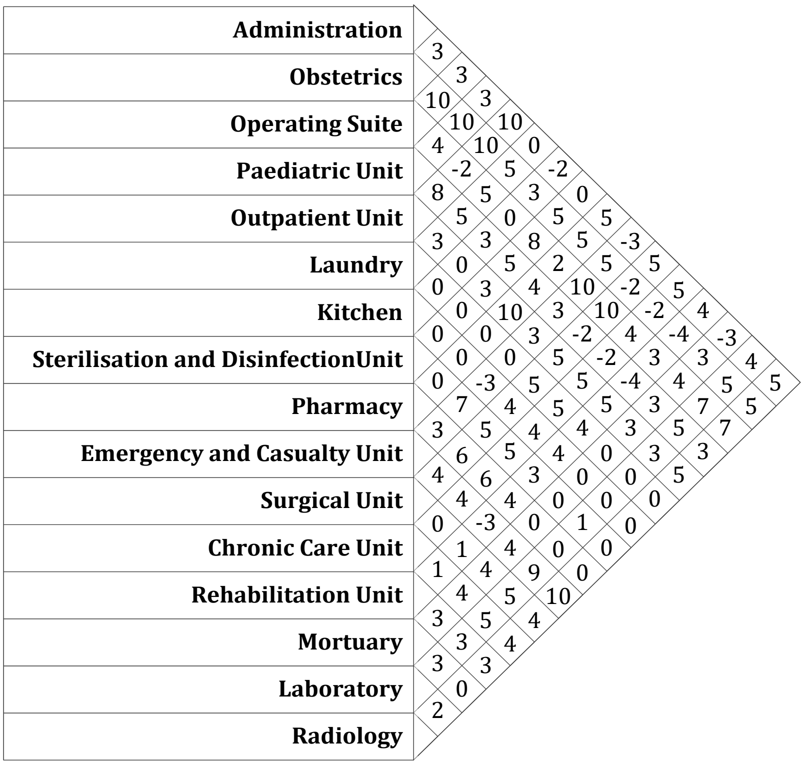


FIGURE 28: DEPARTMENT RELATIONSHIPS SUGGESTED AND SELECTED FOR THE JEHOVAH SHAMMAH HOSPITAL

6.5.2.5 Step 5 Hospital departments

The sizes of rooms in each hospital department were selected. Refer to Appendix A for the minimum areas of each hospital room.

6.5.2.6 Step 6 Summary

This step shows a summary of the sizes (generated in step 5) and construction cost of each department in the Jehovah Shammah Hospital. This is shown in Table 49.

TABLE 49: SUMMARY OF THE SIZES AND COSTS OF EACH DEPARTMENT IN THE JEHOVAH SHAMMAH HOSPITAL

Departments	Sum of room sizes (in m²)	Circulation space (in %)	Total area (in m²)	Cost per department (in Rands)
Administration	202	20	242	3 448 500
Obstetrics	306	30	437	6 227 250
Operating Suite	65	19.5	333	4 745 250
Paediatric Unit	174	30	249	3 548 250
Outpatient Unit	451	20	564	8 037 000
Laundry	102	10	113	1 610 250
Kitchen	153	25	204	2 907 000
Sterilisation and Disinfection Unit	89	25	118	1 681 500
Pharmacy	834	15	981	13 979 250
Emergency and Casualty Unit	792	14.6	927	13 209 750
Surgical Unit	228	30	325	4 631 250
Chronic Care Unit	910	30	1 300	18 525 000
Rehabilitation Unit	210	15	247	3 519 750

SUMMARY OF THE SIZES AND COSTS OF EACH DEPARTMENT IN THE JEHOVAH SHAMMAH HOSPITAL (CONTINUED)

Mortuary	53	15	62	883 500
Laboratory	27	15	31	441 750
Radiology	180	15	209	2 978 250
Total area of hospital rooms	4 774	-	-	-
Total area of hospital	-	-	6 342	-
Total cost	-	-	-	90 373 500

Consequently, a total floor area of 6,342m² is required and will cost approximately R90,373,500 to build the Jehovah Shammah Hospital.

6.5.2.7 Step 7 Approximate the optimal layout using Simulated Annealing

Before using RStudio to approximate the optimal layout solution for the Jehovah Shammah Hospital, it is necessary to consider the site space as well as the dimensions of each department. The areas of each hospital department were chosen to be divided into 4 by 4 meter blocks. The resulting number of blocks required is shown in Table 50. Suggestions for dimensions of each department are also shown.

TABLE 50: DIMENSIONS AND NUMBER OF BLOCKS REQUIRED FOR THE JEHOVAH SHAMMAH HOSPITAL

Departments	**Area (in m²)**	**Number of blocks required**	**Dimensions (in number of blocks)**
Administration	242	15.1	4 x 4
Obstetrics	437	27.3	4 x 7
Operating Suite	333	20.8	4 x 5
Paediatric Unit	249	15.6	4 x 4
Outpatient Unit	564	35.3	6 x 6
Laundry	113	7.1	3 x 3
Kitchen	204	12.8	4 x 3
Sterilisation and Disinfection Unit	118	7.4	3 x 3
Pharmacy	981	61.3	8 x 8
Emergency and Casualty Unit	927	57.9	7 x 8
Surgical Unit	325	20.3	4 x 5
Chronic Care Unit	1 300	81.3	9 x 9
Rehabilitation Unit	247	15.4	4 x 4
Mortuary	62	3.9	2 x 2
Laboratory	31	1.9	2 x 2
Radiology	209	13.1	4 x 3
Total area of hospital	6 342	-	-
Total number of blocks required	-	403	-

From the calculations in Table 50 it is clear that 403 blocks of 4 by 4 meters each are required for building the hospital. The available site space will now be considered.

The site space for the SHP (previously shown in Figure 27) is obtained for three types of buildings, namely the Jehovah Shammah Hospital, a veterinary facility, and staff accommodation. The 103 meter reference line (from Figure 27) can be used to approximate the large rectangle (shown in Figure 29) as

326 by 120 meters. This rectangle can be divided into 81 by 29 blocks (2,430 blocks). However, only 403 blocks are necessary for building the hospital. Therefore, it was decided to use 500 blocks as the available space for the hospital (indicated as the blue rectangle in Figure 29).

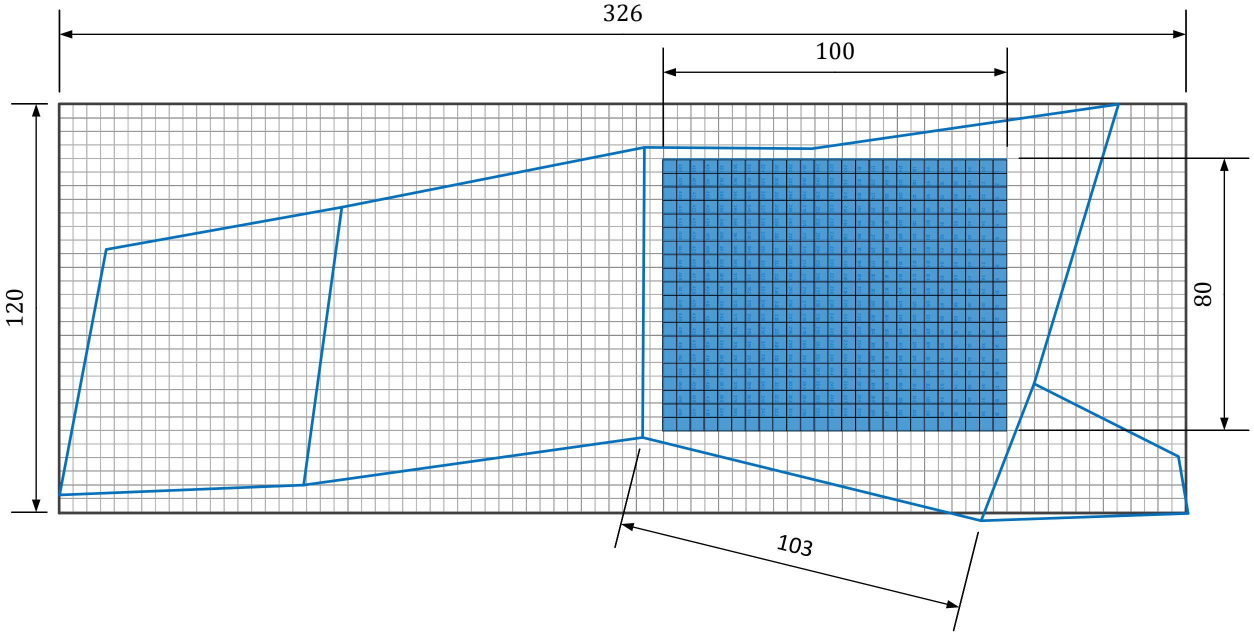


FIGURE 29: DIMENSIONS FOR THE SITE OF THE JEHOVAH SHAMMAH HOSPITAL

The 500 blocks for the hospital can be divided into 20 by 25 blocks. This is shown in Figure 30 along with the possible locations (456 in total) of the centres of the departments of the Jehovah Shammah Hospital.

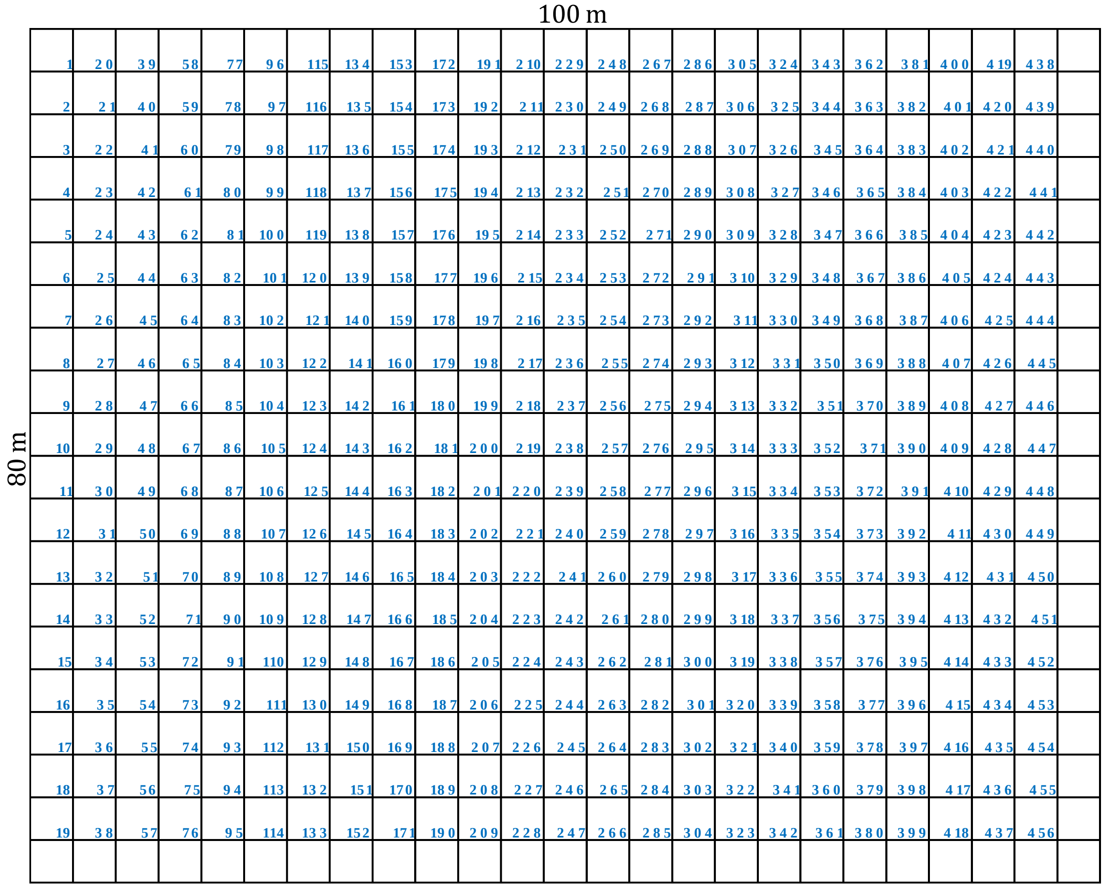


FIGURE 30: POSSIBLE LOCATIONS OF CENTRES OF THE DEPARTMENTS OF THE JEHOVAH SHAMMAH HOSPITAL

Based on calculations of step 7, the RStudio program was used. The values of the input variables include: n equals 16, m equals 456, f refers to the relationship diagram in Figure 28, d refers to the distances between the locations (matrix with 207,936 elements), and t_{ij} refers to fixed cost of placing departments (matrix with 7296 elements). The program was run for 10,000 iterations and took approximately 10 minutes. The solution is shown in Figure 31. An objective function value of 12,234 was obtained.

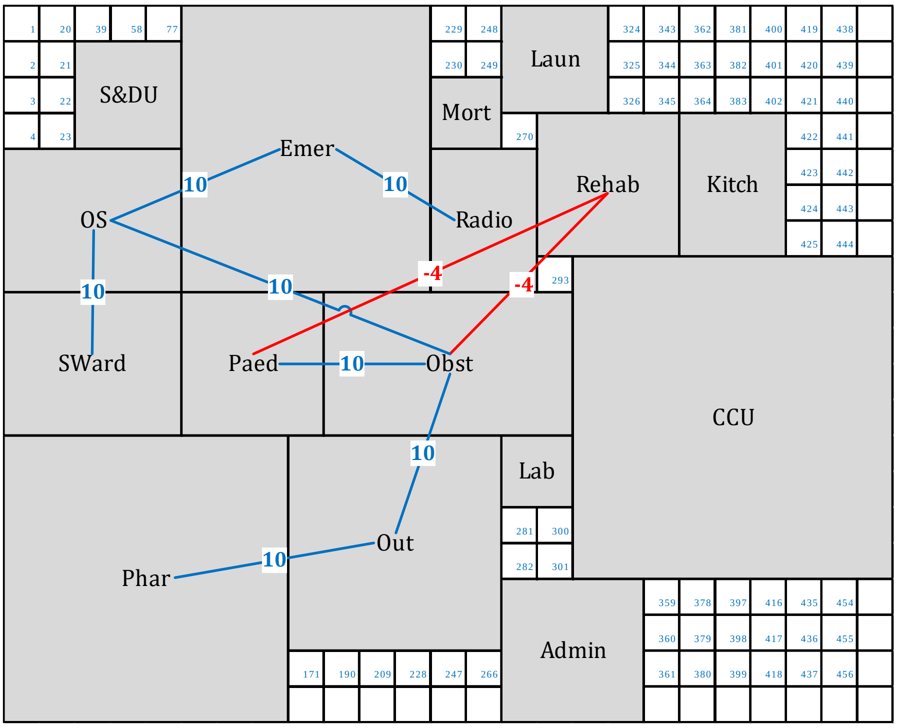


FIGURE 31: PROPOSED LAYOUT OF THE JEHOVAH SHAMMAH HOSPITAL

Table 51 show the relationships that have the highest positive ratings (a rating of 10 refers to absolutely necessary). The distances of between the centroids of these departments are indicated as well as their adjacency. Furthermore, the most important negative relationships are shown (a rating of -3 indicates an undesirable relationship). It is clear that the most important relationships are adhered to and the departments with negative relationships are placed apart.

TABLE 51: EVALUATION OF THE PROPOSED LAYOUT FOR THE JEHOVAH SHAMMAH HOSPITAL

Department relationship	**Priority rating**	**Centroid distance (in blocks)**	**Adjacent**	**Department relationship**	**Priority rating**	**Centroid distance (in blocks)**	**Adjacent**
Admin-Out	10	8	Yes	Admin-SWard	5	22	No
Obst-Paed	10	5	Yes	Admin-Phar	5	14	No
Obst-Out	10	6	Yes	Admin-Radio	5	15	No
OS-Emer	10	8	Yes	Obst-Laun	5	12	No
OS-SWard	10	4	Yes	Paed-Laun	5	17	No
Out-Phar	10	8	Yes	Paed-S&DU	5	12	No
Emer-Radio	10	7	Yes	Paed-Lab	5	11	No
Obst-OS	10	14	No	Out-SWard	5	14	No
Emer-Lab	9	16	No	Out-CCU	5	13	No
OS-S&DU	8	5	Yes	Out-Rehab	5	16	No
Paed-Out	8	9	Yes	Out-Radio	5	11	No
S&DU-Emer	7	7	Yes	Laun-SWard	5	22	No
OS-Lab	7	20	No	Laun-CCU	5	15	No
OS-Radio	7	11	No	S&DU-SWard	5	9	No
Phar-Sward	6	8	Yes	S&DU-CCU	5	26	No
Phar-CCU	6	21	No	SWard-Lab	5	16	No

EVALUATION OF THE PROPOSED LAYOUT FOR THE JEHOVAH SHAMMAH HOSPITAL (CONTINUED)

Admin-CCU	5	11	Yes	OS-Laun	5	18	No
Obst-Emer	5	10	Yes	Admin-Emer	-3	22	No
Obst-Lab	5	6	Yes	Admin-Mort	-3	18	No
Obst-Radio	5	5	Yes	Kitch-Emer	-3	13	No
CCU-Lab	5	7	Yes	Emer-Rehab	-3	10	No
Obst-S&DU	5	17	No	Obst-Rehab	-4	10	No
Obst-Phar	5	14	No	Paed-Rehab	-4	15	No

Another layout arrangement was generated (shown in Figure 32) using a larger site area in the hopes of finding an improved solution without the constraint of the available site area. A site size of 806 blocks (750 possible locations for the centroids of the departments) was used. The program was run for approximately 11 minutes and 10,000 iterations. An objective function value of 37,743 was obtained which is an improvement upon the previous solution since the QSCP is formulated as a minimisation problem. According to this solution, a site area of 84 by 100 meters is required for the optimal layout of the Jehovah Shammah Hospital. The two layout solutions are very similar with the exception of the administration department and the kitchen (outlined in red in Figure 32).

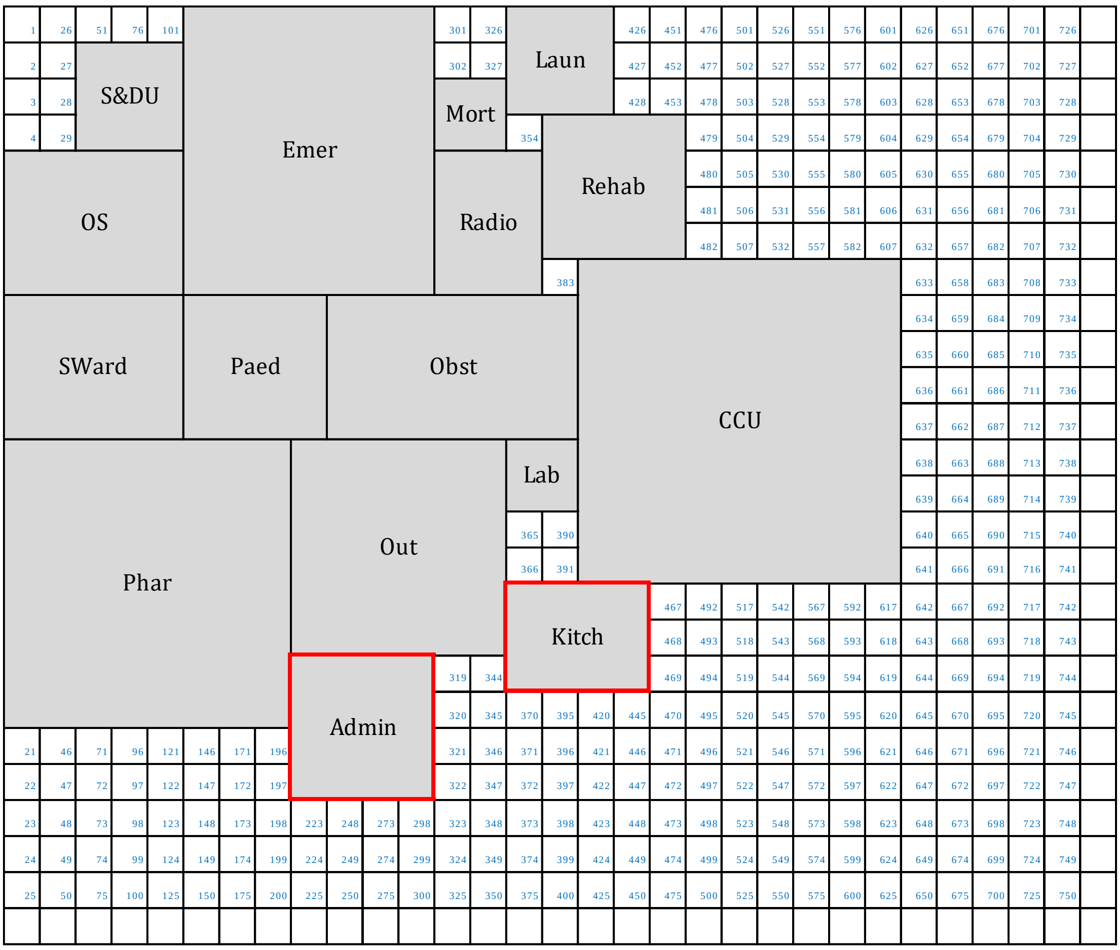


FIGURE 32: RSTUDIO SOLUTION OF THE JEHOVAH SHAMMAH HOSPITAL USING A LARGER SITE AREA

6.5.3 FEEDBACK FROM THE SEMONKONG HOSPITAL PROJECT

Three architects involved with the SHP agreed to act as validators for this study. The validation questions given in Section 6.4.4 were presented to them.

6.5.3.1 Summary of the validation question answers

Table 52 provides a short account of the feedback gained from the interviews with the experts.

TABLE 52 SEMONKONG HOSPITAL PROJECT INTERVIEWEES FEEDBACK SUMMARY

Question	**Answer summary**
1	All the interviewees agreed with the choice of departments for designing a rural hospital layout included in the framework.
2	All the interviewees agreed with the rooms included in each department.
3	All the interviewees agreed that the relationship diagram is realistic and that it is a useful way to decide upon the placement of each hospital department relative to another.
4	One interviewee fully agrees that it is practical form a healthcare point of view. Another one mentioned that it is a reasonable starting point for an architectural team to work with in consultation with medical staff. Another interviewee commented that it is practical from a relationship point of view but not necessary from a dimensional one.
5	Two interviewees agreed that the generated layout will be able to support the healthcare needs of the community or changed accordingly. Another one did not provide an answer since the interviewee believes that there are so many factors that support healthcare needs (not just the layout) that it is nearly impossible to answer.
6	Two interviewees agreed that the framework is useful for the estimation of the initial costs of the hospital. Another interviewee commented that if the framework generates a fair rate (with the required inclusions/exclusions), it would be appropriate to use for an initial cost estimate.
7	All the interviewees agreed that it can be useful for estimating the initial size of the hospital and its departments.
8	Two interviewees mentioned that it using the cost estimate of the framework during the initial designing phase of a new hospital depends on how much tolerance you are willing to accept in budgeting, but it could be useful in the very early design phases as long as it is understood to be a rough indicator. Another interviewee commented that it could be useful if the newest 2016 figures are used in the calculations.
9	Two interviewees agreed that the methods used and calculations are appropriate for designing a hospital layout. Another interviewee stressed that it can be useful to inform the designer, but should not be used by itself to design the final layout.
10	All the interviewees agreed that the framework shows an accurate summary of the applicable laws and standards.
11	All the interviewees find these guidelines useful for designing a hospital.
12	All the interviewees agreed that the framework is useful for generating an initial concept layout that architects and other members of the design team can use as input for the design process.
13	All the interviewees are prepared to use this framework as an aid in the design phase of a rural hospital.
14	Two interviewees agreed did not find any necessary changes or additions to make to the framework. Another interviewee recommended more flexibility regarding the shape of the site.

In conclusion, the SHP architects responded in a positive manner to each of the validation questions.

6.5.3.2 General comments and adjustments

According to one of the interviewees the latest figure on estimating costs is R25,737/m^2 (estimated in March 2016). This new value is thus included in the framework. This interviewee further suggested that a value of R28,835/m^2 should have been used in the cost estimation since the site of the Jehovah Shammah Hospital is remote and transportation of building materials will have a significant impact on this value. The framework allows for such changes during Step 1. Thus, the new estimated cost of the Jehovah Shammah Hospital is R182,871,570.

One of the architects stated that the framework deals with a conundrum every architect designing a hospital faces and that some statistical backup to make decisions in terms of adjacencies are appealing. All three architects of the SHP are prepared to use this framework as an aid in the designing phase of the Jehovah Shammah Hospital and they find it useful for generating an initial concept layout.

6.6 Conclusion

In this chapter, the accuracy of the developed framework was verified, and validated through two routes.

To begin with, it was determined that there exist three possible routes to validate the framework of this study, namely expert analysis, application to a case study, and implementation. Implementation was determined as infeasible and therefore the remaining two routes were followed.

Firstly, a subject-matter expert analysis was employed through conducting interviews with six experts knowledgeable in the areas of layout design, rural communities, and healthcare. As a whole, all the interviewees were supportive of the framework. According to their recommendations, the necessary adjustments were made to the framework before validating it further.

The second route to validation involved applying the framework to the case study of the Semonkong Hospital Project. Three architects involved with this project acted as further validators for the framework. They responded in a positive manner and are prepared to use the results of the case study as an input into the hospital that they are planning to build.

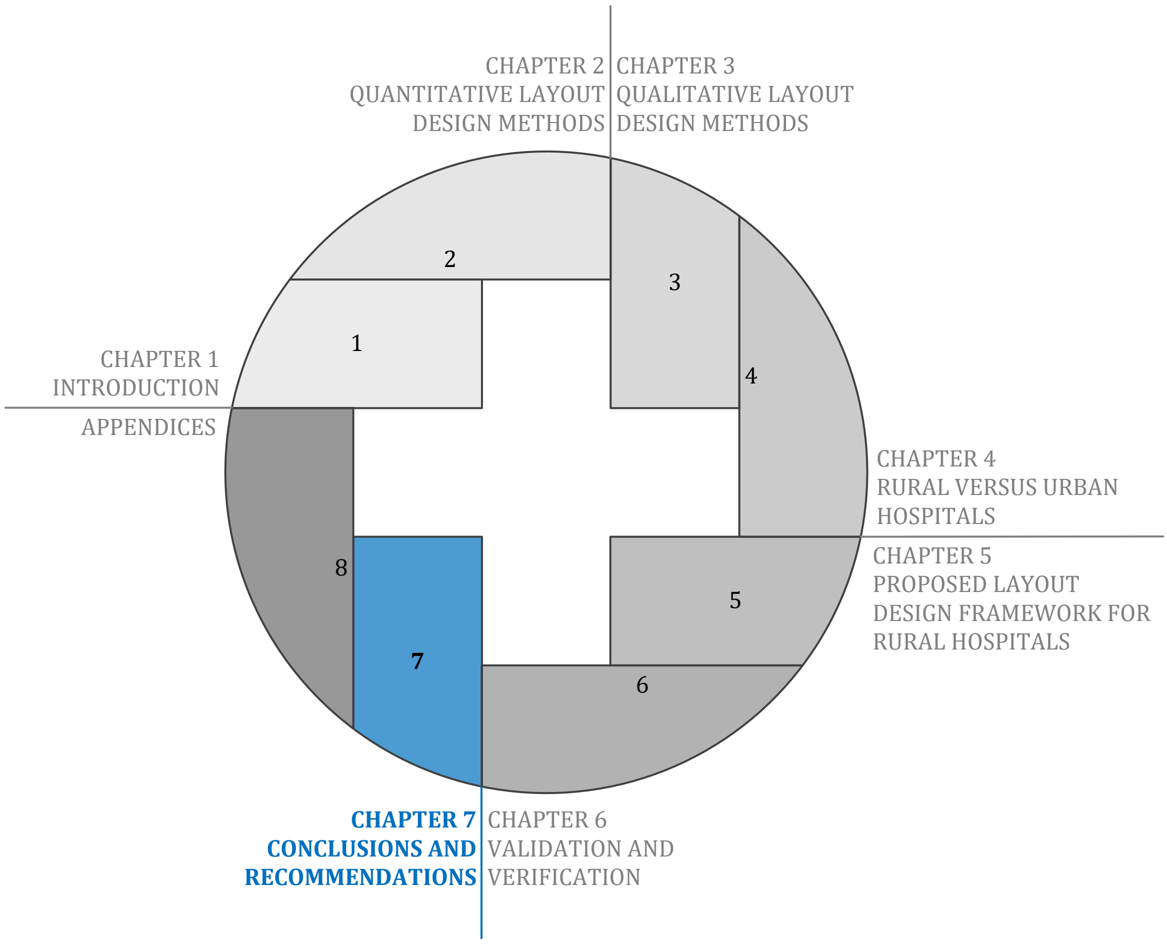
Thus both routes confirmed the validity of the framework and potential for further research were identified, which is discussed in the final chapter.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

"Many discoveries are reserved for ages still to come, when memory of us will have been effaced."

Seneca (2010)



7.1 Introduction

In this chapter, a summary of the research findings of each chapter are presented followed by a discussion of the contributions of the study. Recommendations for future research based on the foundations laid by this study are also discussed.

7.2 Research summary

The thesis opened in Chapter 1 with a discussion of the importance of designing a layout that is functional and supports its operations. The purpose of this study was defined as the development of a layout design decision-support framework and concept demonstrator for rural hospitals using mixed methods. The research methodology involved a concurrent mixed methods approach. It was later on determined that the quantitative and qualitative layout design methods can be integrated via embedding. Thus the research follows a concurrent transformation approach with embedding design features.

Chapter 2 provided an analysis of quantitative layout design methods used for modelling as well as solving layouts. Seven popular layout models were identified, compared, and their mathematical formulations presented. Exact methods and metaheuristics as a means to solve these models were examined. It was found that metaheuristics are commonly used by researchers to approximate the optimal solution of these layout models since the computation time increases significantly with the problem size. Computer-based algorithms for constructing and improving layouts were also discussed.

The qualitative layout design methods and hospital considerations were presented in Chapter 3. Three traditional qualitative approaches to solving the FLP were presented and analysed. It was found that some of the steps of Muther's SLP Procedure can be combined with a layout model analysed in Chapter 2. An investigation was conducted into the most important design considerations applicable to hospital layouts in literature. The results involved considerations related to: patient-centeredness, efficiency, flexibility and expandability, sustainability, and therapeutic environments. The way in which these considerations relate to the layout models presented in Chapter 2 was determined.

In order to understand the context of a rural hospital, the differences and similarities between urban and rural hospitals were investigated in Chapter 4. The most important standards and regulations associated with hospital design pertaining to the floor layout were found to be the National Core Standards and Regulations 158. Using these regulations as well as other guides found in literature, the minimum room areas and departments of a district hospital were identified. The specific difficulties faced in rural settings were deliberated upon to arrive at what appears to be the most important considerations for the layouts of rural hospitals: minimise costs and patient flow through the hospital.

The layout design decision-support framework and concept demonstrator for rural hospitals was developed in Chapter 5. The most appropriate layout model and solution method were determined to be the QSCP formulation and SA respectively. Using these methods and the minimum prescribed areas for each hospital room and department, a user interface was developed using Excel VBA and RStudio. These programs guide the user in adhering to the requirements of the applicable laws and guidelines whilst approximating the optimal hospital layout according to the user's preferences. Four examples of the output of this decision-support framework were also discussed. It was found that the output of each example clearly models the specifications of the layout (i.e. input variables).

In Chapter 6 the decision-support framework was verified and then validated via subject-matter expert analysis and a case study on the Jehovah Shammah Hospital. A total of nine experts knowledgeable in the areas of layout design, rural communities, and healthcare were interviewed. As a whole, every validator responded positively to the framework and each one indicated that they are prepared to use the framework as an aid in the initial design phase of a rural hospital. A few minor recommendations were incorporated into the framework before applying it to the case study. The case study received positive responses from architects who are prepared to use the results of the framework.

7.3 Research contributions

The research contributes to both the academic literature and the design teams of rural hospitals. It adds to the academic literature by applying quantitative and qualitative layout design methods to a real world problem, i.e. designing the layout of a rural hospital. It was acknowledged in Chapter 2 that very few quantitative layout design methods focused on hospital layouts and no study was found that uses the QSCP formulation for modelling a hospital layout. It also adds to literature regarding a mixed methods approach. The chosen quantitative and qualitative layout methods were integrated via embedding. This resulted in the framework generating a layout based on ideal adjacencies or preferences of the designer. These ideal adjacencies were suggested according to research conducted on each hospital department. Thus, the relationship diagram generated in this study adds to hospital layout design literature.

The design teams of rural hospitals can benefit from this research by using the design decision-support framework and concept demonstrator to generate a near optimal layout according to preferences while taking the necessary laws into account. This study provides a summary of the South African laws and standards applicable to layout design, the key hospital design considerations, and design considerations specific to rural hospitals. Although the focus was on rural hospitals, the framework is appropriate for designing a district hospital in an urban setting since all the necessary laws and standards are taken into account and the user of the framework is able to change inputs according to their preferences. Lastly, the SHP benefits by the results of the application of the framework to the Jehovah Shammah Hospital.

7.4 Recommendations for future research

In this study quantitative and qualitative layout design methods were used to generate near optimal arrangements of departments of district hospitals. Using the foundations of this research, it is suggested that future studies could involve the following:

- **Optimising the arrangement of rooms within each hospital department:** The minimum areas and rooms for each hospital department were already determined. This could be a valuable input for the detailed design of a hospital. It is also suggested to adapt the framework to include corridors and fixed points; and
- **Scaling the framework to other types of hospitals:** Regional hospitals, provincial tertiary hospitals, central hospitals, and specialised hospitals are also part of the healthcare delivery system. Further research can involve adjusting the framework for multi-floor layouts.

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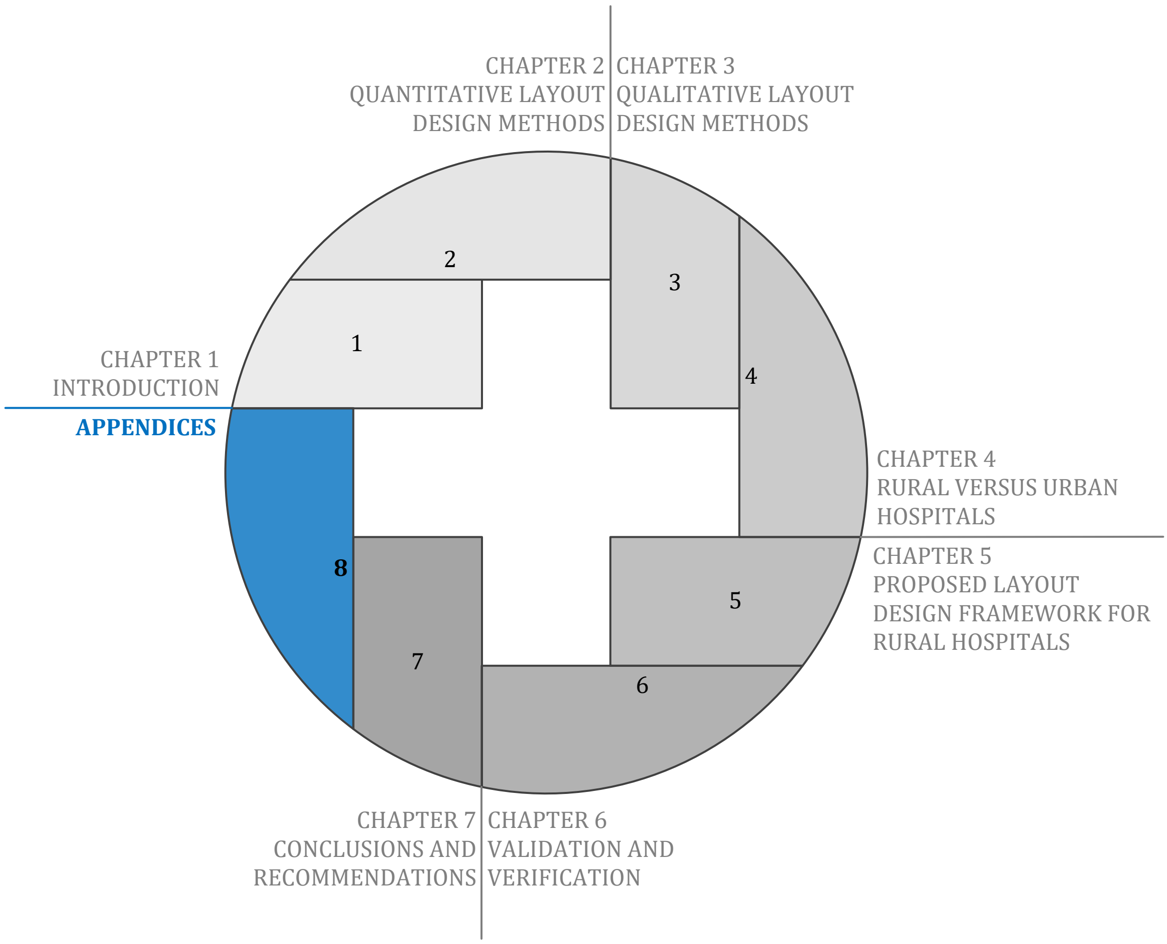
APPENDICES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APPENDIX A: HOSPITAL LAYOUT CONSTRAINTS

TABLE 53: ADMINISTRATION CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Chief executive officer's office	36		Broekmann and Steyn (2014)
Meeting room	30		Department of Health (2004); Broekmann and Steyn (2014)
HR manager	36	x	Department of Health (2004); Broekmann and Steyn (2014)
Clinical manager	25	x	Department of Health (2004); Broekmann and Steyn (2014)
Nursing services manager	25	x	Sharma and Sharma 2007)
Admin manager	25	x	Broekmann and Steyn (2014)
Financial manager	25	x	Broekmann and Steyn (2014)
Staff restroom	30		Broekmann and Steyn (2014)
Toilets	6		Broekmann and Steyn (2014)
Store (stationery)	6		Broekmann and Steyn (2014)
Store (general)	6		Broekmann and Steyn (2014)
Waiting area	25		KwaZulu-Natal Department of Health (2010); Department of Health (2004); Steyn (2014)
Registry	80	x	Broekmann and Steyn (2014)
Cashier	9		Broekmann and Steyn (2014)

TABLE 54: OBSTETRICS CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Maternity unit			
Reception and admissions desk	6		Steyn (2014)
Security area	6		Broekmann and Steyn (2014)
Wheelchair and trolley bay	12		Broekmann and Steyn (2014)
Main waiting area	52		Fleming (2014)
Child play area	12	x	Van der Schyf and Flemming (2015)
Public ablutions	8		Fleming (2014)
Assessment room with toilet and shower	25		Van der Schyf and Flemming (2015)
Unit manager's office	20		Van der Schyf and Flemming (2015)
Doctors' offices	20		Van der Schyf and Flemming (2015)
Staff overnight room with suite toilet and shower (May be shared with postnatal ward if small unit)	9		Fleming (2014)
Dedicated obstetric operating theatre	40	x	Van der Schyf and Flemming (2015); Medical Practice and Licensing Sector (2013)
Training facilities (May be shared with postnatal ward if small unit)	30	x	Steyn (2014)
Staff room	20		Fleming (2014)
Staff changing room	12		Fleming (2014)

Staff shower	2		Fleming (2014)
Staff toilet	2		Fleming (2014)
Delivery room	22		Van der Schyf and Flemming (2015)
Toilets	6		Van der Schyf and Flemming (2015)
Shower	2		Fleming (2014)
Nurses' station	14		Van der Schyf and Flemming (2015)
Clean utility	12		Fleming (2014)
Cleaner's room	4		Fleming (2014)
Dirty utility room	9		Fleming (2014)
X-ray equipment bay	12		Assume similar to trolley bay (Van der Schyf & Flemming, 2015)
IT room	4		Fleming (2014)
Store (medicine, clean linen, consumable and sterile stock, and equipment)	14		Broekmann and Steyn (2014)
Antenatal ward			
Bed area	8.3		National department of health (2013)
Toilets	6		Van der Schyf and Flemming (2015)
Patients' lounge	12		Assume similar to rest room (Van der Schyf & Flemming, 2015)
Storage	6		Broekmann and Steyn (2014)
Nurses' station	6		National department of health (2013)
Consulting rooms	12		Flemming (2014)
Counselling room	10		Flemming (2014)
High-dependency unit			
Bed area	22	x	Van der Schyf and Flemming (2015)
Toilets	6	x	Van der Schyf and Flemming (2015)
Shower	2	x	Fleming (2014)
Nurses' station	14	x	Railoun and Van der Schyf (2014)
Storage	6	x	Broekmann and Steyn (2014)
Postnatal ward			
Postnatal bed area	8.43		National department of health (2013)
Kangaroo mother care bed unit (7.5 per bed)	7.5		Van der Schyf and Flemming (2015)
Toilets (1 per 6 mothers)	6		Van der Schyf and Flemming (2015)
Bath (1 per 6 mothers)	2		Assume similar to shower (Broekmann & Steyn, 2014); (Beach, 2011)
Well-baby nursery (1.5 per basinet)	35	x	Van der Schyf and Flemming (2015)
Day lounge	12		Assume similar to rest room (Van der Schyf & Flemming, 2015)
Storage	6		Broekmann and Steyn (2014)
Cleaner's room	4		Fleming (2014)
Clean utility room	12		Fleming (2014)
Day room	12		Assume similar to rest room (Van der Schyf & Flemming, 2015)
Dirty room	9		Fleming (2014)

Kitchen	8		Railoun and Van der Schyf (2014)
Laundry area	6		Assume similar to general store (Van der Schyf & Flemming, 2015)
Store (clean linen and general)	14		Van der Schyf and Flemming (2015)

TABLE 55: OPERATING SUITE CONSTRAINTS

Requirements		**Minimum area (in m²)**	**Optional**	**References**
Operating room	*Minor*	20		National department of health (2013); Van Reenen (2014)
	General	40		
	Trauma	49		
	Cath lab	49		
	Digital	49		
	General endoscopy	55		
	Urology	55		
	Orthopaedic	60		
	Neurosurgery and spinal	60		
Reception		9		Van Reenen (2014)
Unit manager's office		20	x	Van Reenen (2014); Broekmann and Steyn (2014)
Staff change rooms (4 per person/8 per theatre)		4		National department of health (2013); Van Reenen (2014)
Storage (personal protective equipment)		2		Van Reenen (2014)
Patient-holding bay		9		Van Reenen (2014)
Resuscitation trolley bay		2		Van Reenen (2014)
Recovery area		12		Van Reenen (2014)
Staff rest room		25	x	Broekmann and Steyn (2014)
Anaesthetic induction room (optional)		16	x	National department of health (2013); Van Reenen (2014)
Storage (mobile equipment)		5		Van Reenen (2014); Broekmann and Steyn (2014)
Blood store		5		Van Reenen (2014)
Storage (special instruments)		9		Van Reenen (2014)
Storage (pharmaceutical)		9		Van Reenen (2014)
Scrub-up/gowning room		11		Van Reenen (2014)
Set up room (preparation room) (or 20 for 2)		12		National department of health (2013); Van Reenen (2014)
Sluice		9		Van Reenen (2014)

TABLE 56: PAEDIATRIC UNIT CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Paediatric Inpatient Facility			
Bed/cot area	14		Flemming (2014)
Basinet area (0 to 4 months old)	8.2		Flemming (2014)
High Care Unit (8% of beds)	14.14	x	Flemming (2014)
Isolation bed	14.1	x	Flemming (2014)

Waiting area	40	x	Broekmann and Steyn (2014)
Playroom	12	x	Van der Schyf and Flemming (2015)
Toilets (1 per 8 patients)	2		Flemming (2014)
Bath (1 per 8 patients)	2		Assume similar to shower (Broekmann & Steyn, 2014); (Beach, 2011)
Shower (1 per 12 patients)	2		Fleming (2014)
Sister's office	12	x	Fleming (2014)
Staff room	20	x	Fleming (2014)
Staff ablutions	2		Fleming (2014)
Staff lockers	6		Broekmann and Steyn (2014)
Counselling room	9		Flemming (2014)
Sluice room	9		Van Reenen (2014)
Treatment room	12	x	Flemming (2014)
Clean utility room	12	x	Flemming (2014)
Dirty utility room	5		Flemming (2014)
Ward kitchen (increased by 1.5 m² per 10 beds)	4		Flemming (2014)
Stores (linen, toys, equipment, medicine)	15		Fleming (2014)
Treatment room	12	x	Flemming (2014)
Assisted bathroom	4.05		Department of Public Works (2001)
Cleaner's room	4		Fleming (2014)
Patient kit room	4		Assume similar to change rooms (Van Reenen, 2014)
Education area (optional)	30	x	Assume similar to training room (Steyn, 2014)
Unit manager's office	12		Fleming (2014)
Doctor's office	21		Fleming (2014)
Nurses' station	14	x	Railoun and Van der Schyf (2014)
Clinical work space	12		Fleming (2014)
Neonatal unit			
Nursery bed	9		Flemming (2014)
Work area	6		Flemming (2014)
Baby bath and work surface	0.83		Assume mounted installation (Franke Kitchen Systems Ltd, 2013)
Isolation room	12.8	x	Flemming (2014)
Neonatal bay (for observation and stabilisation)	6		Flemming (2014)
Medicine preparation area	1		Assume at least 1
Central nurses' station	14	x	Railoun and Van der Schyf (2014)
Milk kitchen (required if more than 20 neonatal and paediatric beds)	10.8		De Jager (2014); Ducker, Laing, Leaf and Newmarch (2004); Kitchen Appliances 123 (2015)
Sister's office	12		Fleming (2014)
Counselling room	9		Fleming (2014)
Multipurpose storeroom	6		Broekmann and Steyn (2014)
Small kitchen	10.8	x	De Jager (2014)

Toilet (public/disabled)	5		Fleming (2014)
Interview room	10	x	Assume similar to counselling room (Flemming, 2014)
Clean utility	12		Fleming (2014)
Dirty utility	9		Fleming (2014)
Storage (equipment, linen, surgical)	10	x	Fleming (2014)
Staff changing area	6		Broekmann and Steyn (2014)
Staff resting area	20	x	Flemming (2014)
Staff ablutions	2		Fleming (2014)
Doctor's office	21	x	Fleming (2014)
Overnight facilities for doctors	9	x	Fleming (2014)
Sister's office	12	x	Fleming (2014)
Kangaroo Mother Care Unit			
Bed area	8.43	x	Assume similar to postnatal bed National department of health (2013)
Ablutions	2	x	Fleming (2014)
Day room/lounge	25	x	Assume similar to rest room (Broekmann and Steyn (2014)
Lodger mothers' facilities			
Bed area	8.43	x	Assume similar to postnatal bed National department of health (2013)
Lounge/dining room	10	x	Fleming (2014)
Shower	2	x	Fleming (2014)
Toilet	2	x	Fleming (2014)
Laundry	6	x	Assume similar to general store (Van der Schyf & Flemming, 2015)

TABLE 57: OUTPATIENT DEPARTMENT

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Outpatient Day Unit			
Waiting area with play area	10		Flemming (2014)
Reception	9		Van Reenen (2014)
Patient toilets and showers	6		Broekmann and Steyn (2014)
Nurses' station	14		Railoun and Van der Schyf (2014)
Pre-operative nurses base	14		Assume similar to nurses' station (Railoun & Van der Schyf, 2014)
Scrub-up and gowning	11		Van Reenen (2014)
Operating room	20	x	Van Reenen (2014)
Set-up room	9		Assume similar to pre-discharge area (Flemming, 2014)
Mobile X-ray equipment bay	4		Flemming (2014)
Sluice room	9		Van Reenen (2014)
Equipment store	5		Van Reenen (2014)
Dirty utility	9		Flemming (2014)
Equipment service room	4		Assume similar to equipment bay (Flemming, 2014)
Medical gas cylinder store	6		Assume similar to general store (Broekmann & Steyn, 2014)

Pre-discharge recovery area	9		Flemming (2014)
Disabled ablution	5		Flemming (2014)
Clean utility	12		Flemming (2014)
Cleaner's room	4		Flemming (2014)
Sterile pack store	14		Steyn and Sheard (2004)
Clean linen store	8		Van der Schyf and Flemming (2015)
Switch room	4		Flemming (2014)
Female staff change rooms	12		Flemming (2014)
Male staff change rooms	12		Flemming (2014)
Staff toilets	2		Flemming (2014)
Staff lockers	12	x	Flemming (2014)
Staff room	20	x	Flemming (2014)
Seminar room	30	x	Assume similar to training room (Steyn, 2014)
Unit manager's office	12		Van der Schyf and Fleming (2014)
Sister's office	12		Flemming (2014)
Triage area	8.5		Flemming (2014)
Public ablutions	8		Flemming (2014)
Maternity outpatients			
Reception and admissions desk	9		Van Reenen (2014)
Main waiting area	40	x	Broekmann and Steyn (2014)
Security area	6		Broekmann and Steyn (2014)
Wheelchair and trolley bay	12		Broekmann and Steyn (2014)
Child play area	12		Coetzer and Fleming (2014)
Public ablutions	8		Flemming (2014)
Teaching area	30	x	Assume similar to training room (Steyn, 2014)
Breastfeeding area	12	x	Assume similar to change room (Flemming, 2014)
Staff room	20	x	Flemming (2014)
Staff toilet	2		Flemming (2014)
Office	21	x	Flemming (2014)
Storage	6		Assume similar to general store (Van der Schyf & Flemming, 2015)
Records	16		Broekmann and Steyn (2014)
Specimen collection and testing area	12		Van Reenen (2014)
Sluice room	9		Van Reenen (2014)
Dirty utility	9		Flemming (2014)
Clean linen store	8		Van der Schyf and Flemming (2015)
Surgical store	6		Assume similar to general store (Van der Schyf & Flemming, 2015)
Equipment store	5		Van Reenen (2014)
Medical store	6		Assume similar to general store (Van der Schyf & Flemming, 2015)
Nurses' station	6		National department of health (2013)
Mothers' lodging unit			
Bed area	7.5	x	Flemming (2014)
Bath (1 per 6 mothers)	2	x	Assume similar to shower (Broekmann & Steyn, 2014); (Beach, 2011)
Toilets (1 per 6 mothers)	2	x	Flemming (2014)
Cleaner's room	4	x	Flemming (2014)
Clean utility	12	x	Flemming (2014)

Day room	25	x	Assume similar to rest room (Broekmann and Steyn (2014)
Dirty utility (sluice)	9	x	Flemming (2014)
Kitchen and laundry area	10.8	x	De Jager (2014)
Store (linen and general)	10	x	Van der Schyf and Flemming (2015)

TABLE 58: LAUNDRY CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Receiving/holding area	29		Fourie, Sheared and Steyn (2014)
Sorting/pre-wash area	16		Fourie *et al.* (2014)
Washing-extractors	49	x	Office of the Federal Register (2002); Fourie *et al.* (2014)
Tumble drying	37	x	Fourie *et al.* (2014)
Flat work ironers	57	x	Fourie *et al.* (2014)
Iron presses	33	x	Fourie *et al.* (2014)
Supervisors office	10		Fourie *et al.* (2014)
Sewing/repairs	20	x	Fourie *et al.* (2014)
Detergent store	7		Fourie *et al.* (2014)
Clean linen store	45		Office of the Federal Register (2002); Fourie *et al.* (2014)
Staff facilities	25	x	Fourie *et al.* (2014)

TABLE 59: KITCHEN CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Delivery and reception area	9		National department of health (2013); Gupta, Gupta, Kant, Chandrashekhar & Satpathy (2007); Steyn and Boltman (2014)
Storage areas	37	x	National department of health (2013); Gupta *et al.* (2007); Steyn and Boltman (2014)
Preparation areas	74	x	National department of health (2013), Gupta *et al.* (2007); Steyn and Boltman (2014)
Cooking area	28		Steyn and Boltman (2014)
Wash-up areas	48		Steyn and Boltman (2014)
Cafeteria (optional)	15	x	Steyn and Boltman (2014)

TABLE 60: STERILISATION AND DISINFECTION UNIT CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Waste disposal	4		National department of health (2013), (Gupta, Gupta, Kant, Chandrashekhar & Satpathy, 2007)
Sluice	4		National department of health (2013), (Gupta et al., 2007)
Receiving and sorting	9		Steyn and Sheard (2004)

Trolley wash and holding	3		Steyn and Sheard (2004)
Store	8		Steyn and Sheard (2004)
Decontamination area	37		Gupta *et al.* (2007); Steyn and Sheard (2004)
Textile area	6		Steyn and Sheard (2004)
Inspection and packing	34	x	Steyn and Sheard (2004)
Sterilisation area	10		Steyn and Sheard (2004)
Sterile store	14		Steyn and Sheard (2004)
Steriliser plant room	6		Steyn and Sheard (2004)
Office	4		Steyn and Sheard (2004)

TABLE 61: PHARMACY CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Pharmacy dispensary	38		KwaZulu-Natal Department of Health (2010); Nice (2014)
Store medicine	10		Nice (2014)
Staff room and lockers	18		Nice (2014)
Patient waiting area	16		Fleming (2014)
Box room	6		Steyn (2014)
Bulk store (may be located elsewhere)	100	x	KwaZulu-Natal Department of Health (2010)
Cleaner's store	4		Fleming (2014)
Dirty utility room	9		Fleming (2014)
Good receiving area	6		Steyn (2014)
Office	12		Steyn (2014)

TABLE 62: EMERGENCY AND CASUALTY UNIT CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Bed area	14.145		Fleming (2014)
Resuscitation area	20.5		Fleming (2014)
Calming room (safe room)	7	x	Fleming (2014)
Consulting room	12		Fleming (2014)
Reception/Info/Help desk	12		Herman Miller (1999); Fleming (2014)
Public ablutions	8		Fleming (2014)
Disabled toilet	5		Department of Public Works (2001); Fleming (2014)
Baby change area	6		Fleming (2014)
Waiting area	52		KwaZulu-Natal Department of Health (2010); Fleming (2014)
Triage workstation	10		Fleming (2014)
X-Ray bay (10 per bed)	4		Fleming (2014)
Casualty admissions desk and cubicle	21	x	Fleming (2014)
Children's play area	12	x	Fleming (2014)
Sub-waiting area	16	x	Fleming (2014)
Trauma beds	10	x	Fleming (2014)
Central nurses station	15	x	Fleming (2014)
Counselling room	9		Fleming (2014)

Clean utility	12		Fleming (2014)
Cleaner's room	4		Fleming (2014)
Dirty utility	9		Fleming (2014)
Treatment room	12		Fleming (2014)
Store (equipment, general, clean linen, surgical)	58		Fleming (2014)
Seclusion room	15		Fleming (2014)
Plaster room	16		Fleming (2014)
Procedure room	40		Herman Miller (1999); Fleming (2014)
Patient bay (holding and recovery)	18		Fleming (2014)
Medical head	24		Fleming (2014)
Doctors' office (plan for 3)	21		Fleming (2014)
Meeting room	45	x	Fleming (2014)
Unit manager's office	16	x	Fleming (2014)
Sisters' office	12	x	Fleming (2014)
Overnight stay with bathroom for doctors	9	x	Fleming (2014)
Staff shower	2		Fleming (2014)
Staff toilet	2		Department of Health (2004); Fleming (2014)
Staff rest room	20		Fleming (2014)
Staff change room	12		Fleming (2014)
IT room	4		Fleming (2014)

TABLE 63: ACUTE PSYCHIATRIC FACILITY CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Inpatient Units	14		Van der Schyf and Fleming (2014)
Nurses' station	12		Railoun and Van der Schyf (2014)
Treatment room	6		Assume similar size as general store (Broekmann & Steyn, (2014)
Medicine room	12		Fleming (2014)
Clean utility	12		Fleming (2014)
Clinical administration	12		Fleming (2014)
Consulting room	9		Fleming (2014)
Counselling room	17		Van der Schyf and Fleming (2014)
Stores (linen and general store)	9	x	Fleming (2014)
Dirty utility	12		Fleming (2014)
Seclusion rooms	20		Assume similar to staff rest room (Railoun & Van der Schyf, 2014)
Patient lounge (for at least 15 people)	9	x	R 158; Railoun and Van der Schyf (2014)
Dining room	9		Assume similar size as dining room, National department of health (2013)
Quiet room	8	x	Fleming (2014)
Ablutions	4		Assume similar to change rooms (Van Reenen, 2014)
Kit room	8		Van der Schyf and Fleming (2014)
Ward kitchen	4		Railoun and Van der Schyf (2014)
Cleaner's room	4		Assume similar to cleaner's room (Railoun & Van der Schyf, 2014)
Patient laundry	8		Railoun and Van der Schyf (2014)

Dirty utility and waste management	20		Railoun and Van der Schyf (2014)
Staff rest room	12		Broekmann and Steyn (2014)
Staff ablutions	2		Railoun and Van der Schyf (2014)
Lecture rooms	9	x	Fleming (2014)
Doctors sleep-over	14	x	Van der Schyf and Fleming (2014)
Occupational Therapy Unit			Railoun and Van der Schyf (2014)
Office space	5.02	x	Assume similar space to other hospital offices (Department of Health, 2004)
Group/Interview room	9	x	R 158
Activity/Craft room	30	x	R 158
Relaxation/Therapy/Lecture room	30	x	R 158
Storage	2	x	Assume minimum area is 2, National department of health (2013)

TABLE 64: CHRONIC CARE UNIT CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Bed area	10		Kunders (2008); Van der Schyf and Fleming (2014)
Singe rooms	15		Van der Schyf and Fleming (2014)
Bathroom	6		Van der Schyf and Fleming (2014)
Assisted shower	6.5		Van der Schyf and Fleming (2014)
Day room	12		Van der Schyf and Fleming (2014)
Treatment room	15		Van der Schyf and Fleming (2014)
Clean utility	9		Van der Schyf and Fleming (2014)
Cleaner's room	8		Van der Schyf and Fleming (2014)
Dirty utility	8		Van der Schyf and Fleming (2014)
Inpatient unit kitchen (increased 1.5 for every 10 beds)	8		Van der Schyf and Fleming (2014)
Nurses' station	6		R 158, Van der Schyf and Fleming (2014)
Patient kit room	6		Van der Schyf and Fleming (2014)
Sluice	10		Van der Schyf and Fleming (2014)
Store (clean linen)	8		Van der Schyf and Fleming (2014)
Store (consumables)	9		Van der Schyf and Fleming (2014)
Store (equipment)	12		Van der Schyf and Fleming (2014)
Staffroom	15		Van der Schyf and Fleming (2014)
Staff toilet	3		Van der Schyf and Fleming (2014)
Clinical staff office	9		Van der Schyf and Fleming (2014)
Unit manager's office	12		Van der Schyf and Fleming (2014); Broekmann and Steyn (2014)
Patient waiting area	10		Van der Schyf and Fleming (2014)
Public disabled toilet	5		Van der Schyf and Fleming (2014)

TABLE 65: REHABILITATION UNIT CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Inpatient unit			
Bed area	7.43		Kunders (2008); Department of Health (2004)

Ablution and toilet facilities for patients (1/8 beds)	1.67		National department of health (2013)
Clean utility room	5	x	National department of health (2013)
Treatment room	10	x	National department of health (2013)
Separate storage space (user decides)	1	x	Assume minimum area is 1, National department of health (2013)
Ward kitchen (includes milk kitchen) Increased by 1.5 for every 10 beds above 20 beds	4		National department of health (2013)
Staff toilet	1.67		Department of Health (2004)
Single rooms	10		National department of health (2013)
Disabled ablution facility (1/8 beds)	4.05		Department of Public Works (2001)
Nurse station	6		National department of health (2013), assume similar size as duty station
Shower or bath 1/12 patients	1.05		Beach (2011)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		National department of health (2013)
Hydrotherapy (for spinal/cranial rehabilitation)			
Pool	24	x	Pinelog (2015)
Change rooms and lockers	8	x	National department of health (2013)
Wheel chair toilet	4	x	National department of health (2013)
Occupational Therapy			
One-to-one work room	10		National department of health (2013)
Clean work room	10		National department of health (2013)
Dirty work room	10		National department of health (2013)
Cognitive room (clean work room, dirty work room, and cognitive room may be combined into a single room of 30)	10		National department of health (2013)
Splint room	10		National department of health (2013)
Storage space	6		National department of health (2013)
ADL kitchen	10		National department of health (2013)
Family/group conference room	20		National department of health (2013)
Clinical psychologist			
Group therapy room (may be shared with social worker)	20		National department of health (2013)
Physiotherapy			
One-to-one work room	10		National department of health (2013)
Storage space	9		National department of health (2013)
Gym area	45		National department of health (2013)
Other rooms			

Dining-room/Lounge (minimum of 20 m^2 for 10 patients, and thereafter 1,5 m^2 for each additional patient	20		National department of health (2013)
Emergency room	16		National department of health (2013)

TABLE 66: MORTUARY CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Ablution area	3		Reenen (2014)
Shower facilities	3		Reenen (2014)
Changing room	8		Reenen (2014)
Storage space	8		Reenen (2014)
Offices (interview, body receiving, pathologist)	9		Reenen (2014)
Body/bier room	9		Reenen (2014)
Viewing room	9		National Health Service Scotland (2002); Reenen (2014)
Autopsy room	27		Reenen (2014)

TABLE 67: LABORATORY CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Waiting areas	16		Fleming (2014)
Ablution areas	8		Van Reenen (2014)
Staff changing room	12		Van Reenen (2014)
Storage (equipment and samples)	5		Van Reenen (2014)
Specimen reception	12		Van Reenen (2014)
Storage and treatment of waste	10		Van Reenen (2014); Gupta *et al.* (2007)
Testing area	25		Van Reenen (2014); Gupta *et al.* (2007)

TABLE 68: RADIOLOGY CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Reception	12		Fleming (2014)
Radiographic room	34.1		Coetzer (2013); Department of Health (2004)
Fluoroscopy room	48.75	x	Coetzer (2013)
Patient toilet	3		Reenen (2014)
Waiting area	40		Broekmann and Steyn (2014)
Mammography X-ray-imaging room	18	x	Department of Health (2004); Coetzer (2013)
Change cubicles	6	x	Broekmann and Steyn (2014)
Sub waiting area	16	x	Fleming (2014)
Processing and viewing area	9		Reenen (2014)
Counselling room	9		Fleming (2014)
General ultrasound room	16	x	Coetzer (2013)

Computed Tomography (CT) scanning	32.5	x	Coetzer (2013)
Magnetic resonance imaging room	41.25	x	Coetzer (2013)
Control room	11		Coetzer (2013)
Staff rest room	12		Broekmann and Steyn (2014)
Staff toilet	2		Fleming (2014)
Unit manager's office	16	x	Coetzer (2013)
Radiologist's office	12	x	Assume similar to sister's office, Fleming (2014)
Radiographer's office	12		Assume similar to sister's office, Fleming (2014)
Cleaner's station	4		Fleming (2014)
Dirty utility	9		Fleming (2014)
IT room	4		Fleming (2014)
Stores (equipment, consumables, medicine, linen, and general)	24		Assume similar to general store size, Broekmann and Steyn (2014)

TABLE 69: NEONATAL INTENSIVE CARE UNIT CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Crib area	12.8		Flemming (2014)
Visitor ablution and toilet facilities	1.67	x	Department of Health (2004)
Clean utility room	5		National department of health (2013)
Separate storage space (optional)	1		Assume minimum area is 1, National department of health (2013)
Staff toilet	1.67		Department of Health (2004)
Isolation cubicle	6		National department of health (2013)
Breast feeding area	4.55		York (2008)
Nurse station	6		Assume similar size as duty station National department of health (2013)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		National department of health (2013)

TABLE 70: INTENSIVE CARE UNIT CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Bed area	20		
Waiting area for visitors	10		Assume similar to size of other waiting areas (KwaZulu-Natal Department of Health, 2010)
Visitor toilet facilities	1.67	x	Department of Health (2004)
Ward kitchen	4		National department of health (2013)
Staff toilet	1.67		Department of Health (2004)
Isolation bed	25		National department of health (2013)
Nurse station (1 per 8 beds)	6		Assume similar size as duty station National department of health

			(2013)
Dirty utility room and cleaner's room	7		National department of health (2013)
Equipment storage space (additional 1m² per ICU bed over 8 ICU beds)	16		Assume similar to size of emergency department storage (KwaZulu-Natal Department of Health, 2010)

TABLE 71: HIGH CARE UNIT CONSTRAINTS

Requirements	**Minimum area (in m²)**	**Optional**	**References**
Bed area	15.75		Coetzer and Fleming (2014)
Ablution and toilet facilities for patients (1/8 beds)	1.67		Department of Health (2004)
Clean utility room	5	x	National department of health (2013)
Treatment room	10	x	National department of health (2013)
Separate storage space	1	x	Assume minimum area is 1, National department of health (2013)
Ward kitchen (Increased by 1.5 for every 10 beds above 20 beds)	4		National department of health (2013)
Staff toilet	1.67		Department of Health (2004)
Single rooms	20	x	Coetzer and Fleming (2014)
Disabled ablution facility	4.05	x	National department of health (2013)
Nurse station	6		Assume similar size as duty station, National department of health (2013)
Shower/bath	1.05		Beach (2011)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		National department of health (2013)
Waiting area	10		Coetzer and Fleming (2014)

APPENDIX B: NATIONAL CORE STANDARDS

There is currently very limited knowledge on the procedures or methods required in order to design the optimal floor layout of a hospital for use in remote rural areas of South Africa. South African healthcare provides from the most basic primary care services, offered free by the government, to highly specialised health services in both the private and public sector. However, the public sector is under pressure with low resources and high demands trying to deliver services to about 80% of the population while the state only contributes 40% of all expenditure on health (Media Club South Africa, 2014). This healthcare system is not only inaccessible to many citizens, but public health facilities have suffered poor management, underfunding and deteriorating infrastructure. Serving rural communities in particular is very difficult since resources are even scarcer. Each year about 1200 medical students graduate and only 3% of them end up working in rural communities (Wits Centre for Rural Health Strategy, 2008). Yet, almost half of the population resides in rural areas. Rural communities have specific challenges and characteristics which contribute to their poor health outcomes. These include working conditions, access to medical care, personal health and physical environment.

According to the National Department of Health (2011:18b) the public health sector is under-resourced and serves more patients than the private sector of South Africa. In 2011 the National Department of Health developed the National Health Insurance (NHI) policy in order to improve health. The NHI is aims to ensure that everyone has access to quality healthcare regardless of their socio-economic status. This will lead to changes in management systems, service delivery and administrative systems. In preparation for implementation of the NHI, service delivery in South African healthcare facilities needs improvement. Thus a national quality assurance program called the National Core Standards (NCS) was launched to drive facility improvements and serve as a benchmark for quality. All South African facilities, both in the private and public sectors, shall be required to comply with these standards in the near future (National Department of Health, 2011:3b). The aim of the NCS is therefore to ensure that all health facilities provide quality care. In order to evaluate health facilities, an external audit team measures compliance to a set of standards.

The NCS is currently one of the focus areas in preparation for achieving the NHI. The NHI is a phased project that will be completed in a period of 14 years. The first five years constitute phase one and will include the actual demonstration of the key administrative and technical aspects of the NHI so as to achieve smooth integration of the systems as they mature and new information is obtained. One of the first activities of this phase lies in conducting the Public Health Facility Audit. The audit identifies existing health infrastructure which includes facilities, technology and management capacity. This will allow for planning on how to improve the current health system and increase its capacity and effectiveness of service delivery (Health Systems Trust, 2013). The second phase, period 2016 to 2020, will focus on further real-life demonstration and the contracting of independent providers. In this period the NHI will progressively take over administration, service delivery and technical health functions. Provincial branches of the NHI Fund will be established and the health workforce will be increased. In the third phase, period 2021 to 2025, the NHI will reach its maturing state. Private hospitals will be selectively accredited and contracted and the population will be registered (National Department of Health, 2011:16a).

The NCS are not new or additional standards, but a combination of existing guidelines and policies that set out the basic compulsory requirements and expectations for ensuring quality healthcare facilities in South Africa (National Department of Health, 2011b:82). The main objectives of the NCS include the following:

- To define the quality of care that every health facility in South Africa should comply with and use as a guide to managers, staff and the public
- To provide a benchmark against which healthcare facilities can be measured and shortcomings and strengths identified
- To establish a national structure to certify healthcare facilities as compliant to the NCS

In order for a healthcare facility to meet these standards, staff and managers need to know how far their current performance is from being compliant. Continuous self-assessments are thus required to ensure conformation to these standards. An independent body executes external healthcare establishment audits in order to remove biases. The body will periodically issue audit reports and assess the degree of compliance to the NCS. An independent regulator will issue certificates regarding the extent of compliance to the standards according to the law. The appropriate process to enforce compliance should be followed (National Department of Health, 2011b:51).

TABLE 72: FACILITIES AND INFRASTRUCTURE DOMAIN OF THE NATIONAL CORE STANDARDS

Sub-domain	**Standard**	**Criteria**
7.1 Buildings and grounds	7.1.1 The building meets all applicable regulations	7.1.1.1 The health establishment has been licensed annually against the R158 or R187 regulations * only applicable to the private sector
		7.1.1.2 The health establishment complies with infrastructure standards * only applicable to the public sector
	7.1.2 Infrastructure is appropriately used according to level of care	7.1.2.1 Available facilities are regularly checked to ensure they are fit for purpose
		7.1.2.2 The health establishment layout is planned or adapted to ensure it meets service and patient needs
	7.1.3 Waiting areas are convenient and provide adequate shelter and seating for patients	7.1.3.1 Waiting areas are appropriately located and adequate for the number of patients using them
	7.1.4 Buildings are safe and adequately maintained	7.1.4.1 The health establishment holds regular, documented and comprehensive inspections of its physical facilities
		7.1.4.2 Maintenance is carried out promptly and efficiently by qualified personnel
	7.1.5 The health establishment is	7.1.5.1 All areas are adequately furnished and provide

	organised, furnished and equipped to meet patient needs and comfort	an acceptable environment for patient care
	7.1.6 Grounds are maintained to be safe and orderly	7.1.6.1 A regular maintenance program ensures grounds are safe and attractive
		7.1.6.2 All pedestrian and vehicular access routes are maintained to ensure the smooth running of the health establishment
		7.1.6.3 Emergency vehicle access roads are kept clear
7.2 Machinery and utilities	7.2.1 Electrical power, water, sewerage and other internal bulk supply systems meet the needs of the establishment	7.2.11 Site and floor plans show the location and layout of the main services (e.g. water, sanitation and electricity)
		7.2.1.2 Routine and emergency electrical power services meet the needs of the health establishment
		7.2.1.3 Routine and emergency water supplies meet the needs of the health establishment
		7.2.1.4 The sewerage disposal system is functional and properly maintained
		7.2.1.5 Appropriate ventilation is provided in theatres, patient accommodation and waiting areas
		7.2.1.6 Routine and emergency medical gas and vacuum systems meet the needs of the health establishment
	7.2.2 Operational plant, machinery and equipment is well maintained, fully functional and complies with regulations	7.2.2.1 Operational plant, equipment and installations are tested and properly maintained
		7.2.2.2 The operational plant, machinery and equipment is upgraded, replaced, decommissioned and disposed of according to a documented system
	7.2.3 A reliable internal and external telephone system provides routine and emergency back-up communication	7.2.3.1 The telephone system is functional and reliable
		7.2.3.2 A functional back-up system ensures communication if the telephone system fails
		7.2.3.3 Private telephone facilities are available for communicating confidential information
	7.2.4 A functional public communication system allows communication throughout the health establishment in the event of an emergency	7.2.4.1 A system is in place for alerting occupants in the event of an emergency
		7.2.4.2 Staff are briefed to react to emergency warnings
		7.2.4.3 All beds and ablution facilities have an emergency call system to alert the nursing staff
7.3 Safe and secure environment	7.3.1 People and property are actively protected from safety and security risks	7.3.1.1 Security systems safeguard the building, patients, visitors and staff
		7.3.1.2 The layout of security systems protect vulnerable patients
		7.3.1.3 Adequate internal and external lighting protects patients, visitors and staff
		7.3.1.4 All security incidents are reported and addressed
		7.3.1.5 Safety and security awareness is promoted among staff
		7.3.1.6 Current Local Fire Authority certificates show the health establishment complies with relevant fire safety regulations
		7.3.1.7 An emergency plan is available to show that patient well-being is protected at all times
7.4 Hygiene	7.4.1 The buildings and grounds	7.4.1.1 The health establishment is kept clean, including

and cleanliness	are kept clean and hygienic to maximise safety and comfort	critical areas of public use (especially toilets) and areas for patient care
		7.4.1.2 Appropriate cleaning materials and equipment are available, and properly used and stored
		7.4.1.3 Pests are controlled in internal and external areas, and infestations are dealt with promptly and effectively
		7.4.1.4 There is a no smoking policy
7.5 Waste management	7.5.1 Waste management in the health establishment and surrounding environment complies with legal requirements, national standards and good practice	7.5.1.1 There is a current waste management policy and procedure
		7.5.1.2 A designated and knowledgeable staff member ensures compliance with relevant waste management legislation and standards
	7.5.2 Healthcare risk waste (HCRW) is handled, stored and disposed of safely to reduce potential health risks and to protect the environment	7.5.2.1 The health establishment reviews its HCRW management every two years to identify the hazardous waste it generates and establish processes for its safe management
		7.5.2.2 Documented policies and procedures are available for the collection, handling, segregation, storage and disposal of HCRW
		7.5.2.3 A contract and service level agreement is in place with an approved and legally compliant waste removal service provider
		7.5.2.4 There are sufficient, accessible and appropriate waste disposal containers to handle all the HCRW generated
		7.5.2.5 Anatomical waste is disposed of legally while taking into account cultural preferences
	7.5.3 Management of general waste (e.g. office, kitchen, garden or household waste) ensures general cleanliness and the safety of staff and patients	7.5.3.1 General waste is stored and transported appropriately and securely, and removed promptly
		7.5.3.2 Sufficient numbers of suitable containers are conveniently located to allow safe disposal of waste
7.6 Linen and laundry	7.6.1 Linen and laundry services meet the needs of the hospital or clinic and safety standards	7.6.1.1 The laundry service is effectively managed and delivered (on-site or out-sourced) to meet the needs of the health establishment and laundry standards
		7.6.1.2 All laundry is handled in line with infection control and safety requirements
		7.6.1.3 The laundry has suitable equipment to meet the needs of the health establishment
		7.6.1.4 Adequate stocks of linen are maintained to ensure that items are always available
7.7 Food services	7.7.1 Food services are provided to meet patients' needs as well as safety standards	7.7.1.1 Policies and procedures guide all aspects of food procurement, storage, preparation and serving
		7.7.1.2 Food services are effectively managed and delivered (on-site or out-sourced) to meet the needs of the health establishment
		7.7.1.3 Patients are satisfied with food quality and presentation
		7.7.1.4 Food services provide patients with adequate and nutritious food and drink
		7.7.1.5 Policies and procedures are in place for infection control, safety and food hygiene
		7.7.1.6 Food services meet patients' cultural, religious and dietary needs
		7.7.1.7 Equipment for the safe preparation of food is available

		7.7.1.8 Kitchens meet hygiene and environmental health standards

APPENDIX C: VERIFICATION OF THE FRAMEWORK

In each of the following tables, the requirements for the layout design framework for rural hospitals are verified. Verification of this study is done in three ways namely hospital layout design questions, research objectives, and framework outputs.

C.1 HOSPITAL LAYOUT DESIGN QUESTIONS VERIFICATION

This section checks that all the layout design questions are answered. Table 73 explains how and where each of these questions is addressed in this study.

TABLE 73: HOSPITAL LAYOUT DESIGN QUESTIONS VERIFICATION

Hospital layout design questions	**How each question is addressed**	**Section/s where addressed**
What is the capacity of the hospital?	The capacity of the hospital is suggested according to the population size of the community and desired occupancy rate. Additional South African averages are also used.	5.6.1
Which departments should be included in the hospital layout?	The compulsory departments for a district hospital were identified by using the South African laws as guide. There are also a few optional departments that the user can choose to include in the layout.	Appendix A, 4.1.2
What is the capacity of each department?	The capacity of each department is suggested by using benchmarking five hospitals in South Africa. However, the user is still able to change these values according to preferences.	Appendix A, 5.6.1
Which rooms are necessary for each department?	The required and optional rooms for each department were determined using South Africa's R158.	Appendix A, 4.1.2
How much space is required for each room?	The minimum area for each room was determined according to South Africa's R158, provincial recommendations, other countries' laws, and industrial norms. These values were often linked to the amount of beds or staff where applicable. The user is also able to adjust these areas and include optional rooms in the layout.	Appendix A, 4.1.2
Which departments should and should not be placed in close proximity to each other?	Muther's SLP Procedure's relationship chart was used to model the relationships between departments according to the functionality of each department.	3.3, 5.4.7
Where should each department be located?	The optimal/near optimal location for each department is determined by optimising an Operations Research method namely the Quadratic Set Covering Problem with Simulated Annealing.	2.3.4, 2.4.2.2, 5.6.3, 5.6.4

C.2 RESEARCH OBJECTIVES VERIFICATION

This section verifies that all the research objectives (discussed in Section 1.4) of this study are reached. Table 74 explains how and where each research objective is addressed in this study.

TABLE 74: RESEARCH OBJECTIVES VERIFICATION

Chapter	**Research objectives**	**How each objective is addressed**	**Section/s where addressed**
Quantitative layout design methods	Identify the popular quantitative layout models used to design layouts	The layout models used in articles are researched. A timeline was also constructed. Using these results, the more popular layout models are identified. These layout models were also classified as discrete or continuous.	2.2, 2.3
	Analyse the various components of these layout models	For each of the models the main objective(s), notation, assumptions, inputs, outputs and variations was analysed.	2.3
	Identify and analyse the popular methods for solving these models	The solution methods used in articles are researched. A timeline was also constructed. Using these results, the more popular solution methods are identified.	2.2, 2.4
	Investigate other design methods such as layout software	The more popular layout software found in literature are identified, discussed and classified as construction or improvement algorithm based. A timeline is also constructed.	2.2, 2.5
	Compare the layout models, and solution methods with each other	The layout models are discussed and compared and the most suitable models are proposed. The solution methods are discussed and compared and the most suitable methods are proposed.	2.6
Qualitative layout design methods and other design considerations	Identify the popular qualitative design methods used to plan hospital layouts.	The more popular approaches used to plan hospital layouts are identified.	3.2
	Analyse the various components of these qualitative design methods.	The qualitative design steps are identified and compared to the discussed layout models. The most adequate step is selected and applied.	3.2, 3.3
	Identify the popular design considerations for hospitals.	The most important design considerations applicable to hospital layouts found in literature are identified. Each one is analysed and layout implications identified.	3.4
	Link the hospital design considerations with the quantitative methods.	The hospital design considerations link up the quantitative methods analysed in Chapter 2	3.4.6
Rural versus urban hospitals	Determine the commonalities among rural and urban hospitals.	The commonalities among rural and urban hospitals are identified by analysing general building constraints, hospital layout constraints, and adherence to standards.	4.1
	Determine how laws and standards affect the design of a hospital.	The laws and standards impose various constraints on the hospital layout. These constraints are identified and incorporated into the framework.	Appendix A, 4.1, 4.3
	Identify minimum dimensions and other criteria applicable to the design of a hospital layout.	The minimum dimensions and constraints are identified and incorporated into the framework using Excel VBA.	Appendix A, 4.1
	Determine rural-specific constraints.	Rural-specific constraints are identified using data made available from the South African government. Rural challenges are discussed via literature found on the subject.	4.2

	Determine the layout implications of the rural-specific constraints.	The layout implications of the rural-specific constraints are identified and incorporated into the framework.	4.2, 4.3
Proposed rural hospital design framework	Describe the real world problem and how it differs from the research literature.	The real world problem is described and how it differs from the research literature is discussed.	5.3
	Select the most adequate layout model and solution method.	The most adequate layout model is selected based on a set of criteria namely model objectives, assumptions, inputs, outputs, and qualitative design considerations	5.4, 5.5
	Incorporate qualitative design methods and hospital design considerations into the framework.	The selected qualitative design method is integrated with the selected quantitative design method. The hospital design considerations are incorporated into the framework	5.1, 5.4.7
	Make necessary adjustments to the framework to accurately model the real world problem.	The flow variable is replaced with the relationship diagram in order to take the functionality and interdepartmental relationships of the hospital departments into account	5.4.7
	Development and explanation of framework.	The framework is developed using Excel VBA, and RStudio	5.6

C.3 FRAMEWORK OUTPUTS VERIFICATION

This section checks that the outputs of the developed framework are realistic and works as expected. Table 75 shows evidence that the program works in the desired way.

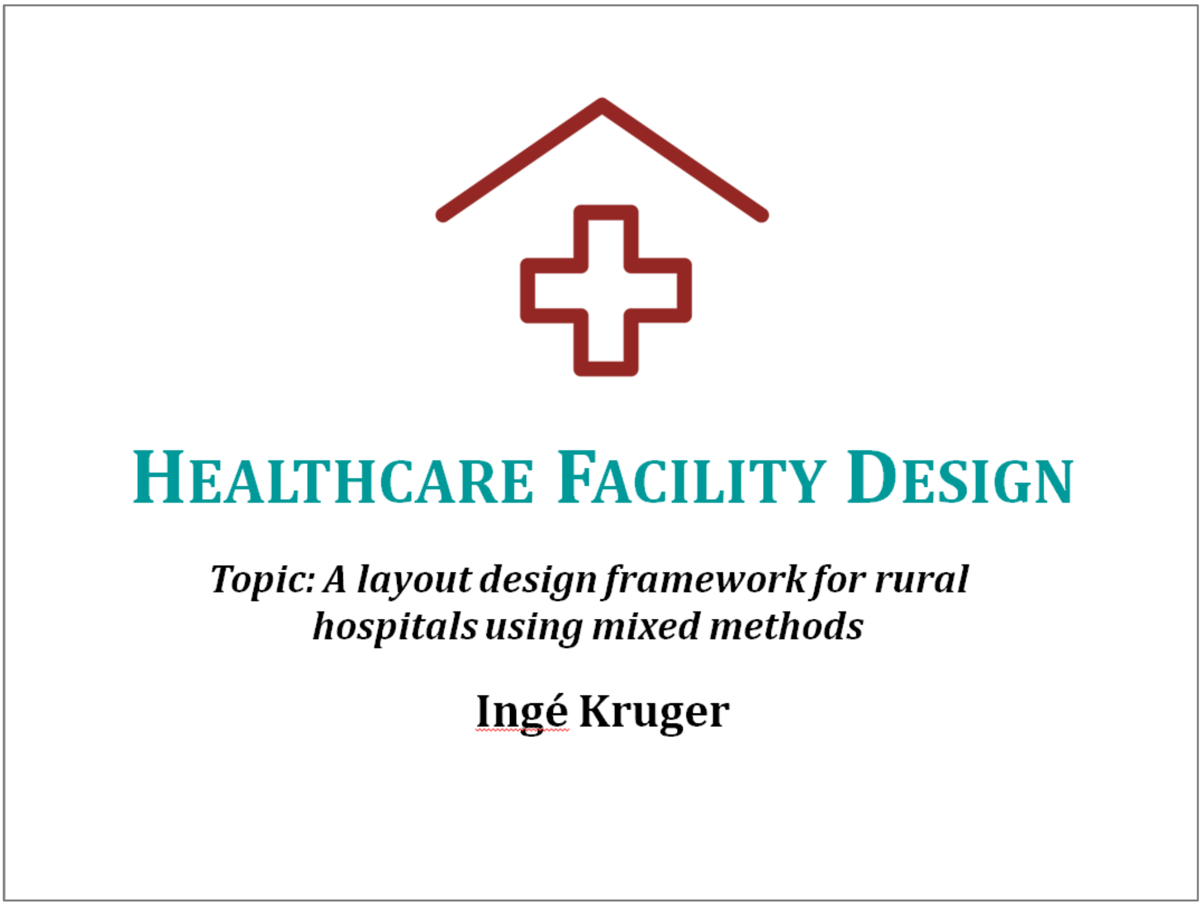
TABLE 75: FRAMEWORK OUTPUTS VERIFICATION

Framework outputs verification	**Evidence**
There are no overlapping departments	Example 1, Example 2, Example 3, Example 4, Case study
All the departments are placed within the available space – the departments centres are within the specified region	Example 1, Example 2, Example 3, Example 4, Case study
The correct number of departments are placed each time	Example 1, Example 2, Example 3, Example 4, Case study
The departments with positive relationships are in general placed closer together and departments with negative relationships are usually placed apart	Example 1, Example 3, Example 4, Case study
An optimal/near optimal layout solution is reached – the objective function is optimised/near optimised	Example 1, Example 2, Example 3, Example 4, Case study

APPENDIX D: DOCUMENT FOR INTERVIEWS WITH EXPERTS

This section contains a presentation, documents used for the purpose of validation, and feedback from experts.

D.1 Validation presentation



Outline

- Introduction
- Framework outline
- Quantitative methods
- Qualitative methods
- Rural considerations
- Example of program
- Examples of outputs
- Conclusions
- Questions

Introduction

Introduction

Background

"measure twice, cut once" (Davis, 2010)

COMMON HOSPITAL PROBLEMS:

- High operations & maintenance costs – 80% over typical 50 year cycle (WBDG, 2014)
- Long term, expensive to change
- Labour costs 60-75% of hospital expenses (WBDG, 2014)
- Hospitals complex building type – wide range of services & functional units
- Laws & standards
- Different users & stakeholders – patients, visitors, staff, suppliers, owners

Introduction

Background

COMMON HOSPITAL LAYOUT CONSIDERATIONS:

- Movement of people, materials & waste
- Critical patients
- Transmission of infections
- Waiting queues
- Minimise movement of staff
- Cost efficient
- Patient safety
- Aesthetically pleasing/healing environment
- Flexible
- Easily accessible
- Sustainable design

Where do we start?

Introduction

Research aim

The primary objective of this study is to develop a framework that will guide a user (layout planner) in designing an optimal layout for a rural hospital while taking into consideration the relevant laws and health outcomes of the surrounding rural community.

The goal is not to replace the role of the architect, but to guide the designer.

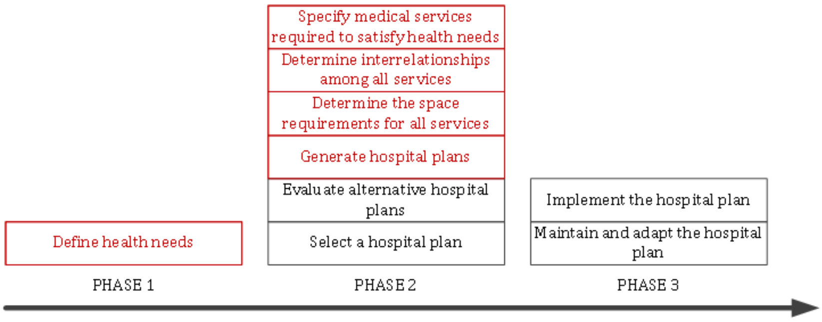
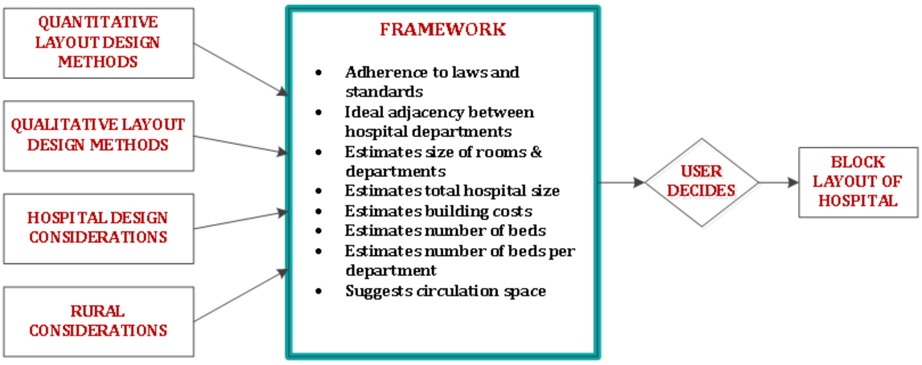


FIGURE 1: HOSPITAL LAYOUT DESIGN STEPS AND PHASES, ADAPTED FROM TOMPKINS, WHITE, BOZER AND TANCHOCO (2010)

Framework outline

Framework outline



Qualitative methods

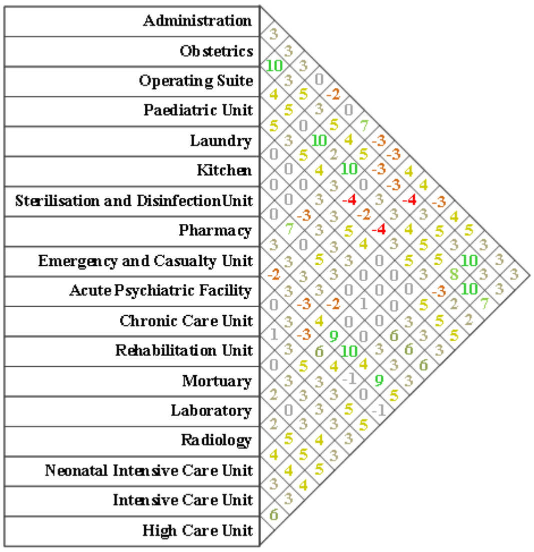
Qualitative methods

The most popular layout procedures found in literature are:

- **APPLE'S PLANT LAYOUT PROCEDURE**
- **REED'S PLANT LAYOUT PROCEDURE**
- **MUTHER'S SYSTEMATIC LAYOUT PLANNING (SLP) METHOD**

Qualitative methods

Muther's SLP relationship chart:



Qualitative methods

Design considerations

The most important design considerations found in literature were investigated and found to be:

- patient-centeredness
- efficiency
- flexibility and expandability
- sustainability
- therapeutic environment

Design objectives	Design measures	Layout model							Incorporated in framework as constraints
		Quadratic Assignment Problem	*Quadratic Set Covering Problem*	*Linear Integer Programming Problem*	*Mixed Integer Programming Problem*	*Graph Theoretic Problem*	*Linear Continuous Model*	*Linear Mixed Integer Model*	
Patient-centeredness	Variable-acuity rooms (private rooms)								x
	Space for family members								x
	Single occupancy rooms								x
Efficiency	Optimise occupant flows	x	x	x	x		x	x	
	Eliminate waste								
	Minimise transportation	x	x	x	x		x	x	
	Minimise waiting times	x						x	
	Minimise cost	x	x	x	x		x		
	Design critical passing spaces	x	x	x	x		x	x	x*
	Design dedicated resource corridors								x*
Flexibility and expandability	Follow modular concepts								x
	Use generic room sizes								x
	Minimise layout size								x
	Minimise travel distances		x	x			x	x	
	Decentralised storage								x
Sustainability	Minimise costs	x	x	x	x		x		
	Maximise daylighting								
Therapeutic environment	Single occupancy rooms								x
	Enclosed examination and treatment areas								x
	Provide private discussion areas								x
	Multi occupancy rooms								x
	Adjacent to gardens								x
	Staff break rooms								x
	Provide waiting areas for family members with access to rest rooms and food								x

Linking qualitative and quantitative methods

Quantitative methods

Quantitative methods

From a quantitative approach, the problem of this study can be seen as a **Facility Layout Problem (FLP)** i.e. finding the most efficient arrangement of *n* indivisible departments with unequal area requirements within a facility. The objective of the FLP is typically to minimise the material handling costs. Most popular **models** found in literature for the FLP are:

- **QUADRATIC ASSIGNMENT PROBLEM**
- **QUADRATIC SET COVERING PROBLEM**
- **LINEAR INTEGER PROGRAMMING PROBLEM**
- **MIXED INTEGER PROBLEM**
- **GRAPH THEORETIC PROBLEM**
- **LINEAR CONTINUOUS MODEL**
- **LINEAR MIXED INTEGER MODEL**

For each of these models the **objectives**, **assumptions**, **inputs**, and **outputs** were analysed.

Quantitative methods

Quadratic Set Covering Problem

Min $$\sum_{i=1}^{n}\sum_{k=1}^{n}\sum_{j=1}^{I(i)}\sum_{l=1}^{I(k)} f_{ik}x_{ij}x_{kl}d_{jl} + \sum_{i=1}^{n}\sum_{j=1}^{I(i)} t_{ij}x_{ij}$$

Subject to

$$\sum_{j=1}^{I(i)} x_{ij} = 1, i = 1,2,\dots,n,$$

$$\sum_{i=1}^{n}\sum_{j=1}^{I(i)} a_{ijt}x_{ij} \leq 1, t = 1,2,\dots,q,$$

$$x_{ij} \in \{0,1\}, i = 1,2,\dots,n; j = 1,2,\dots,I(i).$$

q = Number of blocks into which the total area occupied by all departments is divided into

d_{jl} = Distance between the centroids of locations j and 1 if facility i is assigned to location j and facility k is assigned to location l

f_{ik} = **Flow of patients between department i and department k**

t_{ij} = Fixed cost of locating and operating department i at location k

$I(i)$ = Set of candidate locations for department i

$J_i(j)$ = Set of blocks occupied by facility i if it is assigned to location j

x_{ij} = 1 if department i is at location j; 0 otherwise

x_{ik} = 1 if department k is at location l; 0 otherwise

a_{ijt} = 1 if block $a \in J_i(j)$; 0 otherwise

Solution method

The most popular solution methods for the FLP were researched.

EXACT METHODS	• BRANCH AND BOUND • CUTTING PLANE ALGORITHMS
METAHEURISTICS	• LOCAL SEARCH METHOD • **SIMULATED ANNEALING** • TABU SEARCH • GENETIC ALGORITHMS • ANT COLONY OPTIMISATION • PARTICLE SWARM OPTIMISATION

Rural considerations

Rural considerations

Laws and standards

GENERAL BUILDING CONSTRAINTS

National Building Standards Act 1977

South African National Standard 10400

ADHERENCE TO STANDARDS

National Core Standards (NCS)

Rural considerations

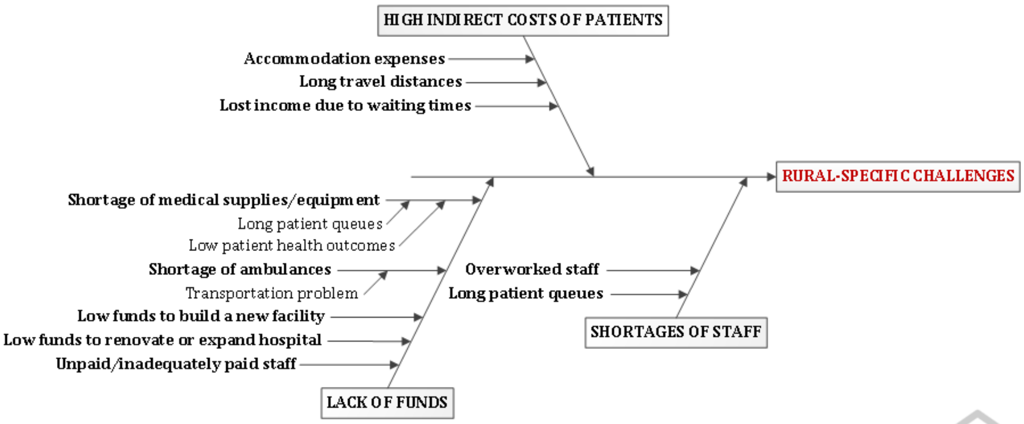
Laws and standards

HOSPITAL LAYOUT CONSTRAINTS

1. SA laws: The Regulations Governing Private Hospitals and Unattached Operating Theatre Units (R158)
2. Provincial laws: Especially the KwaZulu-Natal Department of Health (2010)
3. Articles, books, and industrial norms
4. Constraints of other countries

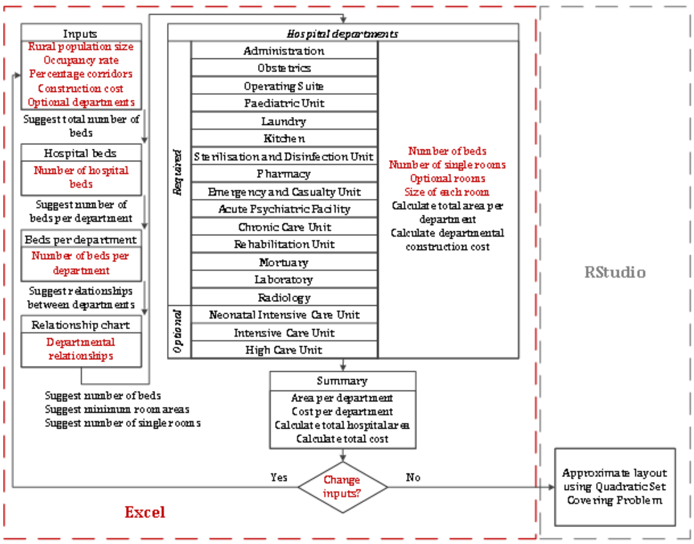
Rural considerations

Rural-specific challenges

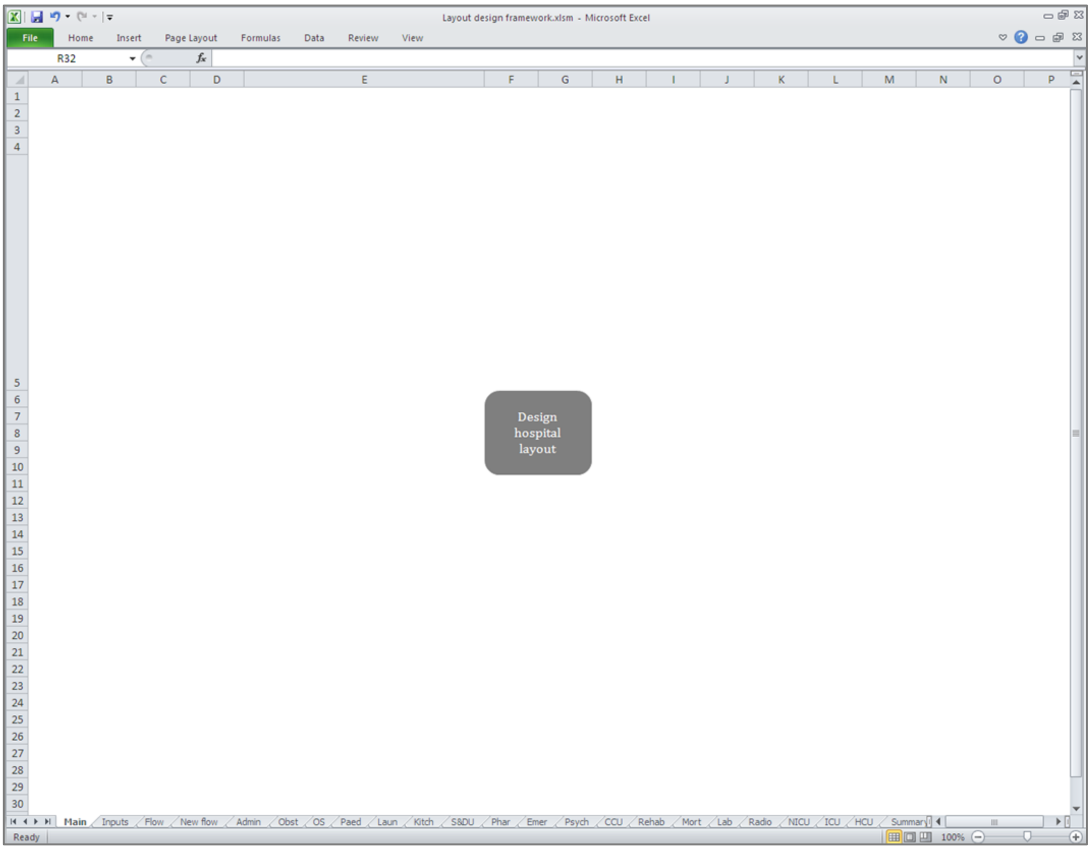


Example of program

Example of program



User can change:
- ✓ Rural population size
- ✓ Occupancy rate
- ✓ Percentage corridors
- ✓ Construction cost
- ✓ Optional departments
- ✓ Number of hospital beds
- ✓ Number of beds per department
- ✓ Departmental relationships
- ✓ Number of single rooms
- ✓ Size of each room
- ✓ Optional rooms


Layout design framework.xlsm - Microsoft Excel
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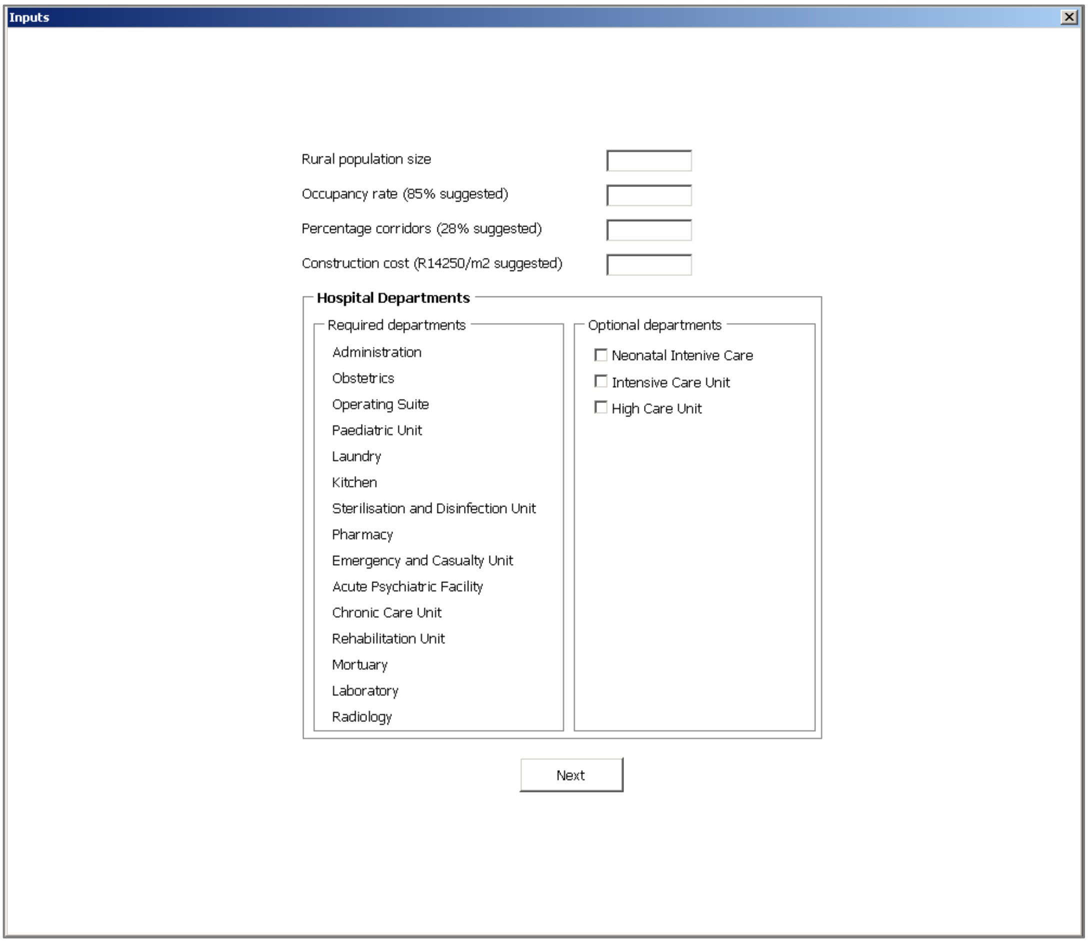
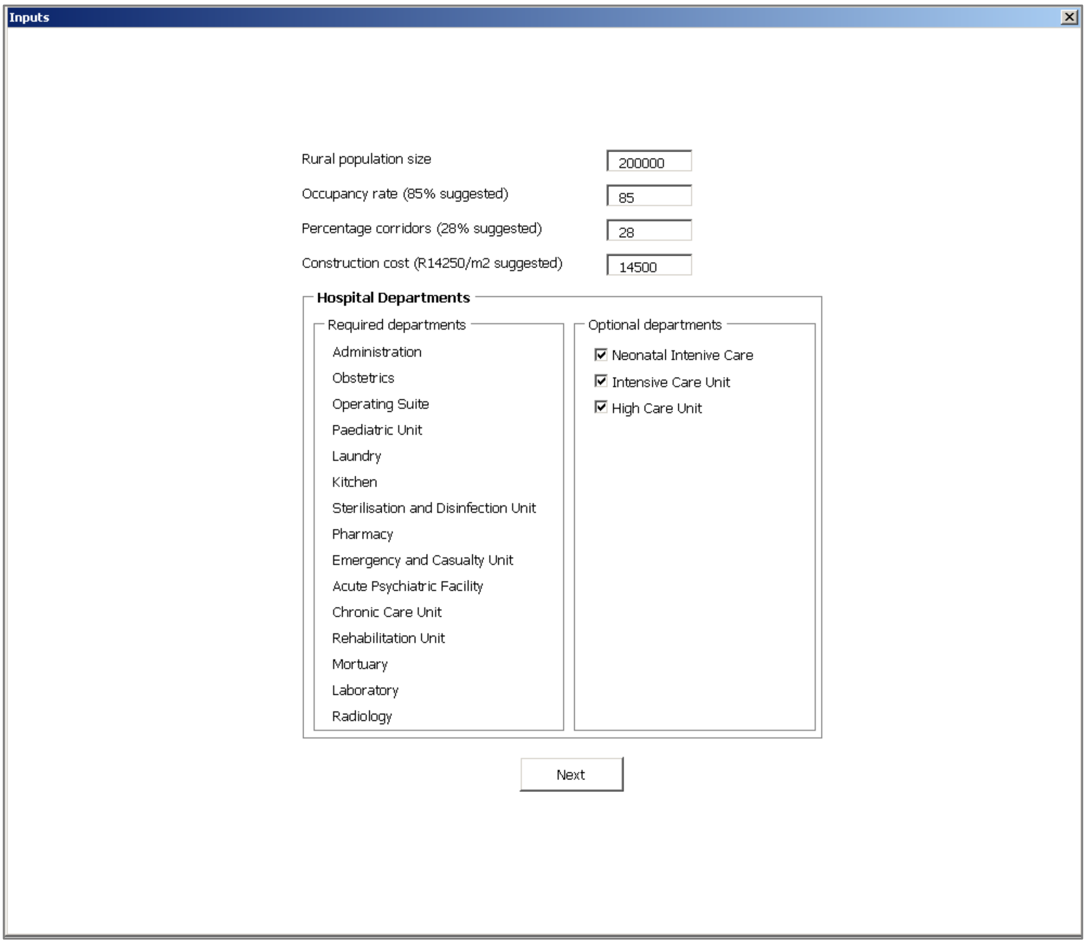
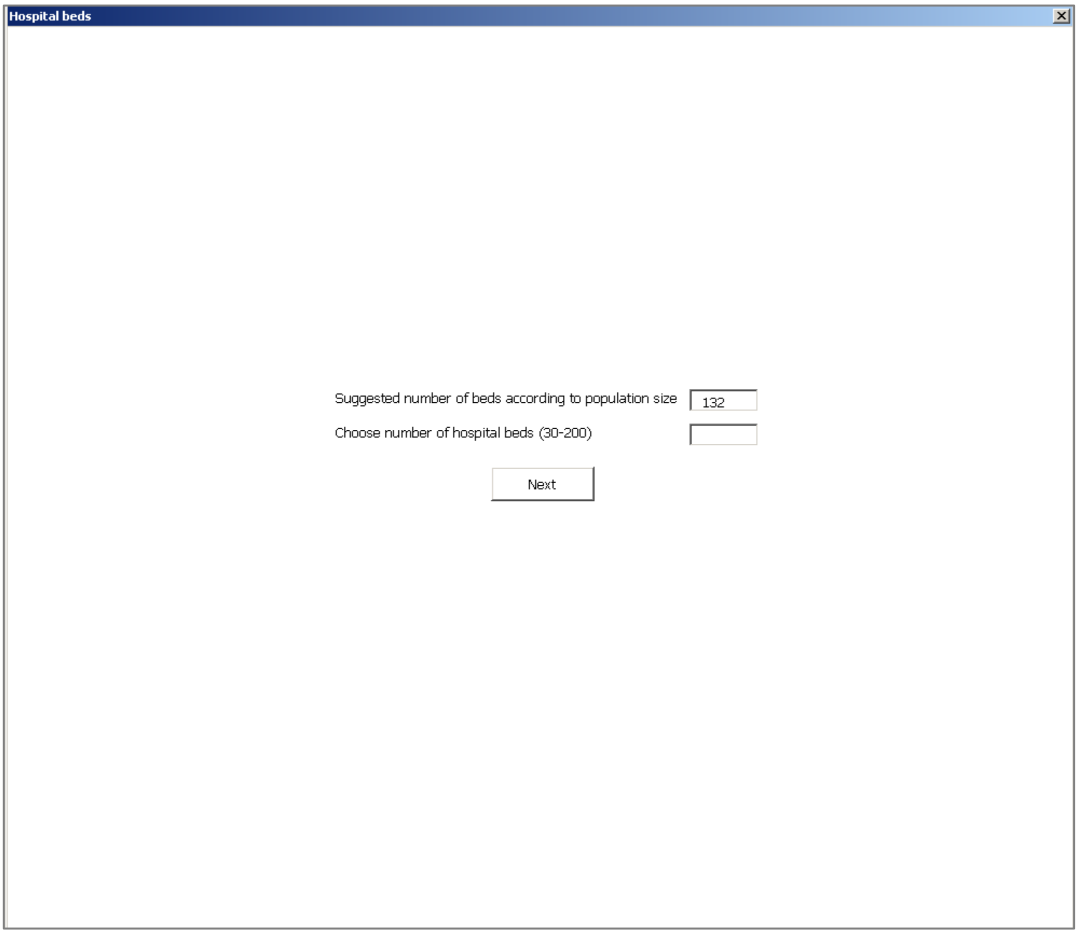
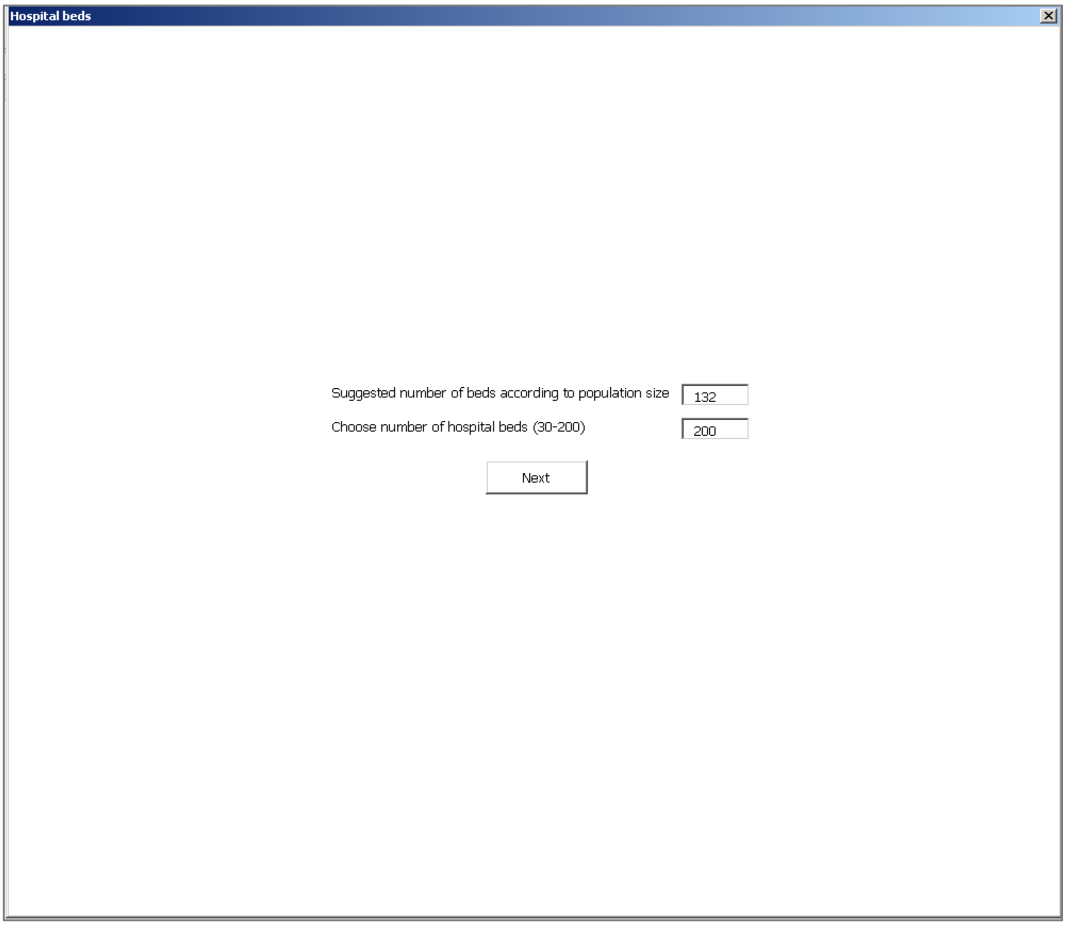
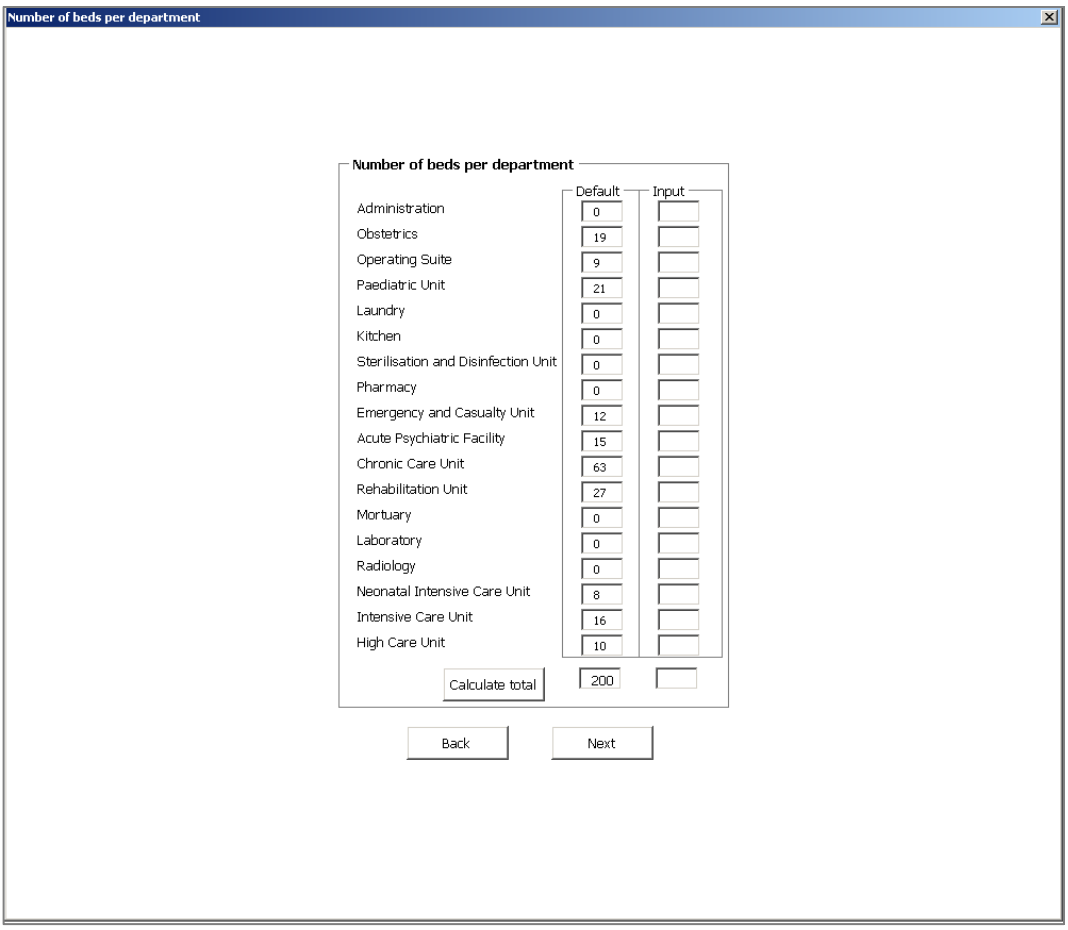
Formulas
Data
Review
View
R32
Design hospital layout
Main
Inputs
Flow
New flow
Admin
Obst
OS
Paed
Laun
Kitch
S&DU
Phar
Emer
Psych
CCU
Rehab
Mort
Lab
Radio
NICU
ICU
HCU
Summary
Ready
100%


Inputs
Rural population size
Occupancy rate (85% suggested)
Percentage corridors (28% suggested)
Construction cost (R14250/m2 suggested)
Hospital Departments
Required departments
Administration
Obstetrics
Operating Suite
Paediatric Unit
Laundry
Kitchen
Sterilisation and Disinfection Unit
Pharmacy
Emergency and Casualty Unit
Acute Psychiatric Facility
Chronic Care Unit
Rehabilitation Unit
Mortuary
Laboratory
Radiology
Optional departments
Neonatal Intenive Care
Intensive Care Unit
High Care Unit
Next


Inputs
Rural population size
200000
Occupancy rate (85% suggested)
85
Percentage corridors (28% suggested)
28
Construction cost (R14250/m2 suggested)
14500
Hospital Departments
Required departments
Administration
Obstetrics
Operating Suite
Paediatric Unit
Laundry
Kitchen
Sterilisation and Disinfection Unit
Pharmacy
Emergency and Casualty Unit
Acute Psychiatric Facility
Chronic Care Unit
Rehabilitation Unit
Mortuary
Laboratory
Radiology
Optional departments
Neonatal Intenive Care
Intensive Care Unit
High Care Unit
Next


Hospital beds
Suggested number of beds according to population size
132
Choose number of hospital beds (30-200)
Next


Hospital beds
Suggested number of beds according to population size 132
Choose number of hospital beds (30-200) 200
Next


Number of beds per department
Number of beds per department
Default
Input
Administration 0
Obstetrics 19
Operating Suite 9
Paediatric Unit 21
Laundry 0
Kitchen 0
Sterilisation and Disinfection Unit 0
Pharmacy 0
Emergency and Casualty Unit 12
Acute Psychiatric Facility 15
Chronic Care Unit 63
Rehabilitation Unit 27
Mortuary 0
Laboratory 0
Radiology 0
Neonatal Intensive Care Unit 8
Intensive Care Unit 16
High Care Unit 10
Calculate total 200
Back
Next

Number of beds per department

Number of beds per department

Department	Default	Input
Administration	0	0
Obstetrics	19	20
Operating Suite	9	10
Paediatric Unit	21	20
Laundry	0	0
Kitchen	0	0
Sterilisation and Disinfection Unit	0	0
Pharmacy	0	0
Emergency and Casualty Unit	12	16
Acute Psychiatric Facility	15	15
Chronic Care Unit	63	60
Rehabilitation Unit	27	25
Mortuary	0	0
Laboratory	0	0
Radiology	0	0
Neonatal Intensive Care Unit	8	8
Intensive Care Unit	16	16
High Care Unit	10	10
Calculate total	200	200

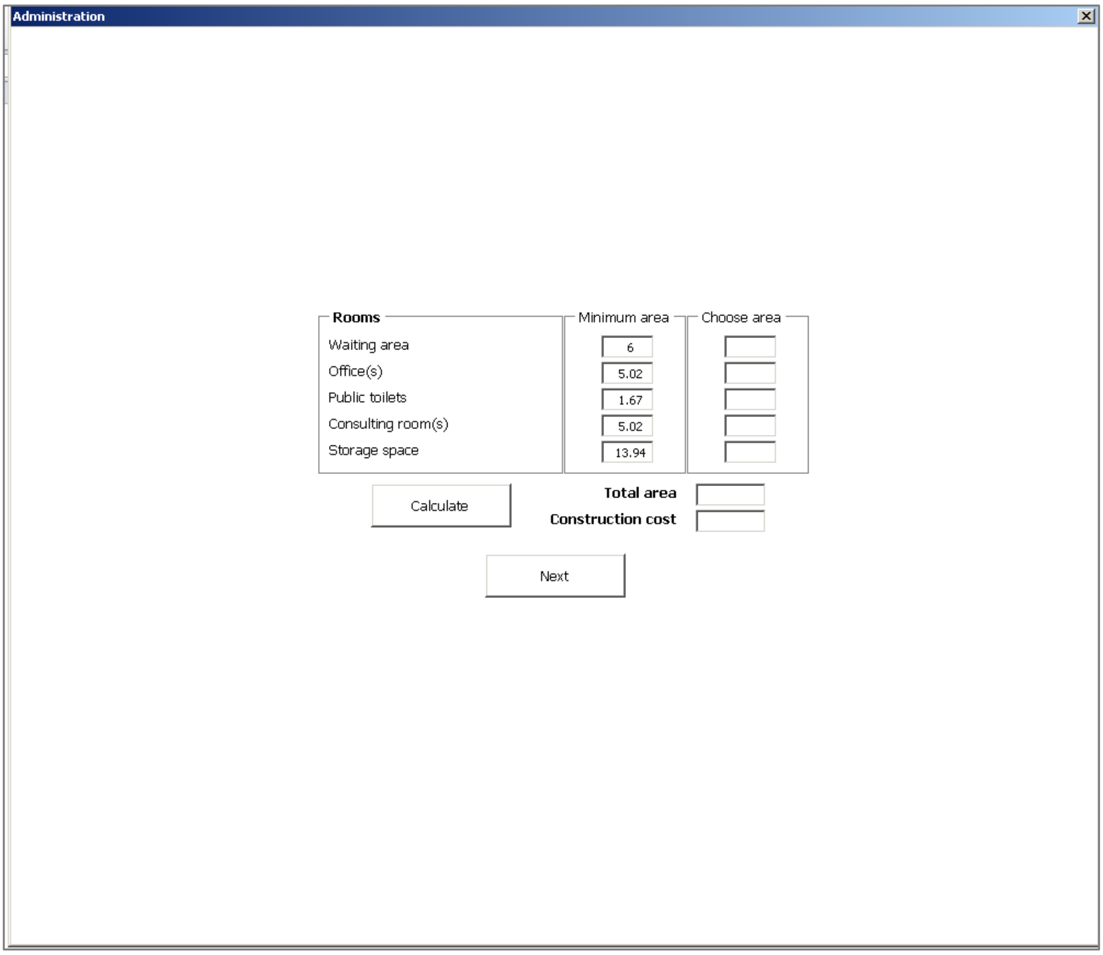
Back | Next

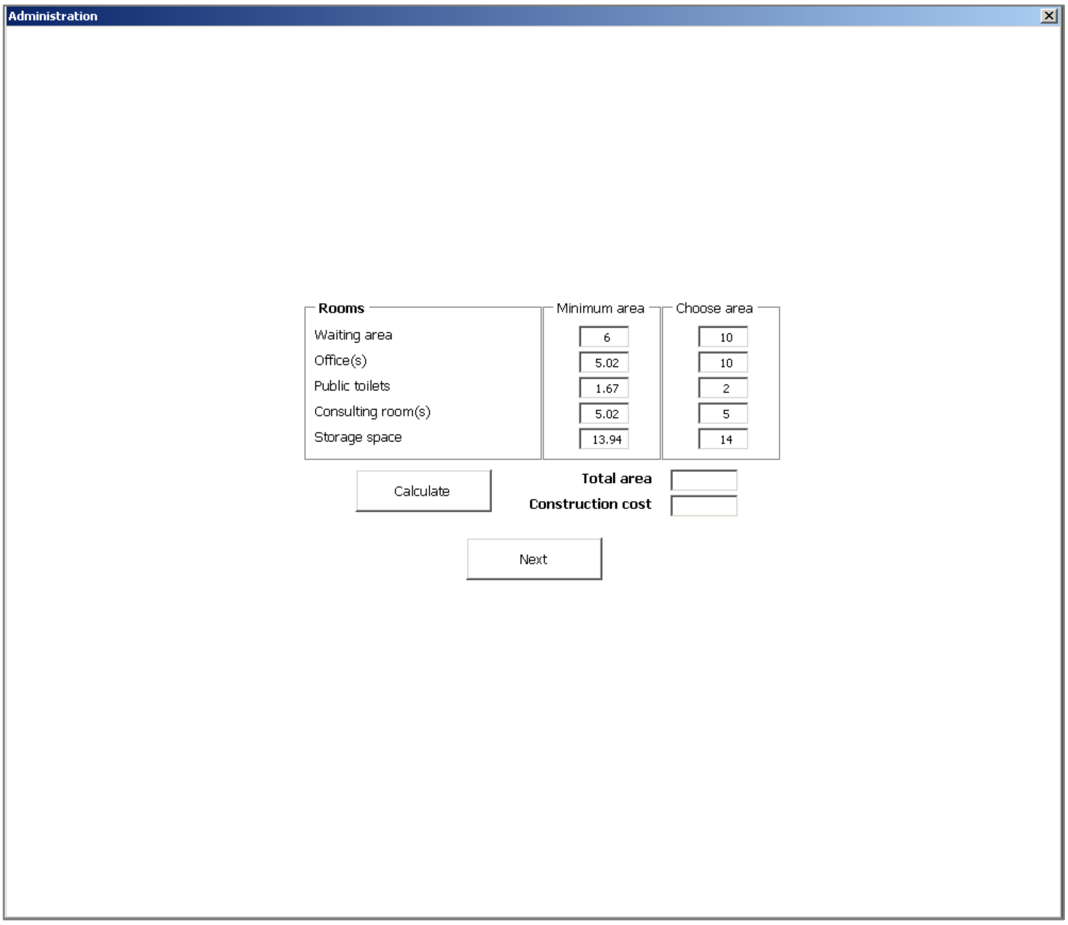
Hospital flow

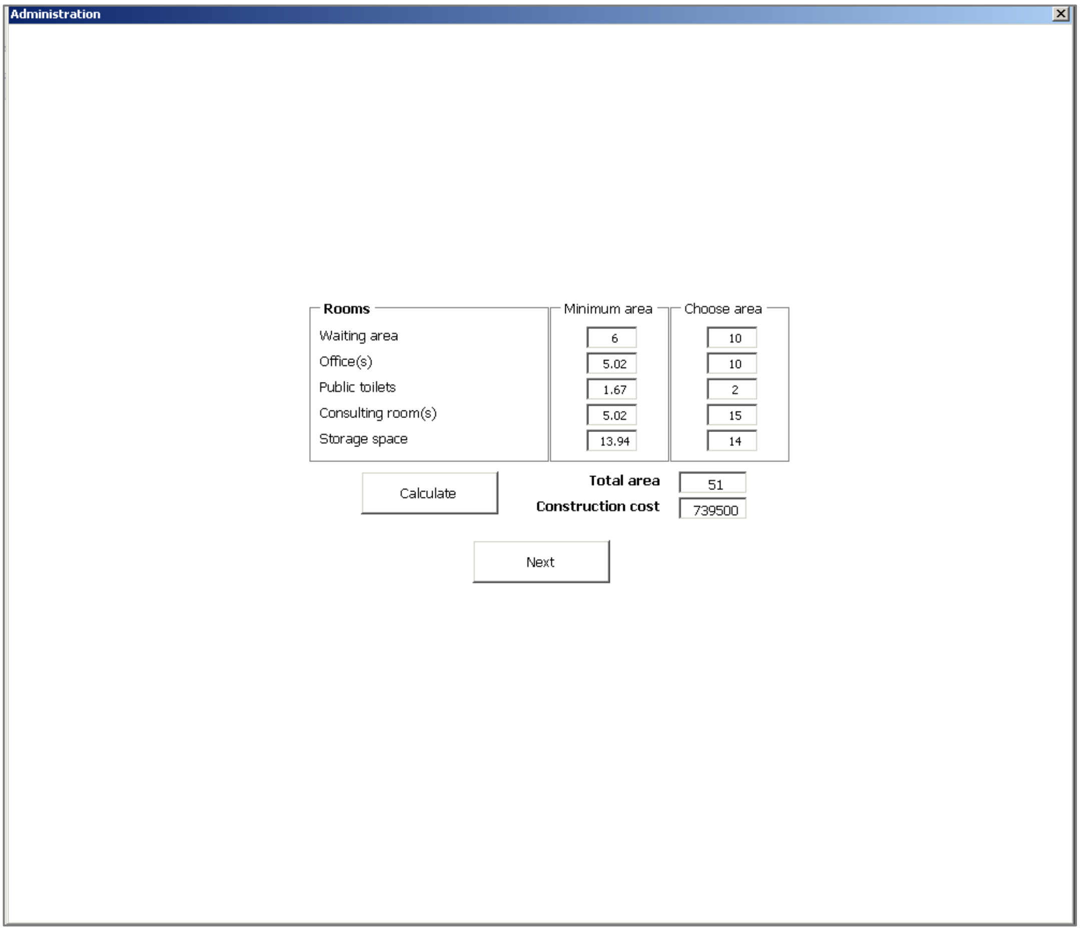
Enter relationship between departments:

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	3	0	-2	0	7	-3	-3	4	4	-3	4	5	3	3	3
Obst	-	0	10	3	5	3	5	4	5	-3	-3	-4	3	5	3	10	3	3
OS	-	-	0	4	5	0	10	2	10	0	3	3	4	5	5	8	10	7
Paed	-	-	-	0	5	3	5	4	3	-4	-2	-4	3	5	3	-3	2	2
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	5	5	5
Kitch	-	-	-	-	-	0	0	0	-3	3	3	3	0	0	0	3	3	3
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	6	6	6
Phar	-	-	-	-	-	-	-	0	3	3	3	3	-2	0	0	3	3	3
Emer	-	-	-	-	-	-	-	-	0	-2	3	-3	4	9	10	4	9	5
Psych	-	-	-	-	-	-	-	-	-	0	0	3	-3	6	4	-1	0	-1
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	3	5	5
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	3	3	3
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	3	4	3
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	5	5	5
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	4	4	4
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	3	3
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	6
HCU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

Next


Administration
Rooms
Minimum area
Choose area
Waiting area
6
Office(s)
5.02
Public toilets
1.67
Consulting room(s)
5.02
Storage space
13.94
Calculate
Total area
Construction cost
Next


Administration
Rooms
Minimum area
Choose area
Waiting area
6
10
Office(s)
5.02
10
Public toilets
1.67
2
Consulting room(s)
5.02
5
Storage space
13.94
14
Calculate
Total area
Construction cost
Next



Administration

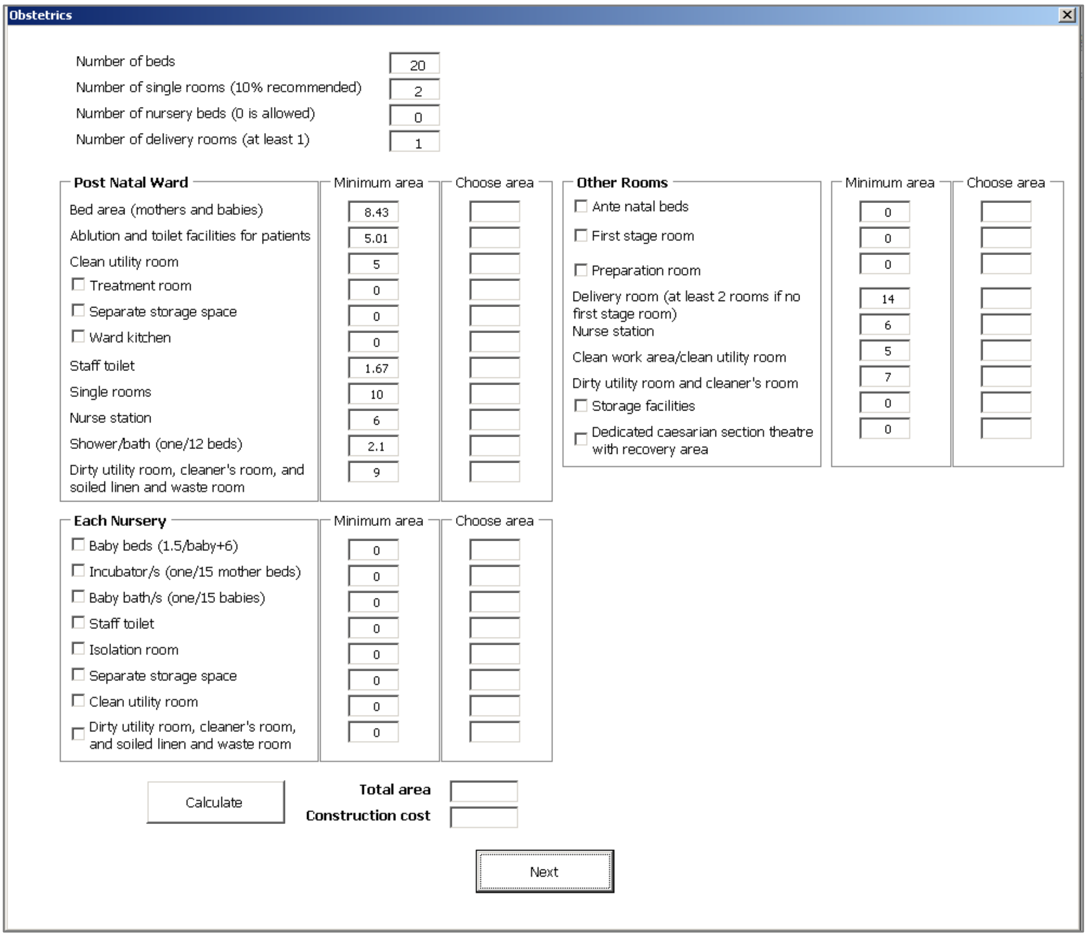
Rooms	Minimum area	Choose area
Waiting area	6	10
Office(s)	5.02	10
Public toilets	1.67	2
Consulting room(s)	5.02	15
Storage space	13.94	14

Calculate

Total area: 51

Construction cost: 739500

Next



Obstetrics

Number of beds	20
Number of single rooms (10% recommended)	2
Number of nursery beds (0 is allowed)	0
Number of delivery rooms (at least 1)	1

Post Natal Ward	Minimum area	Choose area
Bed area (mothers and babies)	8.43	
Ablution and toilet facilities for patients	5.01	
Clean utility room	5	
☐ Treatment room	0	
☐ Separate storage space	0	
☐ Ward kitchen	0	
Staff toilet	1.67	
Single rooms	10	
Nurse station	6	
Shower/bath (one/12 beds)	2.1	
Dirty utility room, cleaner's room, and soiled linen and waste room	9	

Other Rooms	Minimum area	Choose area
☐ Ante natal beds	0	
☐ First stage room	0	
☐ Preparation room	0	
Delivery room (at least 2 rooms if no first stage room)	14	
Nurse station	6	
Clean work area/clean utility room	5	
Dirty utility room and cleaner's room	7	
☐ Storage facilities	0	
☐ Dedicated caesarian section theatre with recovery area	0	

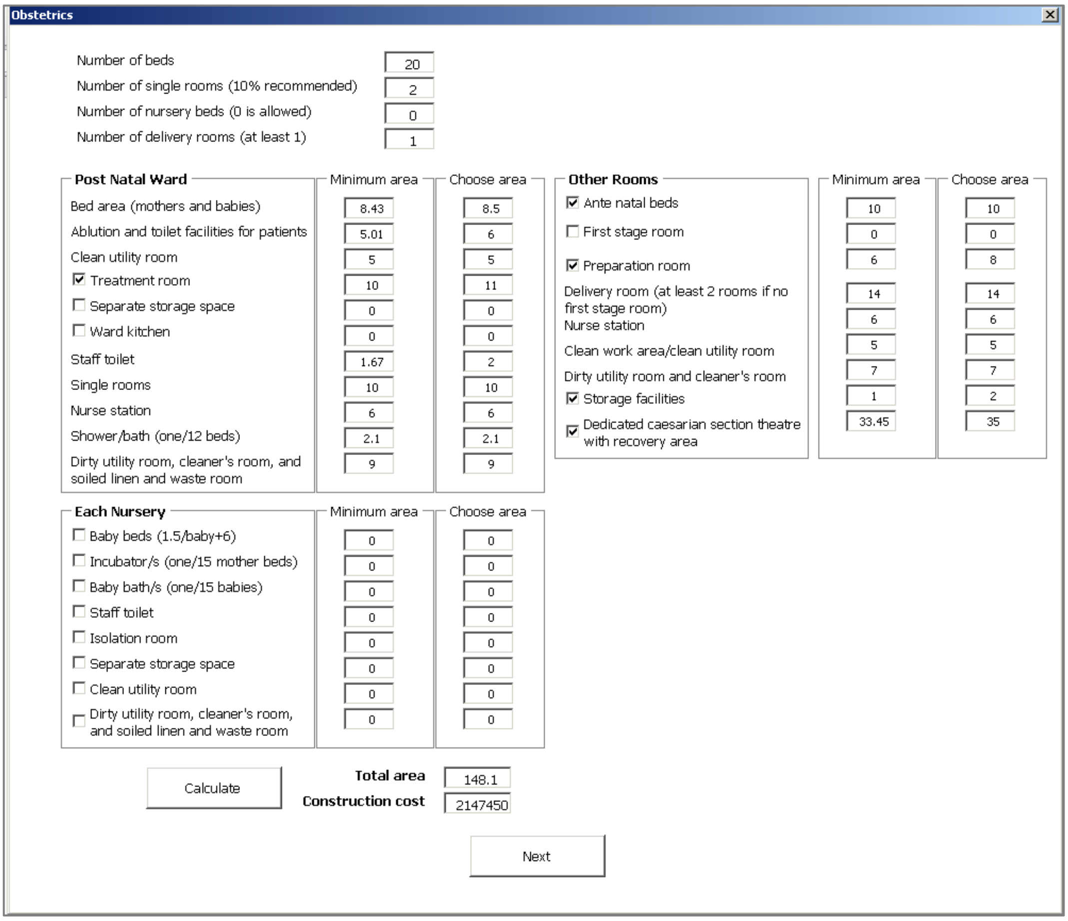
Each Nursery	Minimum area	Choose area
☐ Baby beds (1.5/baby+6)	0	
☐ Incubator/s (one/15 mother beds)	0	
☐ Baby bath/s (one/15 babies)	0	
☐ Staff toilet	0	
☐ Isolation room	0	
☐ Separate storage space	0	
☐ Clean utility room	0	
☐ Dirty utility room, cleaner's room, and soiled linen and waste room	0	

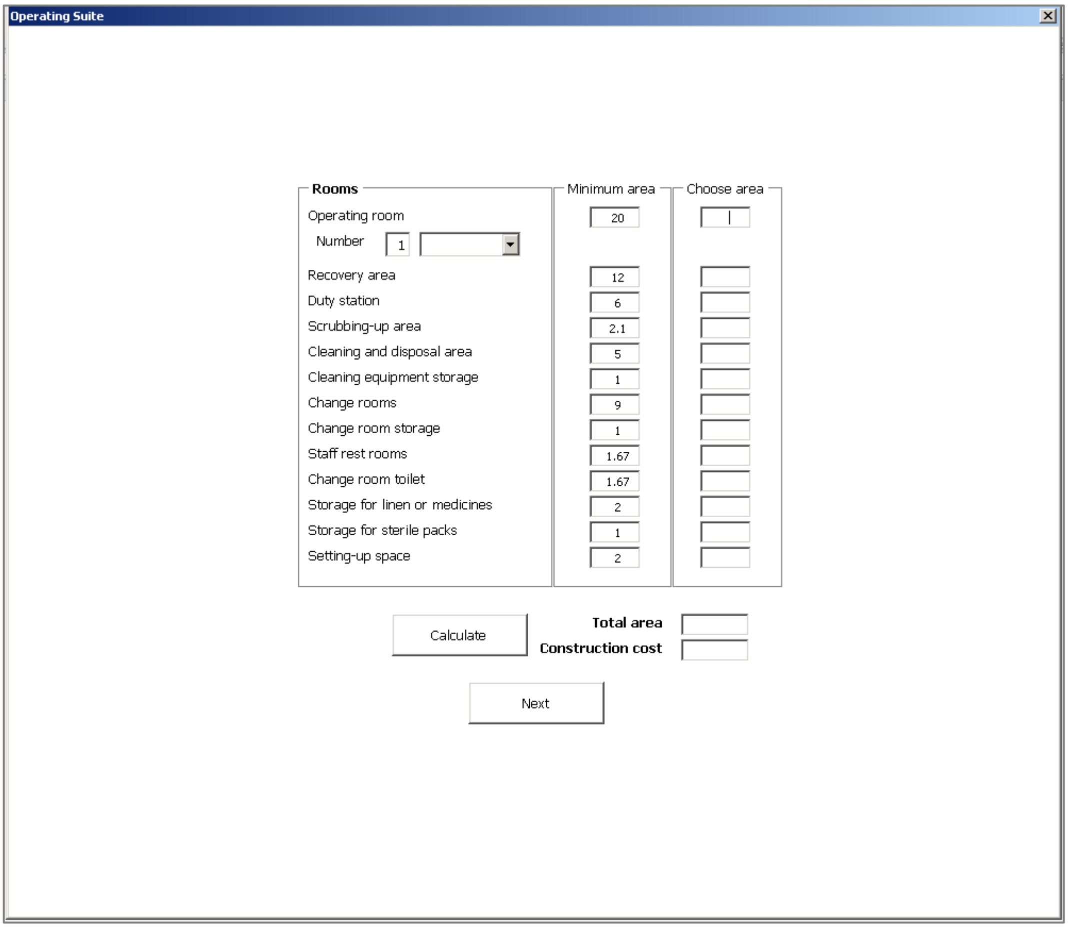
Calculate

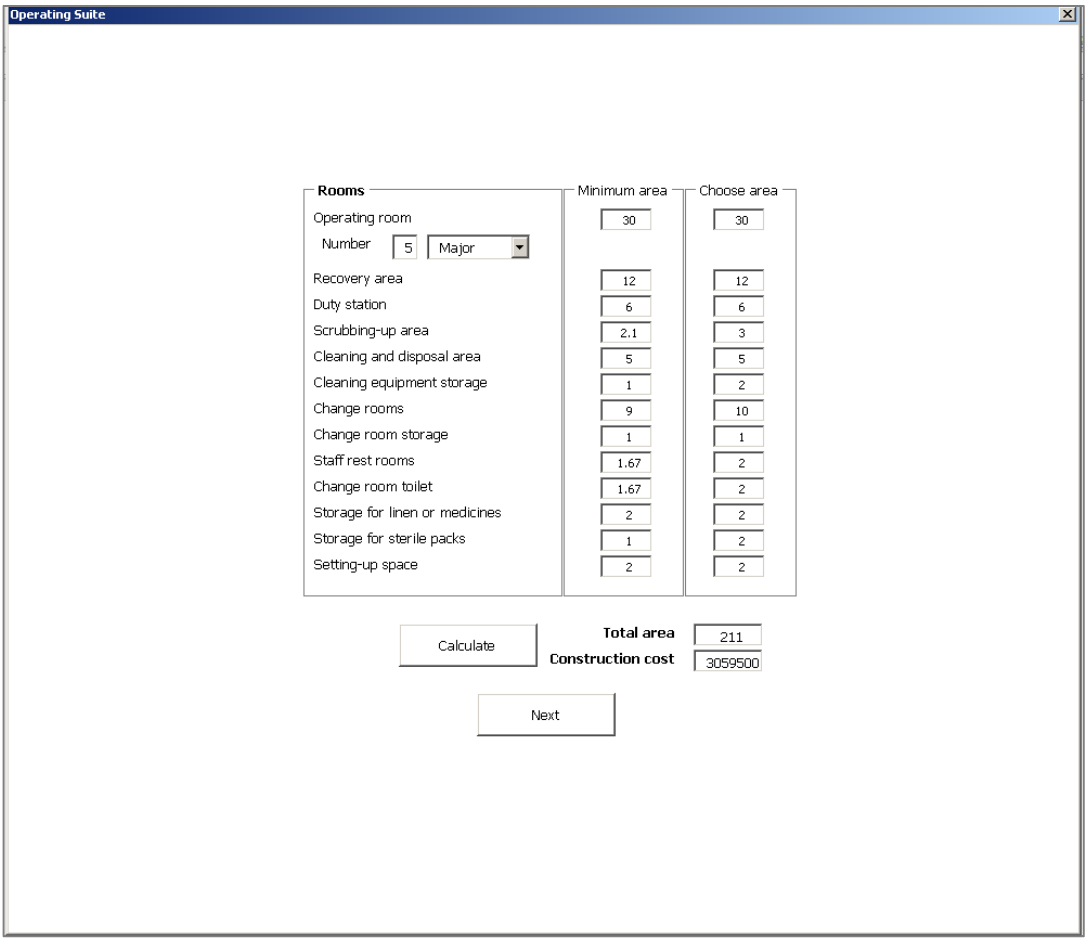
Total area:

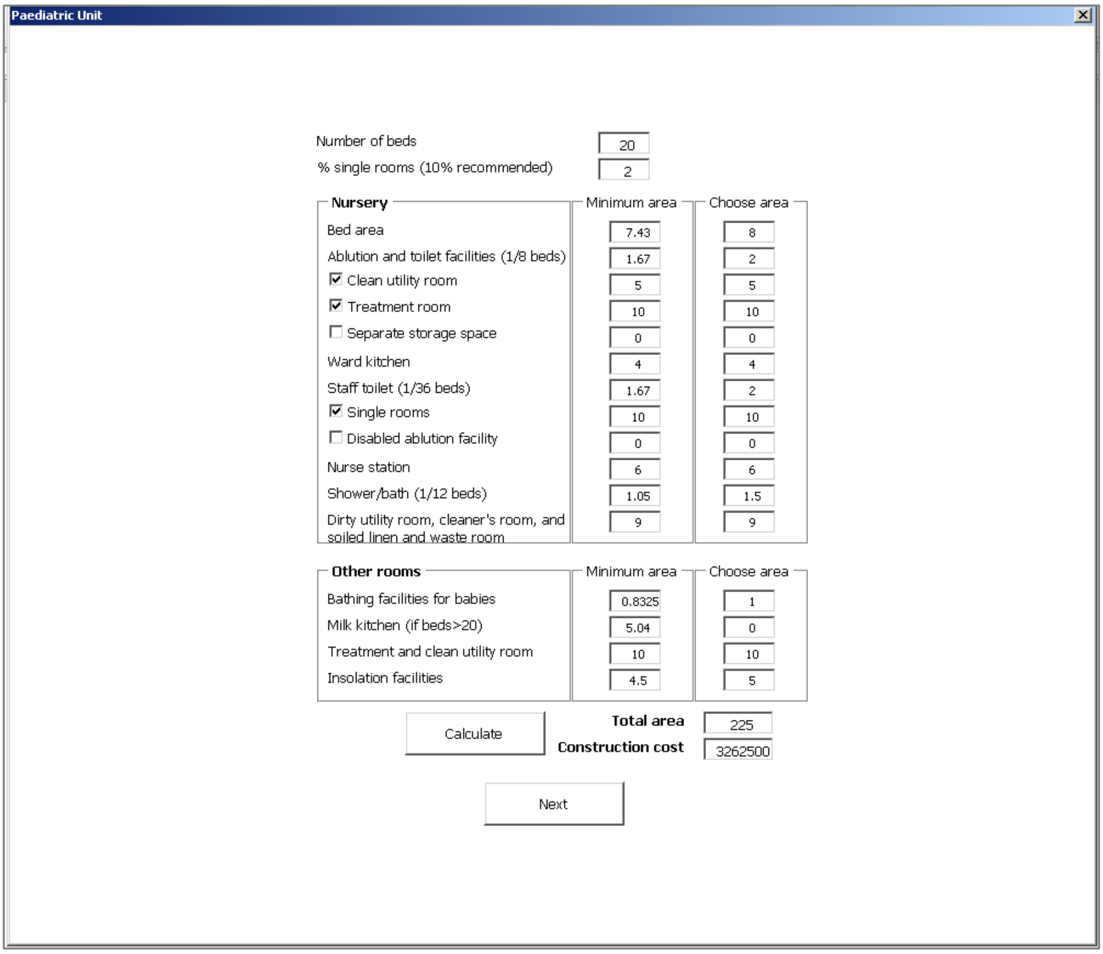
Construction cost:

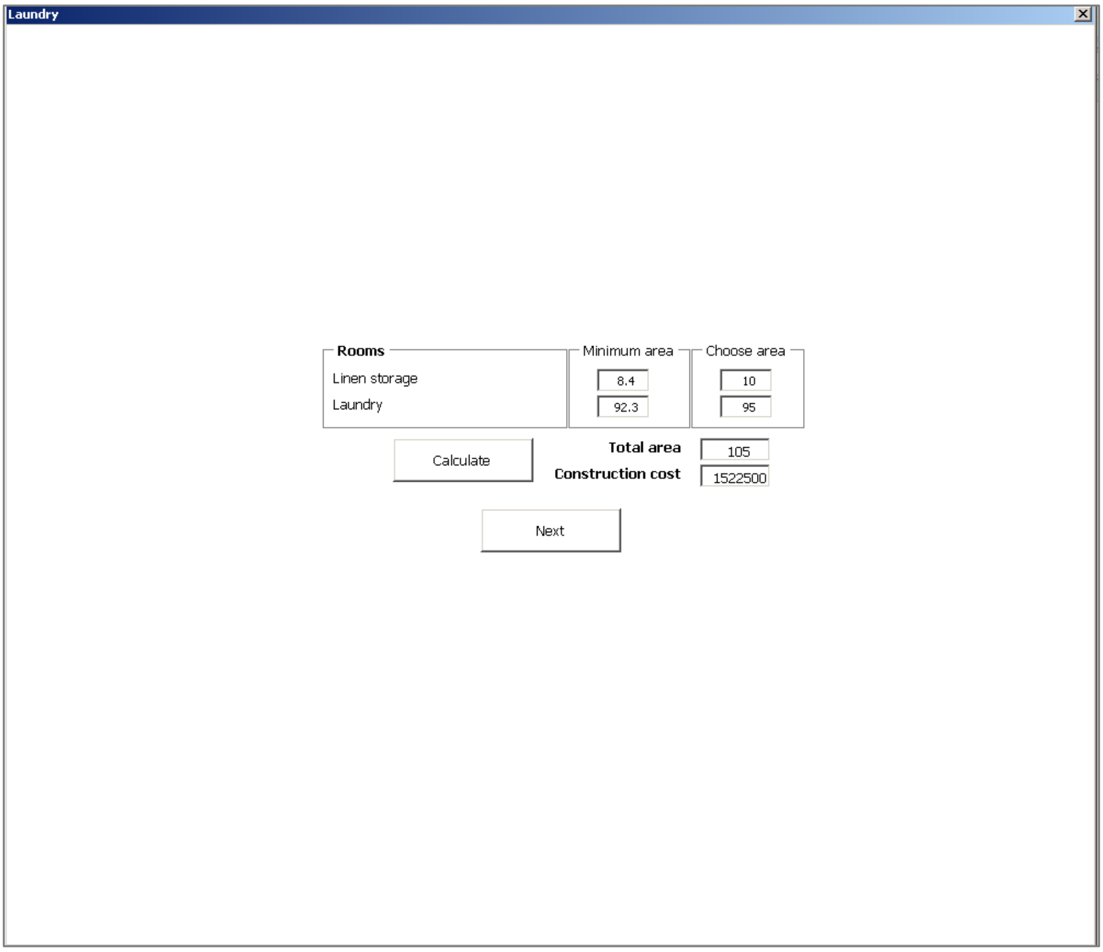
Next

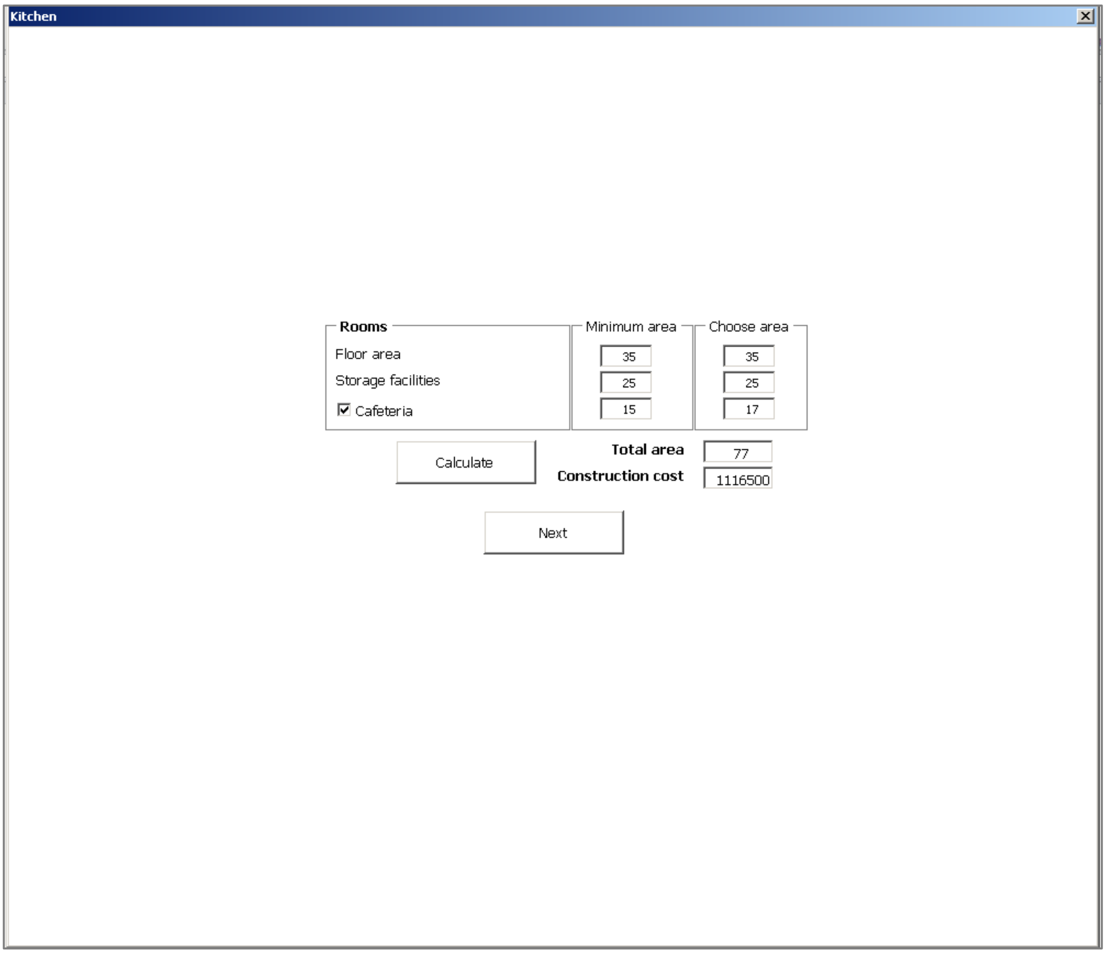

Obstetrics
Number of beds 20
Number of single rooms (10% recommended) 2
Number of nursery beds (0 is allowed) 0
Number of delivery rooms (at least 1) 1
Post Natal Ward
Minimum area
Choose area
Bed area (mothers and babies) 8.43 8.5
Ablution and toilet facilities for patients 5.01 6
Clean utility room 5 5
Treatment room 10 11
Separate storage space 0 0
Ward kitchen 0 0
Staff toilet 1.67 2
Single rooms 10 10
Nurse station 6 6
Shower/bath (one/12 beds) 2.1 2.1
Dirty utility room, cleaner's room, and soiled linen and waste room 9 9
Other Rooms
Minimum area
Choose area
Ante natal beds 10 10
First stage room 0 0
Preparation room 6 8
Delivery room (at least 2 rooms if no first stage room) 14 14
Nurse station 6 6
Clean work area/clean utility room 5 5
Dirty utility room and cleaner's room 7 7
Storage facilities 1 2
Dedicated caesarian section theatre with recovery area 33.45 35
Each Nursery
Minimum area
Choose area
Baby beds (1.5/baby+6) 0 0
Incubator/s (one/15 mother beds) 0 0
Baby bath/s (one/15 babies) 0 0
Staff toilet 0 0
Isolation room 0 0
Separate storage space 0 0
Clean utility room 0 0
Dirty utility room, cleaner's room, and soiled linen and waste room 0 0
Calculate
Total area 148.1
Construction cost 2147450
Next

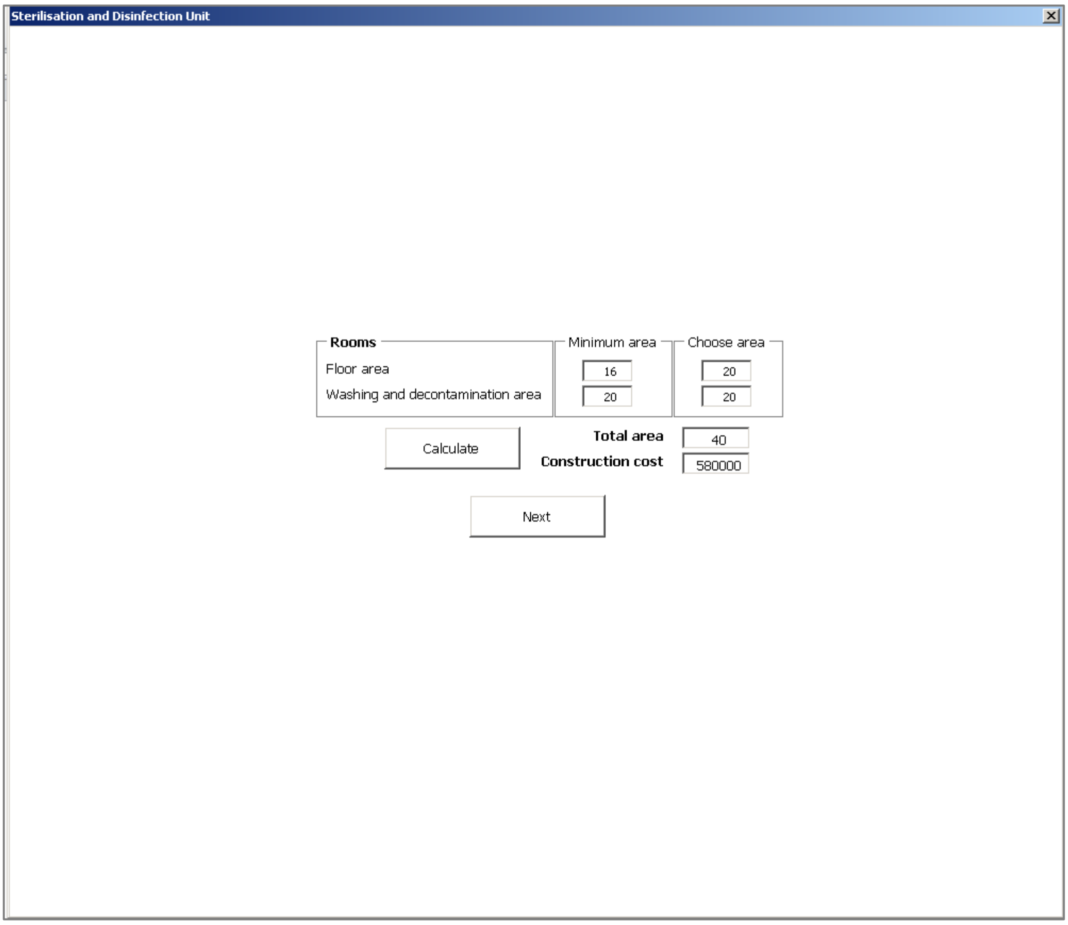

Operating Suite
Rooms
Minimum area
Choose area
Operating room 20
Number 1
Recovery area 12
Duty station 6
Scrubbing-up area 2.1
Cleaning and disposal area 5
Cleaning equipment storage 1
Change rooms 9
Change room storage 1
Staff rest rooms 1.67
Change room toilet 1.67
Storage for linen or medicines 2
Storage for sterile packs 1
Setting-up space 2
Calculate
Total area
Construction cost
Next

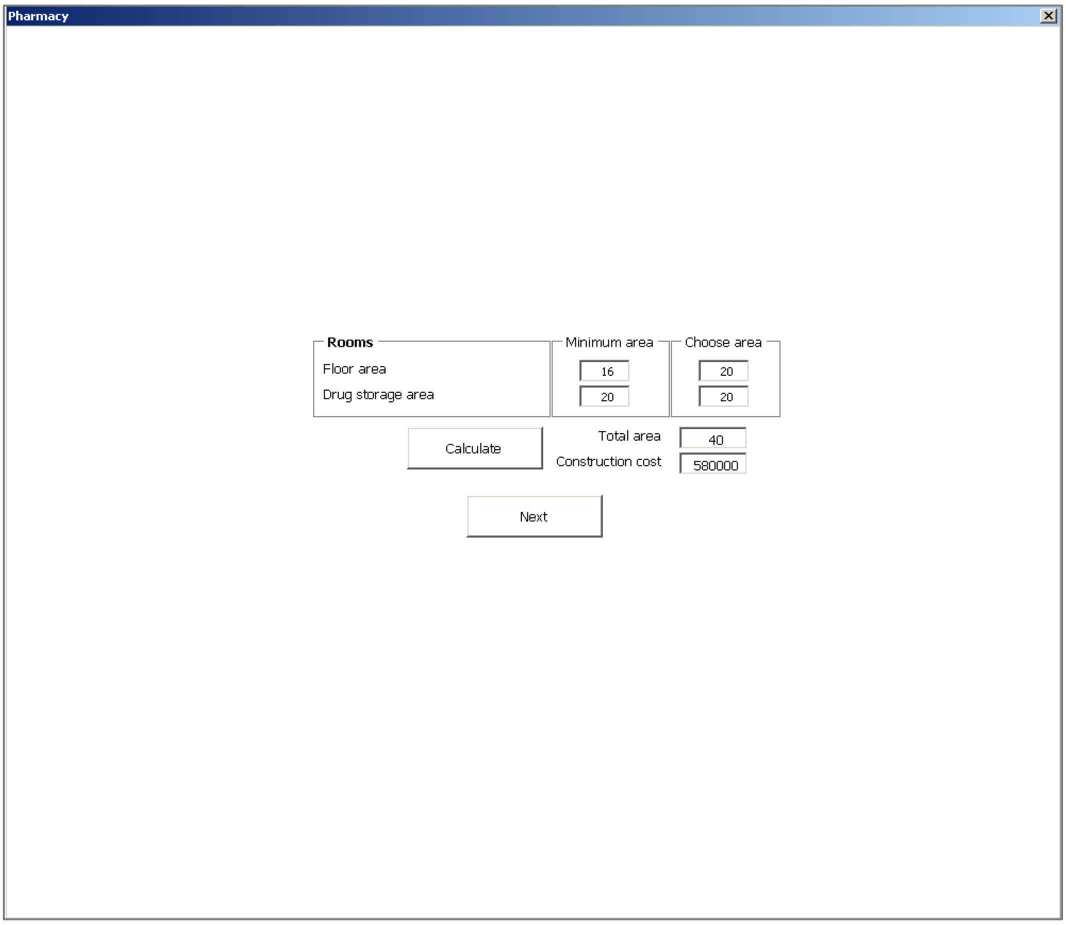

Operating Suite
Rooms
Minimum area
Choose area
Operating room
30
30
Number
5
Major
Recovery area
12
12
Duty station
6
6
Scrubbing-up area
2.1
3
Cleaning and disposal area
5
5
Cleaning equipment storage
1
2
Change rooms
9
10
Change room storage
1
1
Staff rest rooms
1.67
2
Change room toilet
1.67
2
Storage for linen or medicines
2
2
Storage for sterile packs
1
2
Setting-up space
2
2
Calculate
Total area
211
Construction cost
3059500
Next


Paediatric Unit
Number of beds
20
% single rooms (10% recommended)
2
Nursery
Minimum area
Choose area
Bed area
7.43
8
Ablution and toilet facilities (1/8 beds)
1.67
2
Clean utility room
5
5
Treatment room
10
10
Separate storage space
0
0
Ward kitchen
4
4
Staff toilet (1/36 beds)
1.67
2
Single rooms
10
10
Disabled ablution facility
0
0
Nurse station
6
6
Shower/bath (1/12 beds)
1.05
1.5
Dirty utility room, cleaner's room, and soiled linen and waste room
9
9
Other rooms
Minimum area
Choose area
Bathing facilities for babies
0.8325
1
Milk kitchen (if beds>20)
5.04
0
Treatment and clean utility room
10
10
Insolation facilities
4.5
5
Calculate
Total area
225
Construction cost
3262500
Next


Laundry
Rooms
Linen storage
Laundry
Minimum area
8.4
92.3
Choose area
10
95
Calculate
Total area
105
Construction cost
1522500
Next


Kitchen
Rooms
Floor area
Storage facilities
Cafeteria
Minimum area
35
25
15
Choose area
35
25
17
Calculate
Total area
77
Construction cost
1116500
Next


Sterilisation and Disinfection Unit
Rooms
Floor area
Washing and decontamination area
Minimum area
16
20
Choose area
20
20
Calculate
Total area
40
Construction cost
580000
Next


Pharmacy
Rooms
Floor area
Drug storage area
Minimum area
16
20
Choose area
20
20
Calculate
Total area
40
Construction cost
580000
Next

Emergency or Casualty Unit

Rooms	Minimum area	Choose area
Reception area with office space	9.29	10
Waiting area	6	6
Public toilet	3.34	4
Wheelchair toilet	4.05	5
Resuscitation and procedure room	20	20
Dirty utility room	5	5
Cleaner's room	2	2
Staff toilets	1.67	2
Nurse station/duty room	6	6
Room(s) and/or cubicles	6	60
Dedicated trauma theatre	37.16	38
Clean utility area with storage space for pharmaceutical substances	5	5

Calculate

Total area 163

Construction cost 2363500

Next

Acute Psychiatric Facility

Number of beds 15

% single rooms (10% recommended) 2

Nursery	Minimum area	Choose area
Bed area	7.5	8
Ablution and toilet facilities for	1.67	2
☐ Clean utility room	0	0
☑ Treatment room	10	10
☐ Separate storage space	0	0
Ward kitchen	4	4
Staff toilet	1.67	1.67
☑ Single rooms	10	10
☑ Disabled ablution facility(1/floor)	4.05	5
Nurse station	6	6
Shower/bath (1/12 beds)	1.05	1.05
Dirty utility room, cleaner's room, and soiled linen and waste room	9	9

Other rooms	Minimum area	Choose area
☑ Lounge	9	10
Group room	9	9
Consulting room	6	6
Observation room	10	10
Dining-room	9	9
☑ Recreation area	20	20
Procedure room	12	12
Recovery facility	9	9
Staff toilet facilities	1.67	1.67

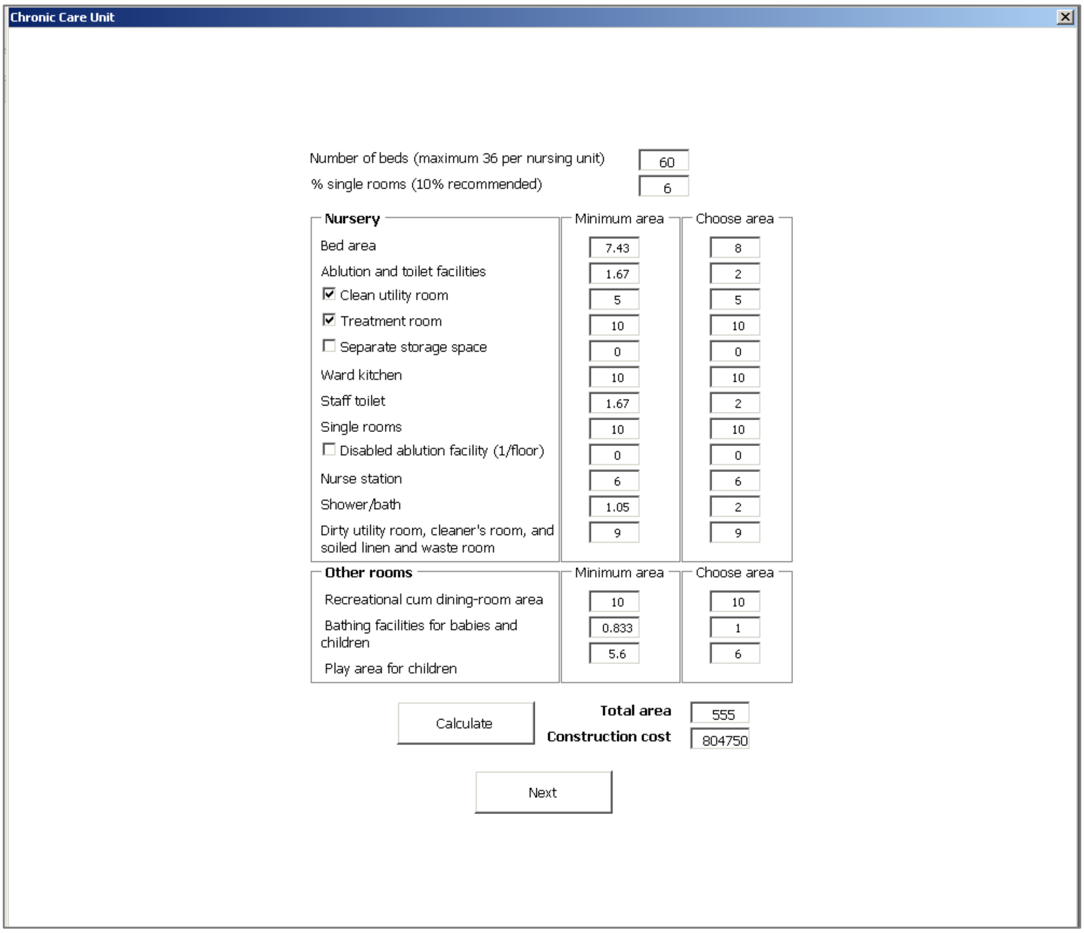
Occupational Therapy Unit	Minimum area	Choose area
Office space	5.02	9
Group/Interview room	9	9
Activity/Craft room	30	30
Relaxation/Therapy/Lecture room	30	30
Storage for equipment and materials	2	2

Calculate

Total area 329.39

Construction cost 4776155

Next



Chronic Care Unit

Number of beds (maximum 36 per nursing unit): 60

% single rooms (10% recommended): 6

Nursery	Minimum area	Choose area
Bed area	7.43	8
Ablution and toilet facilities	1.67	2
☑ Clean utility room	5	5
☑ Treatment room	10	10
☐ Separate storage space	0	0
Ward kitchen	10	10
Staff toilet	1.67	2
Single rooms	10	10
☐ Disabled ablution facility (1/floor)	0	0
Nurse station	6	6
Shower/bath	1.05	2
Dirty utility room, cleaner's room, and soiled linen and waste room	9	9

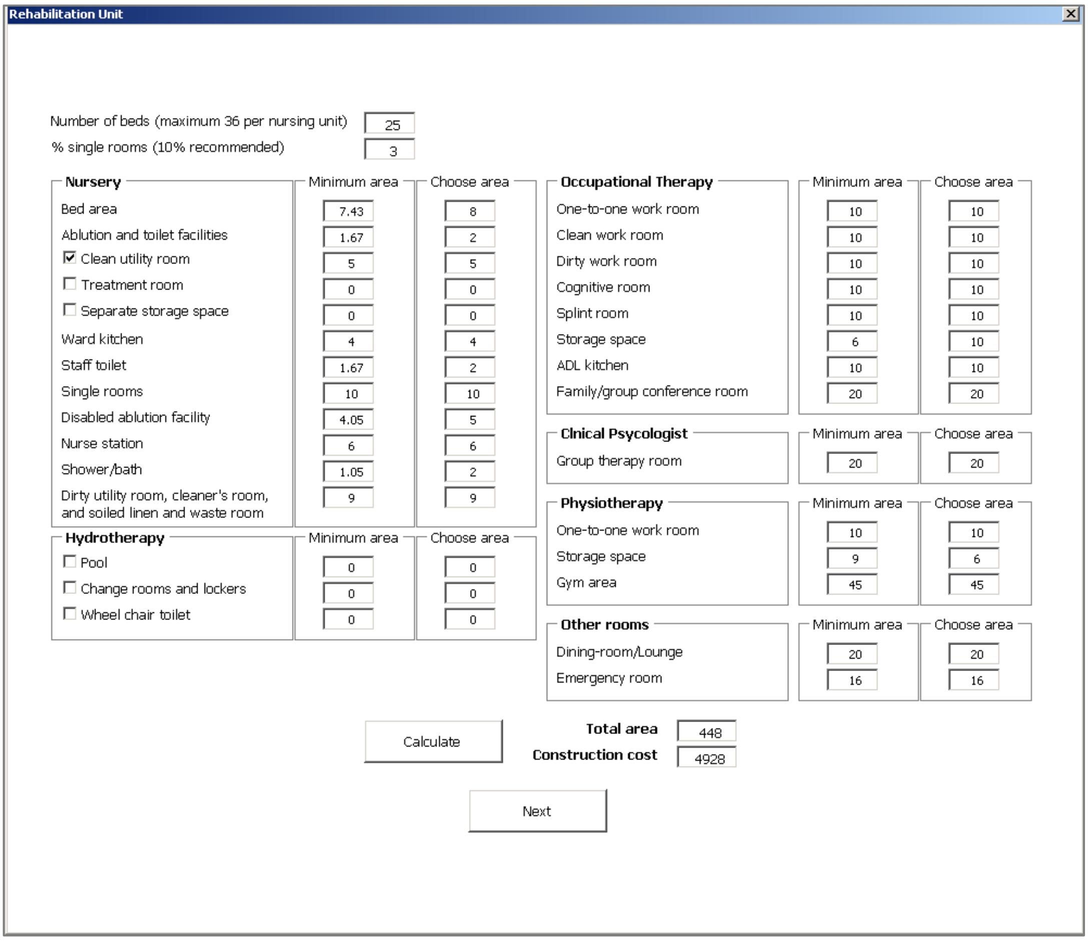
Other rooms	Minimum area	Choose area
Recreational cum dining-room area	10	10
Bathing facilities for babies and children	0.833	1
Play area for children	5.6	6

Calculate

Total area: 555

Construction cost: 804750

Next



Rehabilitation Unit

Number of beds (maximum 36 per nursing unit): 25

% single rooms (10% recommended): 3

Nursery	Minimum area	Choose area
Bed area	7.43	8
Ablution and toilet facilities	1.67	2
☑ Clean utility room	5	5
☐ Treatment room	0	0
☐ Separate storage space	0	0
Ward kitchen	4	4
Staff toilet	1.67	2
Single rooms	10	10
Disabled ablution facility	4.05	5
Nurse station	6	6
Shower/bath	1.05	2
Dirty utility room, cleaner's room, and soiled linen and waste room	9	9

Hydrotherapy	Minimum area	Choose area
☐ Pool	0	0
☐ Change rooms and lockers	0	0
☐ Wheel chair toilet	0	0

Occupational Therapy	Minimum area	Choose area
One-to-one work room	10	10
Clean work room	10	10
Dirty work room	10	10
Cognitive room	10	10
Splint room	10	10
Storage space	6	10
ADL kitchen	10	10
Family/group conference room	20	20

Clnical Psycologist	Minimum area	Choose area
Group therapy room	20	20

Physiotherapy	Minimum area	Choose area
One-to-one work room	10	10
Storage space	9	6
Gym area	45	45

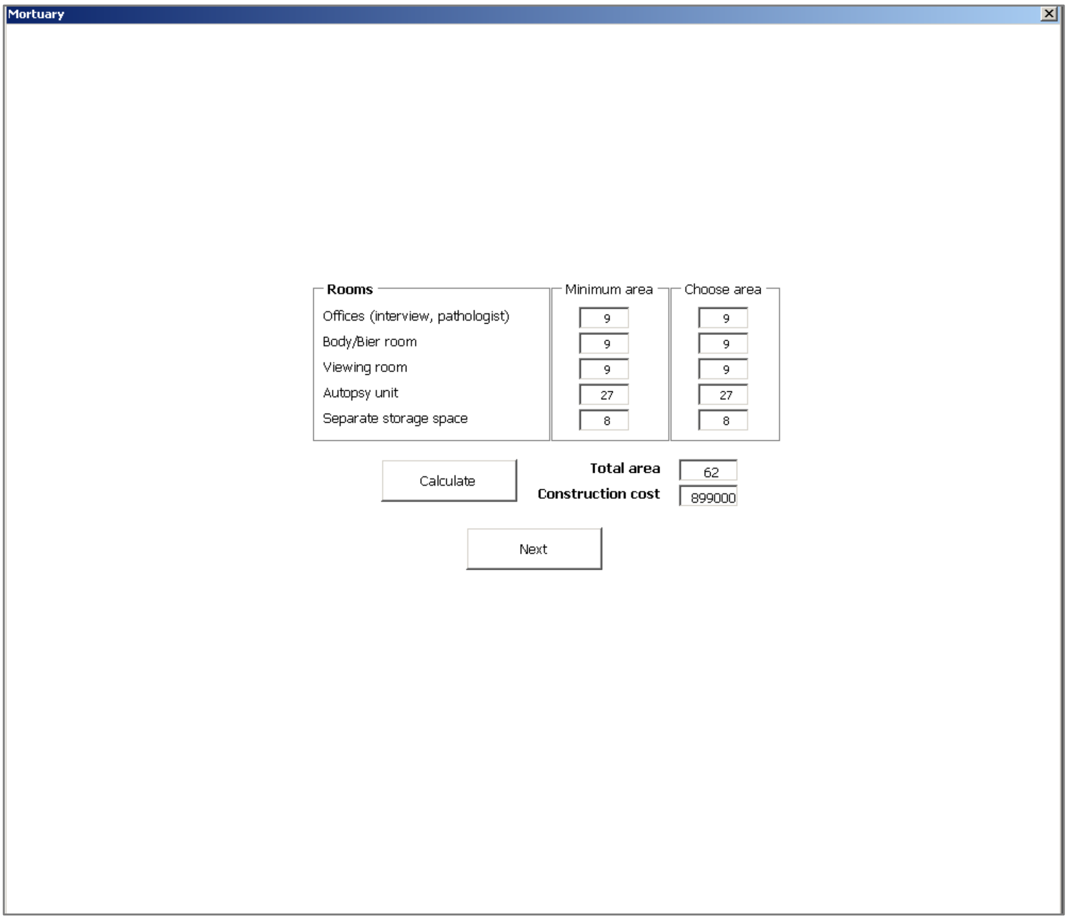
Other rooms	Minimum area	Choose area
Dining-room/Lounge	20	20
Emergency room	16	16

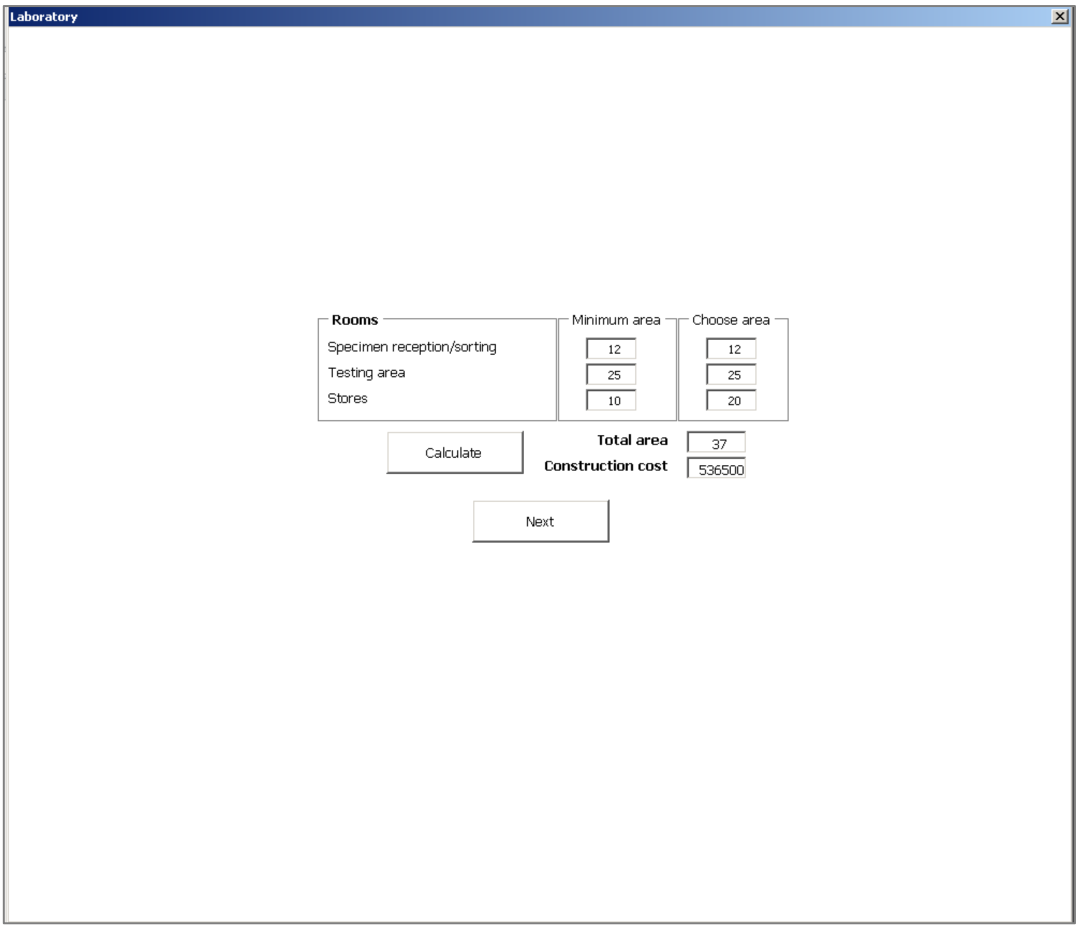
Calculate

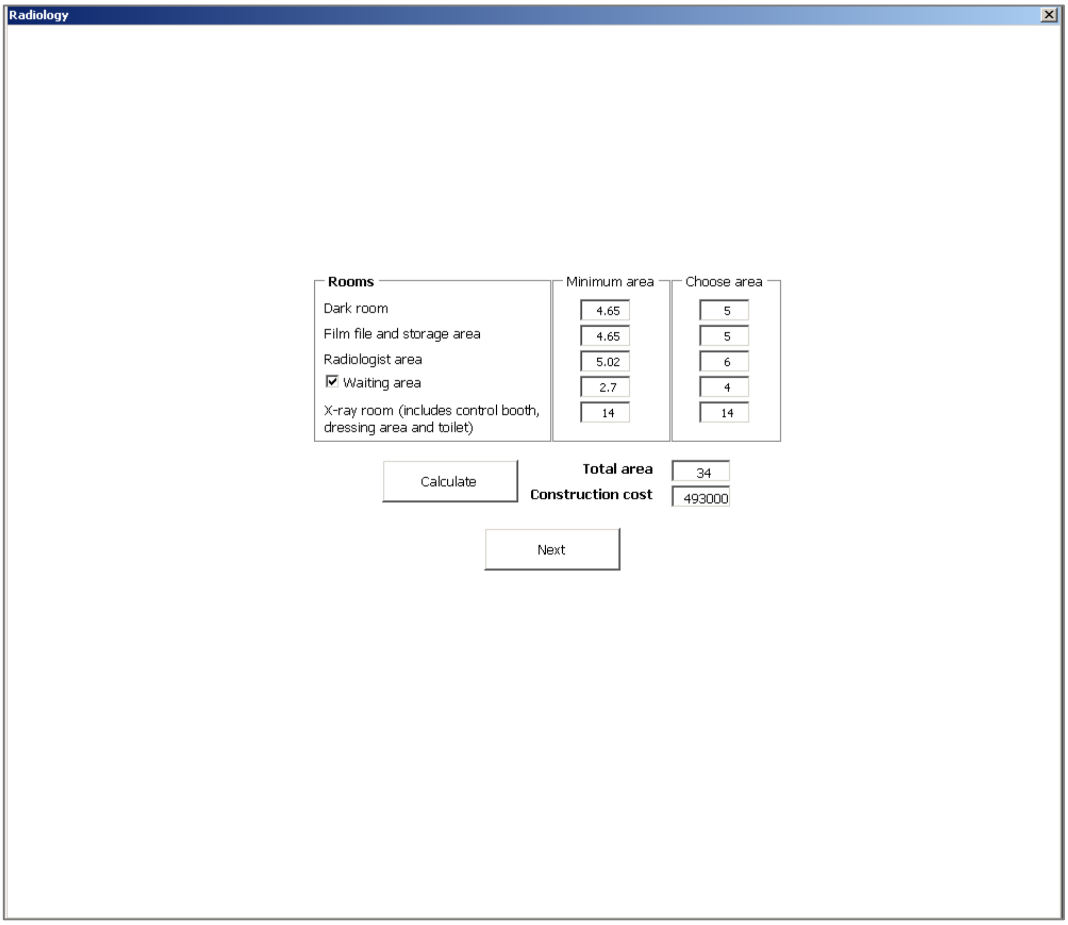
Total area: 448

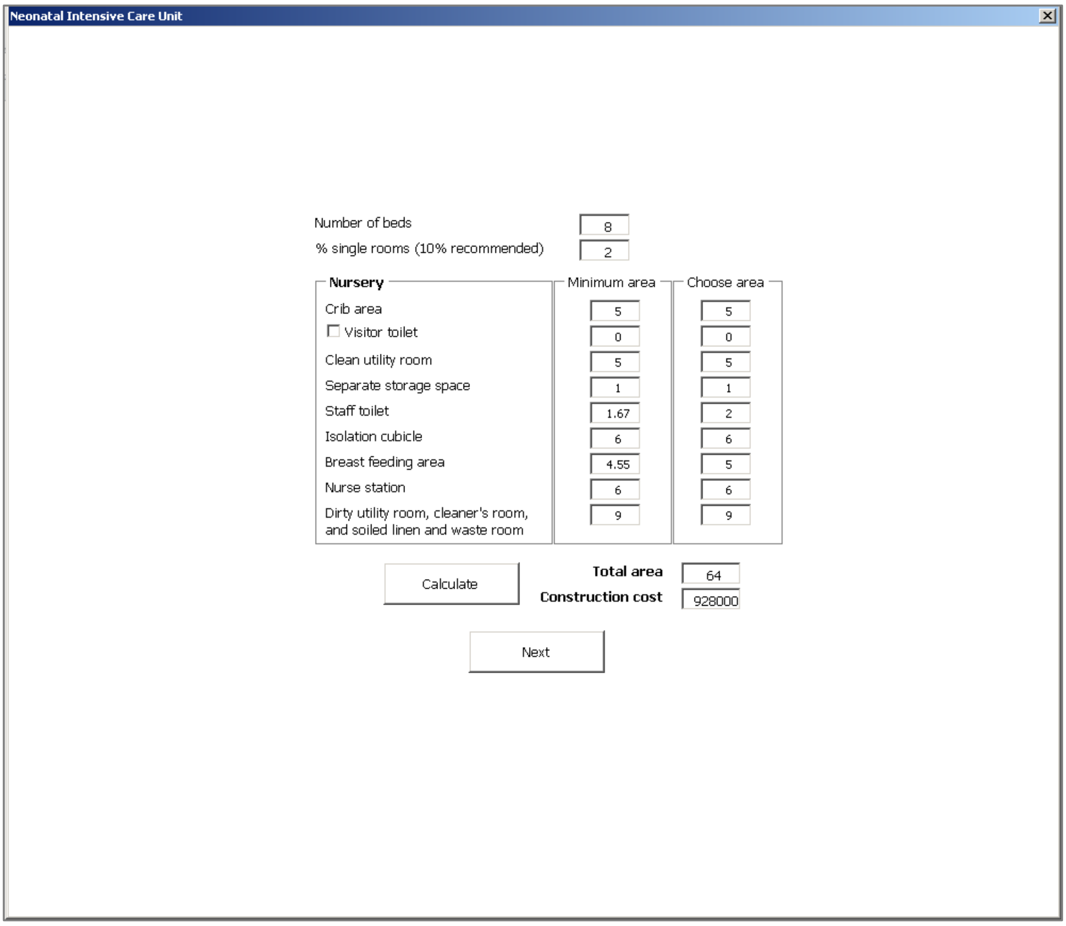
Construction cost: 4928

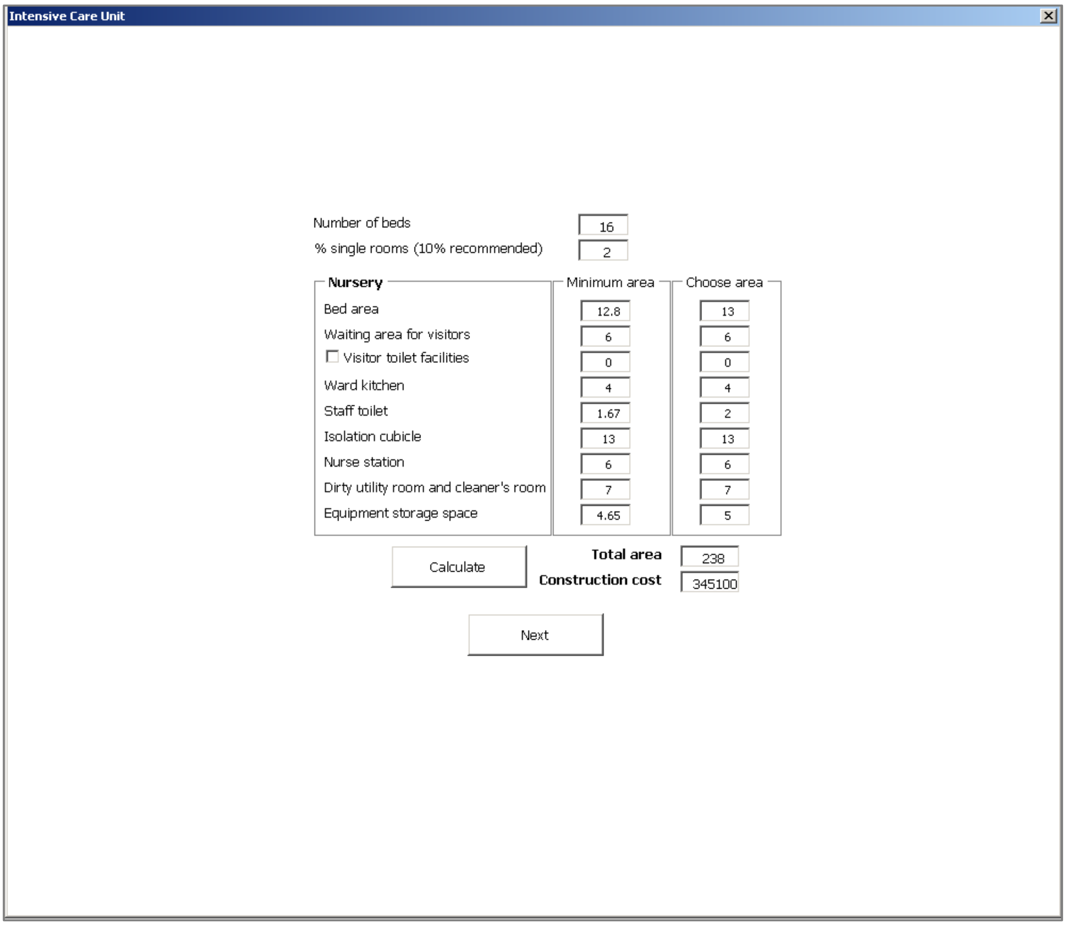
Next

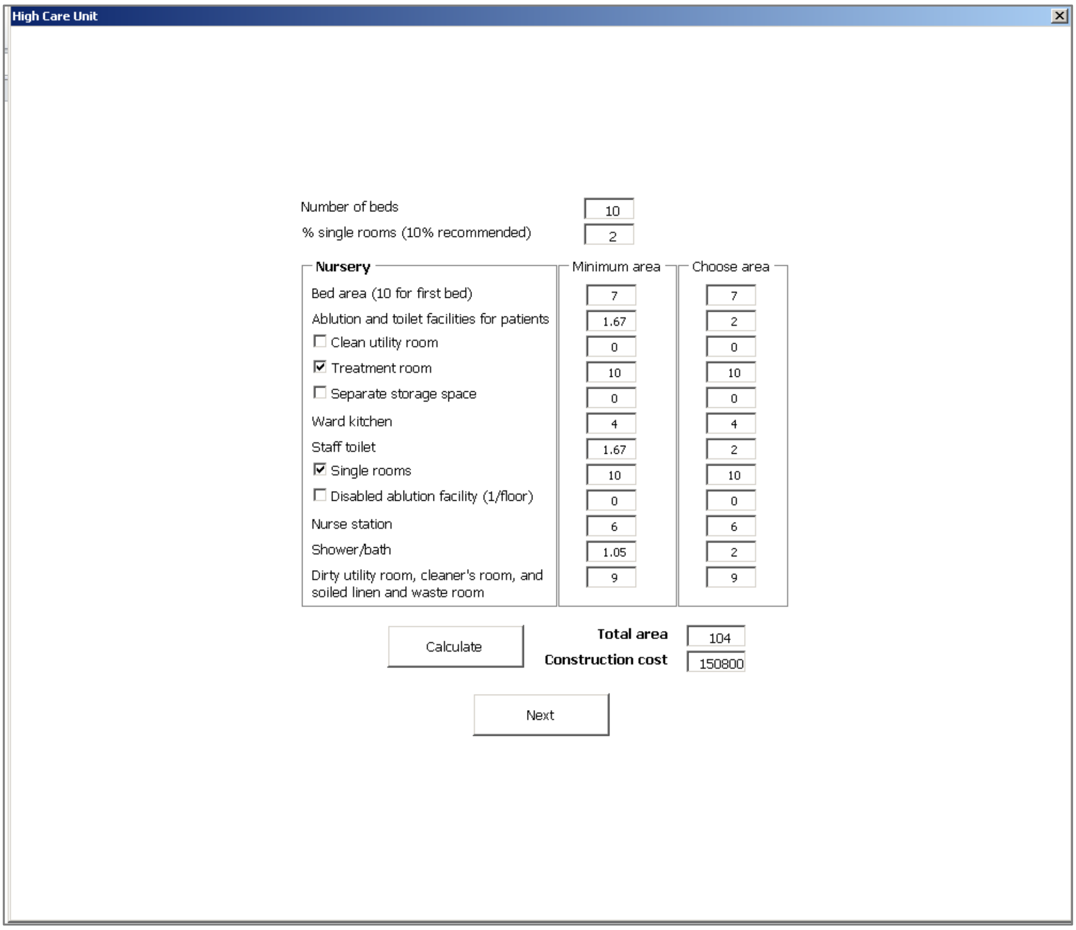

Mortuary
Rooms
Minimum area
Choose area
Offices (interview, pathologist)
9
9
Body/Bier room
9
9
Viewing room
9
9
Autopsy unit
27
27
Separate storage space
8
8
Calculate
Total area
62
Construction cost
899000
Next

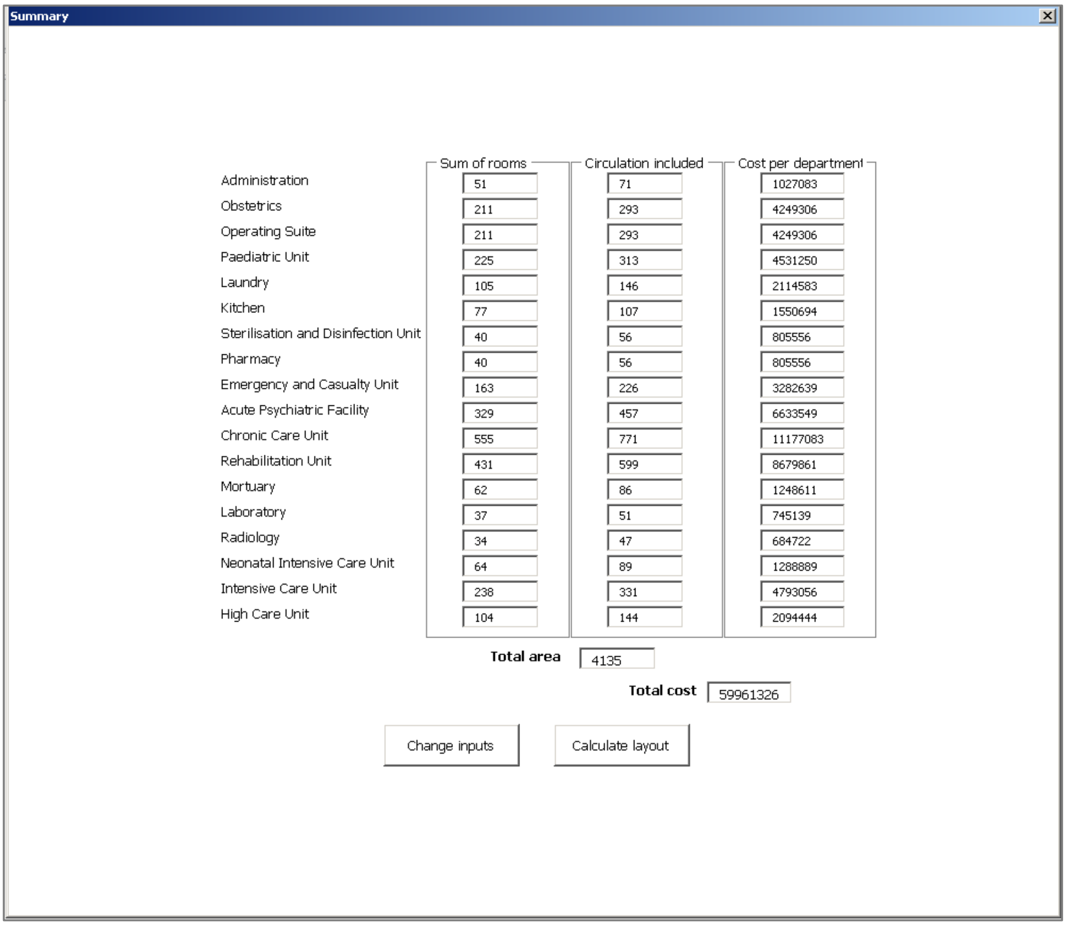

Laboratory
Rooms
Minimum area
Choose area
Specimen reception/sorting
12
12
Testing area
25
25
Stores
10
20
Calculate
Total area
37
Construction cost
536500
Next


Radiology
Rooms
Minimum area
Choose area
Dark room
4.65
5
Film file and storage area
4.65
5
Radiologist area
5.02
6
Waiting area
2.7
4
X-ray room (includes control booth, dressing area and toilet)
14
14
Calculate
Total area
34
Construction cost
493000
Next


Neonatal Intensive Care Unit
Number of beds
8
% single rooms (10% recommended)
2
Nursery
Minimum area
Choose area
Crib area
5
5
Visitor toilet
0
0
Clean utility room
5
5
Separate storage space
1
1
Staff toilet
1.67
2
Isolation cubicle
6
6
Breast feeding area
4.55
5
Nurse station
6
6
Dirty utility room, cleaner's room, and soiled linen and waste room
9
9
Calculate
Total area
64
Construction cost
928000
Next


Intensive Care Unit
Number of beds
16
% single rooms (10% recommended)
2
Nursery
Minimum area
Choose area
Bed area
12.8
13
Waiting area for visitors
6
6
Visitor toilet facilities
0
0
Ward kitchen
4
4
Staff toilet
1.67
2
Isolation cubicle
13
13
Nurse station
6
6
Dirty utility room and cleaner's room
7
7
Equipment storage space
4.65
5
Calculate
Total area
238
Construction cost
345100
Next


High Care Unit
Number of beds
10
% single rooms (10% recommended)
2
Nursery
Minimum area
Choose area
Bed area (10 for first bed)
7
7
Ablution and toilet facilities for patients
1.67
2
Clean utility room
0
0
Treatment room
10
10
Separate storage space
0
0
Ward kitchen
4
4
Staff toilet
1.67
2
Single rooms
10
10
Disabled ablution facility (1/floor)
0
0
Nurse station
6
6
Shower/bath
1.05
2
Dirty utility room, cleaner's room, and soiled linen and waste room
9
9
Calculate
Total area
104
Construction cost
150800
Next



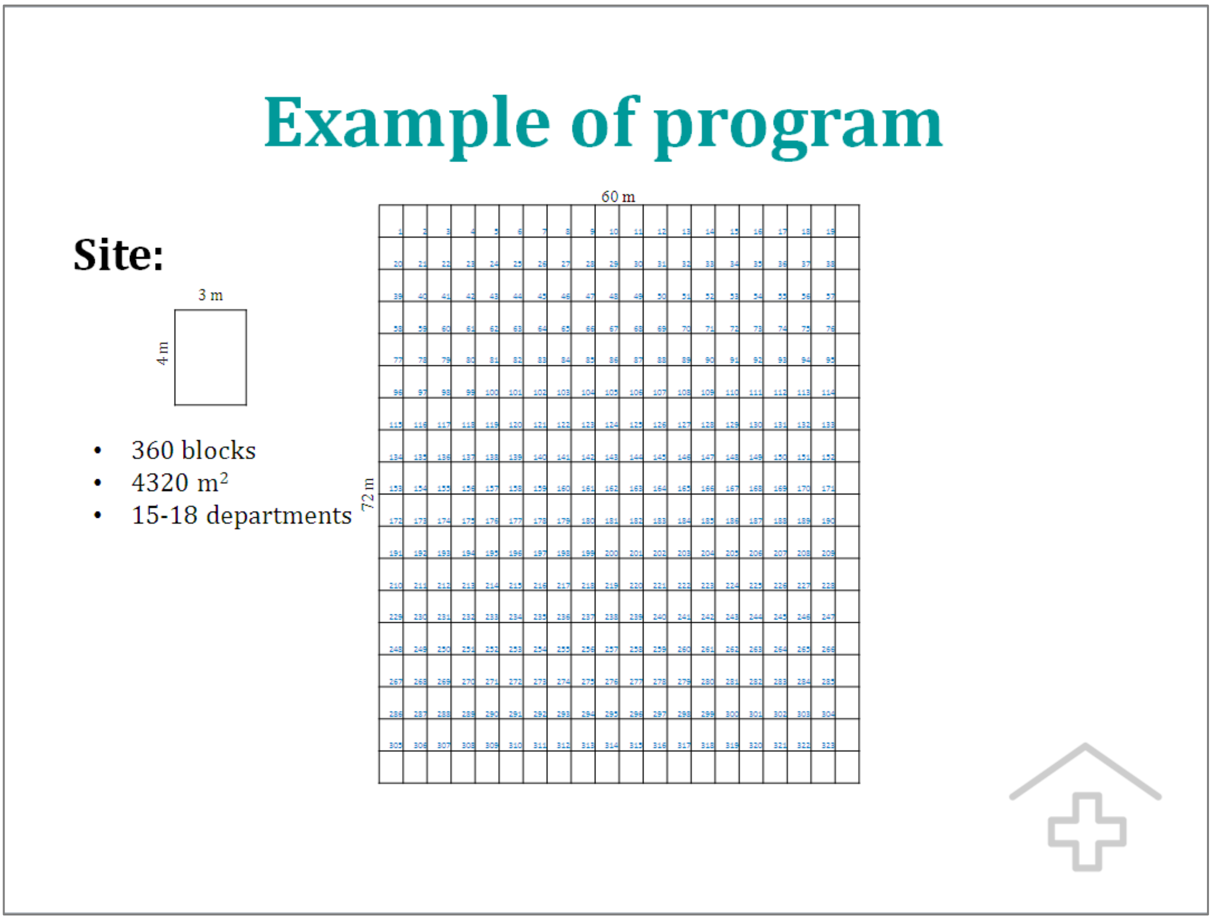
Summary

	Sum of rooms	Circulation included	Cost per department
Administration	51	71	1027083
Obstetrics	211	293	4249306
Operating Suite	211	293	4249306
Paediatric Unit	225	313	4531250
Laundry	105	146	2114583
Kitchen	77	107	1550694
Sterilisation and Disinfection Unit	40	56	805556
Pharmacy	40	56	805556
Emergency and Casualty Unit	163	226	3282639
Acute Psychiatric Facility	329	457	6633549
Chronic Care Unit	555	771	11177083
Rehabilitation Unit	431	599	8679861
Mortuary	62	86	1248611
Laboratory	37	51	745139
Radiology	34	47	684722
Neonatal Intensive Care Unit	64	89	1288889
Intensive Care Unit	238	331	4793056
High Care Unit	104	144	2094444

Total area 4135

Total cost 59961326

Change inputs | Calculate layout



Example of outputs

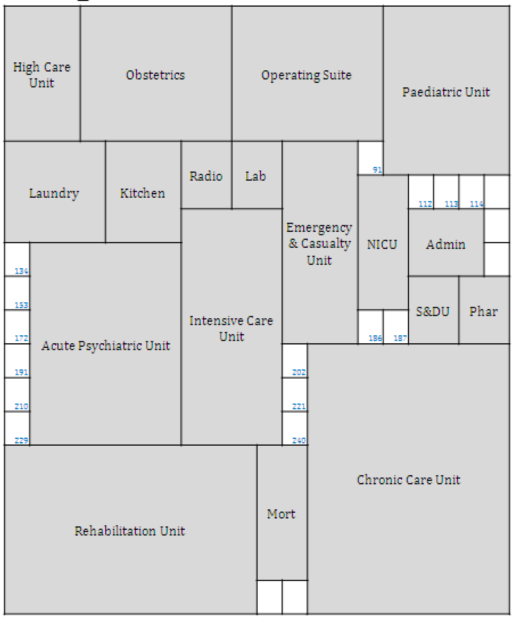
Example 1

Inputs:

- 18 departments
- Relationships between departments

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	3	0	-2	0	7	-3	-3	4	4	-3	4	5	3	3	3
Obst	-	0	10	3	5	3	5	4	5	-3	-3	-4	3	5	3	10	3	3
OS	-	-	0	4	5	0	10	2	10	0	3	3	4	5	5	8	10	7
Paed	-	-	-	0	5	3	5	4	3	-4	-2	-4	3	5	3	-3	2	2
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	5	5	5
Kitch	-	-	-	-	-	0	0	0	-3	3	3	3	0	0	0	3	3	3
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	6	6	6
Phar	-	-	-	-	-	-	-	0	3	3	3	3	-2	0	0	3	3	3
Emer	-	-	-	-	-	-	-	-	0	-2	3	-3	4	9	10	4	9	5
Psych	-	-	-	-	-	-	-	-	-	0	0	3	-3	6	4	-1	0	-1
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	3	5	5
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	3	3	3
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	3	4	3
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	5	5	5
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	4	4	4
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	3	3
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	6
HCU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

Outputs:



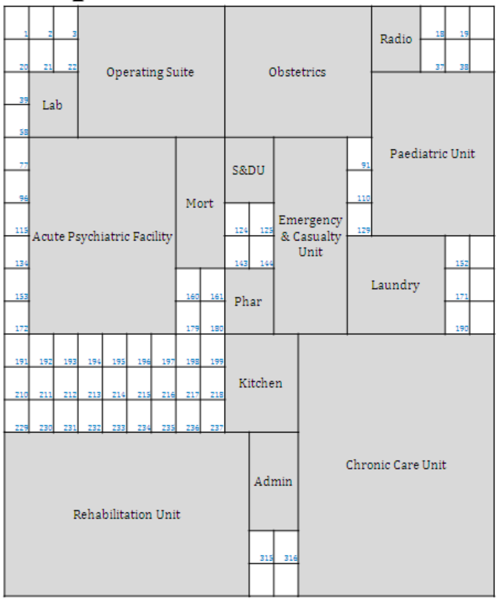
Example 2

Inputs:

- 15 departments
- Relationships between departments

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	3	0	2	0	7	3	3	4	4	3	4	5	-	-	-
Obst	-	0	10	3	5	3	5	4	5	3	3	4	3	5	3	-	-	-
OS	-	-	0	4	5	0	10	2	10	0	3	3	4	5	5	-	-	-
Paed	-	-	-	0	5	3	5	4	3	4	2	4	3	5	3	-	-	-
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	-	-	-
Kitch	-	-	-	-	-	0	0	0	3	3	3	3	0	0	0	-	-	-
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	-	-	-
Phar	-	-	-	-	-	-	-	0	3	3	3	3	2	0	0	-	-	-
Emer	-	-	-	-	-	-	-	-	0	2	3	3	4	9	10	-	-	-
Psych	-	-	-	-	-	-	-	-	-	0	0	3	3	6	4	-	-	-
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	-	-	-
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	-	-	-
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	-	-	-
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	-	-	-
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	-	-
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HCU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Outputs:



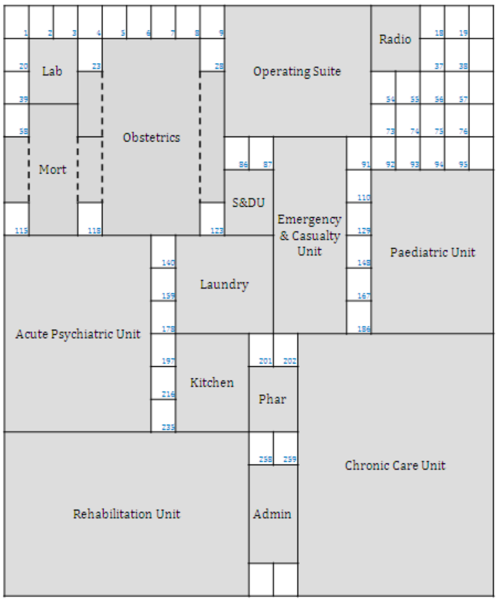
Example 3

Inputs:

- 15 departments
- Relationships between departments

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	3	0	-2	0	7	-3	-3	4	4	-3	4	5	-	-	-
Obst	-	0	10	3	5	3	5	4	5	-3	-3	-4	3	5	3	-	-	-
OS	-	-	0	4	5	0	10	2	10	0	3	3	4	5	5	-	-	-
Paed	-	-	-	0	5	3	5	4	3	-4	-2	-4	3	5	3	-	-	-
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	-	-	-
Kitch	-	-	-	-	-	0	0	0	-3	3	3	3	0	0	0	-	-	-
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	-	-	-
Phar	-	-	-	-	-	-	-	0	3	3	3	3	-2	0	0	-	-	-
Emer	-	-	-	-	-	-	-	-	0	-2	3	-3	4	9	10	-	-	-
Psych	-	-	-	-	-	-	-	-	-	0	0	3	-3	6	4	-	-	-
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	-	-	-
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	-	-	-
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	-	-	-
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	-	-	-
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	-	-
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HCU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Outputs:



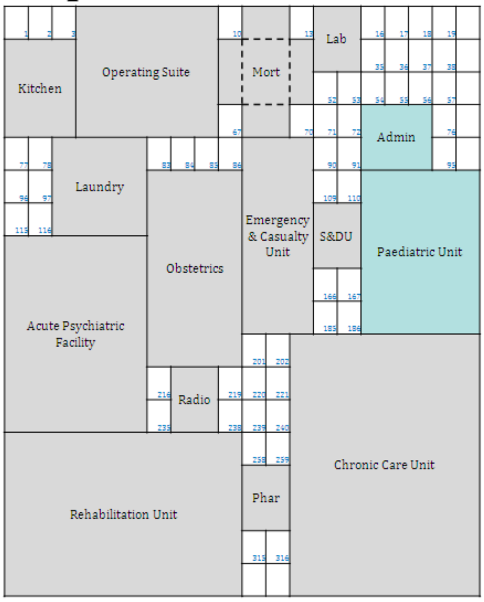
Example 4

Inputs:

- 15 departments
- Relationships between departments

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	**10**	0	0	0	7	0	0	4	4	0	4	0	-	-	-
Obst	-	0	3	3	5	3	5	4	7	0	0	0	3	5	3	-	-	-
OS	-	-	0	4	5	0	6	2	6	0	3	3	4	5	5	-	-	-
Paed	-	-	-	0	5	3	5	4	3	0	0	0	3	5	3	-	-	-
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	-	-	-
Kitch	-	-	-	-	-	0	0	0	0	3	3	3	0	0	0	-	-	-
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	-	-	-
Phar	-	-	-	-	-	-	-	0	3	3	3	3	0	0	0	-	-	-
Emer	-	-	-	-	-	-	-	-	0	0	3	0	4	6	6	-	-	-
Psych	-	-	-	-	-	-	-	-	-	0	0	3	0	6	4	-	-	-
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	-	-	-
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	-	-	-
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	-	-	-
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	-	-	-
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	-	-
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HCU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Outputs:



Conclusion

Conclusion

Benefits of framework

- ✓ Forms the basis for planning rural (as well as other district) hospital layouts
- ✓ Takes into consideration both the flow between departments and the functionality of each
- ✓ Adjustable to suit the needs of the designer with regards to:
  - Size of the site and ability to change shape in a rectangular fashion
  - Accuracy – number of blocks the site is divided into
  - Total number of hospital beds
  - Which optional departments are included in the layout
  - Number of beds in each department
  - Size of each department
  - Orientation and dimensions of each department
  - Circulation space in each department
  - Relationship between departments – degree to which departments should be placed in close proximity to each other and which ones should be separated
  - Size of each room within departments
  - Which optional rooms are included in each department

Conclusion

Benefits of framework

- ✓ User-friendly interface to determine room and departmental sizes department (Excel VBA)
- ✓ Ability to give a draft layout in a relatively short time
- ✓ Quick way to determine the areas required for each hospital department
- ✓ All the necessary hospital layout laws are adhered to by using the framework
- ✓ Calculates and recommends the following:
  - Total number of beds – dependent on the community's population size and the occupancy rate
  - Number of beds per department – according to benchmarking of 5 South African hospitals
  - Total building cost of each department
  - Circulation space
  - Size of each room – according to the South African law requirements
  - Relationship between departments – according to literature research on hospitals

Thank you!

D.2 VALIDATION DOCUMENT AND QUESTIONNAIRE

Healthcare Facility Design

Topic: A layout design framework for rural hospitals using mixed methods

Stellenbosch University

Supervisor: Mrs Louzanne Bam (Pr.Eng.)

Ingé Kruger

CONTENTS

INTRODUCTION

The purpose of this document is for validation of a developed layout design framework for rural hospitals using mixed methods (integration of quantitative and qualitative methods) and determining the usefulness thereof. This framework aims to guide a user in designing an optimal layout for a rural hospital while taking into consideration the relevant laws and health outcomes of the surrounding rural community. The goal is not to replace the role of the architect, but to guide the designer. The hospital layout constraints applicable to the designing of rural hospital layouts are outlined in Appendix A.

Advantages of using the framework include:

- ✓ Forms the basis for planning rural (as well as other district) hospital layouts
- ✓ Takes into consideration both the flow between departments and the functionality of each
- ✓ User-friendly interface to determine room and departmental sizes department (Excel VBA)
- ✓ Ability to give a draft layout in a relatively short time
- ✓ Quick way to determine the space required for each hospital department
- ✓ All the necessary hospital layout laws are adhered to by using the framework
- ✓ Adjustable to suit the needs of the designer with regards to:
    - Size of the site and ability to change shape in a rectangular fashion
    - Accuracy – number of blocks the site is divided into
    - Total number of hospital beds
    - Which optional departments are included in the layout
    - Number of beds in each department
    - Size of each department
    - Orientation and dimensions of each department
    - Circulation space in each department
    - Relationship between departments – degree to which departments should be placed in close proximity to each other and which ones should be separated
    - Size of each room within departments
    - Which optional rooms are included in each department
- ✓ Calculates and recommends the following:
    - Total number of beds – dependent on the community's population size and the occupancy rate
    - Number of beds per department – according to benchmarking of 5 South African hospitals
    - Total building cost of each department
    - Circulation space

- Size of each room – according to the South African law requirements
- Relationship between departments – according to literature research on hospitals

A summary of how the framework operates is shown in Figure 1. Four examples of outputs of the framework are provided in Appendix B.

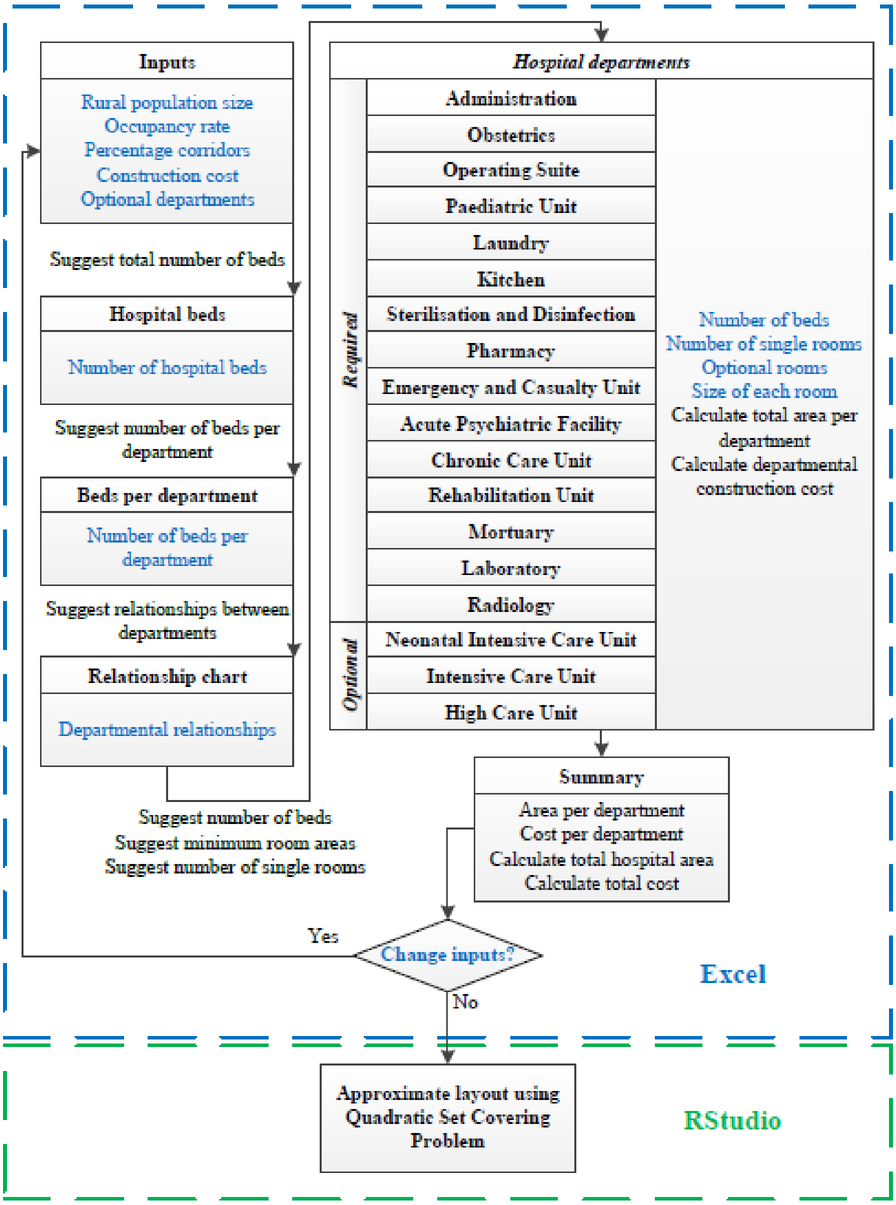
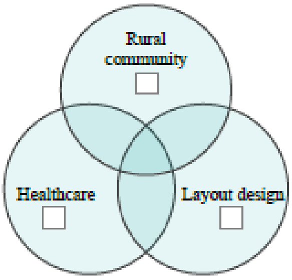


FIGURE 1: SUMMARY OF FRAMEWORK

VALIDATION QUESTIONS

Please indicate your area of expertise:



	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	◯ Yes ◯ No
2	Do you agree with the **rooms** included in each department?	◯ Yes ◯ No
3	Do you think the **relationship diagram** is realistic?	◯ Yes ◯ No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	◯ Yes ◯ No
4	Do you think the generated layout is **practical** from a healthcare point of view?	◯ Yes ◯ No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	◯ Yes ◯ No
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	◯ Yes ◯ No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	◯ Yes ◯ No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	◯ Yes ◯ No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	◯ Yes ◯ No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards**?	◯ Yes ◯ No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	◯ Yes ◯ No
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	◯ Yes ◯ No

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	◯ Yes ◯ No
14	Are there any changes or additions to the framework that you think would be useful?	

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APPENDIX A: HOSPITAL LAYOUT CONSTRAINTS

Hospitals have specific layout constraints that they need to adhere to e.g. certain departments and rooms are compulsory. Each department and room also needs to be bigger than a specific size to accommodate the necessary number of patients, staff, and equipment. Therefore, this section examines the minimum area for each hospital room according to the size of the hospital (i.e. number of hospital beds) as well as determine which rooms and departments are optional.

According to De Jager (2011) the Regulations Governing Private Hospitals and Unattached Operating Theatre Units (also known as the R158) are still in use for governing the design and operations of hospitals in South Africa, having been developed in 1980 and last updated in 1993. The Western Cape developed and gazetted their provincial regulations, R187 in 2001 and modified it in 2003. The Eastern Cape and Gauteng both prepared draft provincial regulations, but neither have been finalised or formally approved. According to Baloyi (2011) those developed by Gauteng appear to be the most comprehensive and it is proposed that these be accepted as a discussion document and put out for comment with a view to being developed for national use. Since the provincial standards are not accepted as the national standards yet, this study focuses on the requirements of R158.

Therefore, all the constraints of the R158 were first analysed. However, this document does not specify or recommend all the sizes of each room. Thus we referred to layout constraints provided by the KwaZulu-Natal Department of Health (2010). After this, constraints of other countries such as Scotland and the United Arab Emirates were utilised. Additionally, articles, books, and industrial norms were researched. This analysis is shown in this section including the minimum dimensions for each room, the applicable references as well as which rooms are optional. The following hospital departments were analysed:

- Administration
- Obstetrics
- Operating Suite
- Paediatric Unit
- Laundry
- Kitchen
- Sterilisation and Disinfection Unit
- Pharmacy
- Emergency and Casualty Unit
- Acute Psychiatric Facility
- Chronic Care Unit
- Rehabilitation Unit
- Mortuary

- Laboratory
- Radiology
- Neonatal Intensive Care Unit
- Intensive Care Unit
- High Care Unit

TABLE 1: ADMINISTRATION CONSTRAINTS

Requirements	Minimum area (in m²)	Optional	References
Waiting area (0.65/person)	6		(KwaZulu-Natal Department of Health, 2010), Department of Health, 2004
Office (5.02/staff)	5.02		(Department of Health, 2004)
Public toilets	1.67		(Department of Health, 2004)
Consulting room(s) (5.02/staff)	5.02		(Department of Health, 2004)
Storage space	13.94		(Sharma & Sharma, 2007)

TABLE 2: OBSTETRICS CONSTRAINTS

Requirements	Minimum area (in m²)	Optional	References
Post Natal ward			
Bed area (8.43/bed) (mothers and babies)	8.43		R158
Ablution and toilet facilities for patients (one/8 beds)	1.67		(Department of Health, 2004)
Clean utility room	5		R158
Treatment room (optional)	10	x	R158
Separate storage space (optional)	1	x	Assume minimum area is 1, R158
Ward kitchen includes milk kitchen (may be shared with paediatric unit) (Increased by 1.5 for every 10 beds above 20 beds)	4	x	R158
Staff toilet	1.67		(Department of Health, 2004)
Single rooms	10		R158
Nurse station	6		R158, assume similar size as duty station
Shower/bath (one/12 beds)	1.05		(Beach, 2011)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		R158
Each nursery (optional)			
Baby beds (1.5/baby+6)	7.5	x	R158
Incubator/s (one/15 mother beds)	1.5	x	R158
Baby bath/s (one/15 babies)	0.83	x	Assume mounted installation (Franke Kitchen Systems (Pty) Ltd, 2013)
Staff toilet	1.67	x	(Department of Health,

			2004)
Isolation room (optional)	4.5	x	(IUSS, 2011)
Storage space (optional)	1	x	Assume minimum area is 1, R158
Clean utility room	5	x	R158
Dirty utility room, cleaner's room, and soiled linen and waste room	9	x	R158
Other rooms			
First stage room/s (10 for one bed, 15 for two beds) (optional if ante natal beds or more than 1 delivery room)	10	x	R158
Delivery room (for maternity unit) (At least 2 rooms if no first stage room)	14	x	R158
Ante natal beds	10	x	Assume similar size as first stage room R158
Preparation room (for maternity unit) (Optional, if ante natal beds are provided)	6	x	R158
Nurse station	6		R158, assume similar size as duty station
Clean work area/clean utility room	5		R158
Dirty utility room and cleaner's room	7		R158
Storage facilities	1		Assume minimum area is 1, R158
Dedicated caesarean section theatre with recovery area (optional)	33.45	x	(Medical Practice and Licensing Sector, 2013)

TABLE 3: OPERATING SUITE CONSTRAINTS

Requirements		Minimum area (in m²)	Optional	References
Operating room	Minor	20		R158
	Major	30		
	Cardiac	45		
	Cath Lab	42		
Recovery area (depended on number of operating rooms)		12/16/24		R158
Duty station		6		R158
Scrubbing-up area		2.1		R158
Cleaning and disposal area		5		R158
Cleaning equipment storage (user decides)		1		Assume minimum area is 1, R158
Change rooms		9		R158
Change room storage		1		Assume minimum area is 1, R158
Change room toilet		1.67		(Department of Health, 2004)
Staff rest rooms		1.67		(Department of Health, 2004)
Storage for linen, medicines or equipment		2		Assume minimum area is 2, R158
Storage for sterile packs		1		Assume minimum area is 1, R158
Setting-up space (may be within operating room)		2		Assume minimum area is 2, R158

TABLE 4: PAEDIATRIC UNIT CONSTRAINTS

Nursery	Minimum area	Optional	References
Bed area	7.43/bed		Same area required as adult beds (Kunders, 2008) (Department of
Ablution and toilet facilities for patients (1/8 beds)	1.67		R158
Clean utility room	5	x	R158
Treatment room	10	x	R158
Separate storage space (user decides)	1	x	Assume minimum area is 1,
Ward kitchen (includes milk kitchen) Increased by 1.5 for every 10 beds above 20 beds	4		R158
Staff toilet	1.67		(Department of Health,
Single rooms	10	x	R158
Disabled ablution facility (at least 1 on every floor)	4.05	x	(Department of Public Works,
Nurse station	6		R158, assume similar size as duty
Shower or bath 1/12 patients	1.05		(Beach, 2011)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		R158
Other rooms			
Bathing facilities for babies 1bath/10babies(1.5x0.555)	0.833		Assume mounted installation (Franke Kitchen Systems
Milk kitchen (May be shared with a nursery) (0.6x6x1.4) (required if more than 20 beds)	5.04	x	(Ducker, Laing, Leaf & Newmarch, 2004), (Kitchen Appliances 123,
Treatment and clean utility room	10		R158
Insolation facilities (one per 15 cots)	4.5		(IUSS, 2011)

TABLE 5: LAUNDRY CONSTRAINTS

Requirements	Minimum area (in m²)	Optional	References
Linen storage room	8.4		(Office of the Federal Register, 2002)
Laundry	92.3		(Office of the Federal Register, 2002)

TABLE 6: KITCHEN CONSTRAINTS

Requirements	Minimum area (in m²)	Optional	References
Floor area	35		R158, (Gupta *et al.*, 2007)
Storage facilities	25		R158, (Gupta *et al.*, 2007)
Cafeteria	15	x	R158, (Gupta *et al.*, 2007)

TABLE 7: STERILISATION AND DISINFECTION UNIT CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Floor area	16		R158, (Gupta, Gupta, Kant, Chandrashekhar & Satpathy, 2007)
Washing and decontamination area	20		R158, (Gupta *et al.*, 2007)

TABLE 8: PHARMACY CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Floor area (in-patient & outpatient dispensary)	45		(KwaZulu-Natal Department of Health, 2010)
Drug storage area (bulk store combined)	100		(KwaZulu-Natal Department of Health, 2010)

TABLE 9: EMERGENCY AND CASUALTY UNIT CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Reception area with office space	9.29		(Miller, 1999)
Waiting area	6		(KwaZulu-Natal Department of Health, 2010)
Public toilet (men and women separate)	3.34		(Department of Health, 2004)
Wheelchair toilet	4.05		(Department of Public Works, 2001)
Resuscitation room and procedure room (may be split)	20		R158
Dirty utility room	5		R158, assume similar size to description in general nursing unit
Cleaner's room (if combined with dirty utility room)	2		R158, assume similar size to description in general nursing unit
Staff toilets	1.67		(Department of Health, 2004)
Nurse station/duty room	6		R158, assume similar size as duty station
Rooms(s) and/ cubicles	6		R158
Dedicated trauma theatre (or immediate access to the general theatre complex)	37.16		(Miller, 1999)
Clean utility area with storage space for pharmaceutical substances	5		R158, assume similar size to description in general nursing unit

TABLE 10: ACUTE PSYCHIATRIC FACILITY CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Nursery			
Bed area	7.5/bed		R158
Ablution and toilet facilities for patients (1/8 beds)	1.67		R158
Clean utility room	5	x	R158
Treatment room	10	x	R158
Separate storage space (user decides)	1	x	Assume minimum area is 1, R158
Ward kitchen (includes milk kitchen) Increased by 1.5 for every 10 beds above 20 beds	4		R158
Staff toilet	1.67		(Department of Health, 2004)
Single rooms	10	x	R158
Disabled ablution facility (at least 1 on every floor)	4.05	x	(Department of Public Works, 2001)
Nurse station	6		R158, assume similar size as duty station
Shower or bath 1/12 patients	1.05		(Beach, 2011)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		R158
Occupational Therapy Unit			
Office space	5.02		Assume similar space to other hospital offices (Department of Health, 2004)
Group/Interview room	9		R158
Activity/Craft room	30		R158
Relaxation/Therapy/Lecture room	30		R158
Storage for equipment and materials (user decides)	2		Assume minimum area is 2, R158
Other rooms			
Lounge (optional, if dining room is used instead)	9	x	Assume similar size as group room
Group room	9		R158
Consulting room	6		(KwaZulu-Natal Department of Health, 2010)
Observation room	10		R158
Dining-room	9		Assume similar size as group room
Recreation area (may be shared with the lounge, dining-room or occupational therapy areas)	20	x	R158
Procedure room	12		R158
Recovery facility	9		R158
Staff toilet facilities	1.67		(Department of Health, 2004)

TABLE 11: CHRONIC CARE UNIT CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Nursery			
Bed area	7.43/bed		(Kunders, 2008) (Department of Health, 2004)
Ablution and toilet facilities for patients (1/8 beds)	1.67		R158
Clean utility room	5	x	R158
Treatment room	10	x	R158
Separate storage space (user decides)	1	x	Assume minimum area is 1, R158
Ward kitchen (includes milk kitchen) Increased by 1.5 for every 10 beds above 20 beds	4		R158
Staff toilet	1.67		(Department of Health, 2004)
Single rooms	10		R158
Disabled ablution facility (at least 1 on every floor)	4.05	x	(Department of Public Works, 2001)
Nurse station	6		R158, assume similar size as duty station
Shower or bath 1/12 patients	1.05		(Beach, 2011)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		R158
Other rooms	Minimum area		
Recreational cum dining-room area (minimum of 10 m^2 for 5 patients. 1 m^2 must be added for each additional patient)	10		R158
Bathing facilities for babies and children	0.833		Assume mounted installation (Franke Kitchen Systems (Pty) Ltd, 2013)
Play area for children (2.8/child)	5.6		Assume minimum 2 children (Ontario Ministry of Education, 2006)

TABLE 12: REHABILITATION UNIT CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Nursery			
Bed area	7.43/bed		(Kunders, 2008) (Department of Health, 2004)
Ablution and toilet facilities for patients (1/8 beds)	1.67		R158
Clean utility room	5	x	R158
Treatment room	10	x	R158
Separate storage space (user decides)	1	x	Assume minimum area is 1, R158
Ward kitchen (includes milk kitchen) Increased by 1.5 for every 10 beds above 20 beds	4		R158
Staff toilet	1.67		(Department of Health, 2004)

Single rooms	10		R158
Disabled ablution facility (1/8 beds)	4.05		(Department of Public Works, 2001)
Nurse station	6		R158, assume similar size as duty station
Shower or bath 1/12 patients	1.05		(Beach, 2011)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		R158
Hydrotherapy (for spinal/cranial rehabilitation)			
Pool	24	x	(Pinelog Ltd, 2015)
Change rooms and lockers	8	x	R158
Wheel chair toilet	4	x	R158
Occupational Therapy			
One-to-one work room	10		R158
Clean work room	10		R158
Dirty work room	10		R158
Cognitive room (clean work room, dirty work room, and cognitive room may be combined into a single room of 30)	10		R158
Splint room	10		R158
Storage space	6		R158
ADL kitchen	10		R158
Family/group conference room	20		R158
Clinical Psychologist			
Group therapy room (may be shared with social worker)	20		R158
Physiotherapy			
One-to-one work room	10		R158
Storage space	9		R158
Gym area	45		R158
Other rooms			
Dining-room/Lounge (minimum of 20 m^2 for 10 patients, and thereafter 1,5 m^2 for each additional patient	20		R158
Emergency room	16		R158

TABLE 13: MORTUARY CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Offices (interview, body receiving, pathologist)	9		(IUSS, 2014)
Body/Bier room	9		(IUSS, 2014)
Viewing room (external to body-layout area)	9		(National Health Service Scotland, 2002)
Autopsy unit	27		(IUSS, 2014)
Separate storage space	8		(IUSS, 2014)

TABLE 14: LABORATORY CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Specimen reception/sorting	12		(Gupta *et al.*, 2007)
Testing area	25		(Gupta *et al.*, 2007)
Stores	10		(Gupta *et al.*, 2007)

TABLE 15: RADIOLOGY CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
X-ray room (includes control booth, dressing area and toilet)	14		(Department of Health, 2004)
Dark room	4.65		(Department of Health, 2004)
Film file and storage area	4.65		(Department of Health, 2004)
Radiologist area	5.02		(Department of Health, 2004)
Waiting area	2.7	x	Assume similar area as In-Patient Lobby

TABLE 16: NEONATAL INTENSIVE CARE UNIT CONSTRAINTS

Requirements	Minimum area (in m^2)	Optional	References
Crib area (2x2.5)	5		R158
Visitor ablution and toilet facilities	1.67	x	(Department of Health, 2004)
Clean utility room	5		R158
Separate storage space	1		Assume minimum area is 1, R158
Staff toilet	1.67		(Department of Health, 2004)
Isolation cubicle	6		R158
Breast feeding area	4.55		(York, 2008)
Nurse station	6		R158, assume similar size as duty station
Dirty utility room, cleaner's room, and soiled linen and waste room	9		R158

TABLE 17: INTENSIVE CARE UNIT CONSTRAINTS

Requirements	Minimum area (in m²)	Optional	References
Bed area (3.2x4)	12.8		
Waiting area for visitors	6		Assume similar to size of other waiting areas (KwaZulu-Natal Department of Health, 2010)
Visitor toilet facilities	1.67	x	(Department of Health, 2004)
Ward kitchen (includes milk kitchen) Increased by 1.5 for every 10 beds above 20 beds	4		R158
Staff toilet	1.67		(Department of Health, 2004)
Isolation cubicle	13		R158
Nurse station	6		R158, assume similar size as duty station
Dirty utility room and cleaner's room	7		R158
Equipment storage space	4.65		Assume similar to size of emergency department storage (KwaZulu-Natal Department of Health, 2010)

TABLE 18: HIGH CARE UNIT CONSTRAINTS

Requirements	Minimum area (in m²)	Optional	References
Bed area (10 for first bed)	7		R158
Ablution and toilet facilities for patients (1/8 beds)	1.67		(Department of Health, 2004)
Clean utility room	5	x	R158
Treatment room	10	x	R158
Separate storage space	1	x	Assume minimum area is 1, R158
Ward kitchen (Increased by 1.5 for every 10 beds above 20 beds)	4		R158
Staff toilet	1.67		(Department of Health, 2004)
Single rooms	10	x	R158
Disabled ablution facility (1/floor)	4.05	x	R158
Nurse station	6		R158, assume similar size as duty station
Shower/bath	1.05		(Beach, 2011)
Dirty utility room, cleaner's room, and soiled linen and waste room	9		R158

APPENDIX B: FRAMEWORK EXAMPLES

All four examples are based on an available site space of 60x72 meters. Each small block is chosen to be 3x4 meters.

EXAMPLE 1

The first example includes 18 hospital departments in the layout and the relationships between these are shown in Table 1. The output is provided in Figure 2.

TABLE 1: EXAMPLE 1 RELATIONSHIPS

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	3	0	-2	0	7	-3	-3	4	4	-3	4	5	3	3	3
Obst	-	0	10	3	5	3	5	4	5	-3	-3	-4	3	5	3	10	3	3
OS	-	-	0	4	5	0	10	2	10	0	3	3	4	5	5	8	10	7
Paed	-	-	-	0	5	3	5	4	3	-4	-2	-4	3	5	3	-3	2	2
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	5	5	5
Kitch	-	-	-	-	-	0	0	0	-3	3	3	3	0	0	0	3	3	3
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	6	6	6
Phar	-	-	-	-	-	-	-	0	3	3	3	3	-2	0	0	3	3	3
Emer	-	-	-	-	-	-	-	-	0	-2	3	-3	4	9	10	4	9	5
Psych	-	-	-	-	-	-	-	-	-	0	0	3	-3	6	4	-1	0	-1
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	3	5	5
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	3	3	3
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	3	4	3
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	5	5	5
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	4	4	4
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	3	3
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	6
HCU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

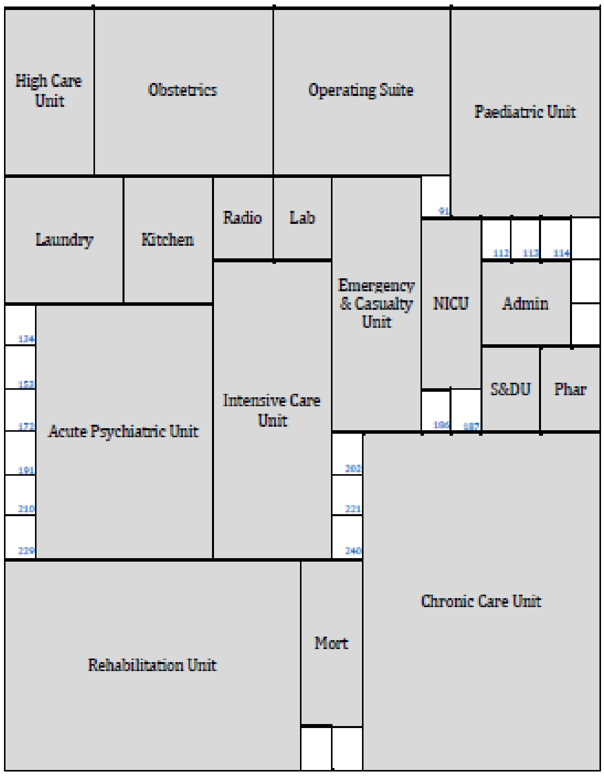

FIGURE 2: EXAMPLE 1 OUTPUT

EXAMPLE 2

The second example includes 15 hospital departments in the layout and the relationships between these are shown in Table 2. The output is provided in Figure 3.

TABLE 2: EXAMPLE 2 RELATIONSHIPS

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	3	0	2	0	7	3	3	4	4	3	4	5	-	-	-
Obst	-	0	10	3	5	3	5	4	5	3	3	4	3	5	3	-	-	-
OS	-	-	0	4	5	0	10	2	10	0	3	3	4	5	5	-	-	-
Paed	-	-	-	0	5	3	5	4	3	4	2	4	3	5	3	-	-	-
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	-	-	-
Kitch	-	-	-	-	-	0	0	0	3	3	3	3	0	0	0	-	-	-
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	-	-	-
Phar	-	-	-	-	-	-	-	0	3	3	3	3	2	0	0	-	-	-
Emer	-	-	-	-	-	-	-	-	0	2	3	3	4	9	10	-	-	-
Psych	-	-	-	-	-	-	-	-	-	0	0	3	3	6	4	-	-	-
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	-	-	-
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	-	-	-
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	-	-	-
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	-	-	-
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	-	-
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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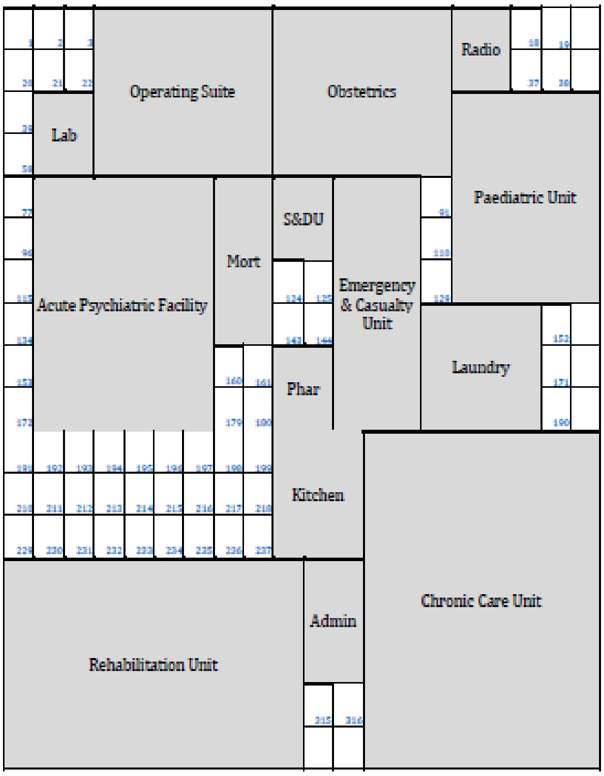

FIGURE 3: EXAMPLE 2 OUTPUT

EXAMPLE 3

The third example includes 15 hospital departments in the layout and the relationships between these are shown in Table 3. The output is provided in Figure 4.

TABLE 3: EXAMPLE 3 RELATIONSHIPS

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	3	0	-2	0	7	-3	-3	4	4	-3	4	5	-	-	-
Obst	-	0	10	3	5	3	5	4	5	-3	-3	-4	3	5	3	-	-	-
OS	-	-	0	4	5	0	10	2	10	0	3	3	4	5	5	-	-	-
Paed	-	-	-	0	5	3	5	4	3	-4	-2	-4	3	5	3	-	-	-
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	-	-	-
Kitch	-	-	-	-	-	0	0	0	-3	3	3	3	0	0	0	-	-	-
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	-	-	-
Phar	-	-	-	-	-	-	-	0	3	3	3	3	-2	0	0	-	-	-
Emer	-	-	-	-	-	-	-	-	0	-2	3	-3	4	9	10	-	-	-
Psych	-	-	-	-	-	-	-	-	-	0	0	3	-3	6	4	-	-	-
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	-	-	-
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	-	-	-
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	-	-	-
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	-	-	-
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	-	-
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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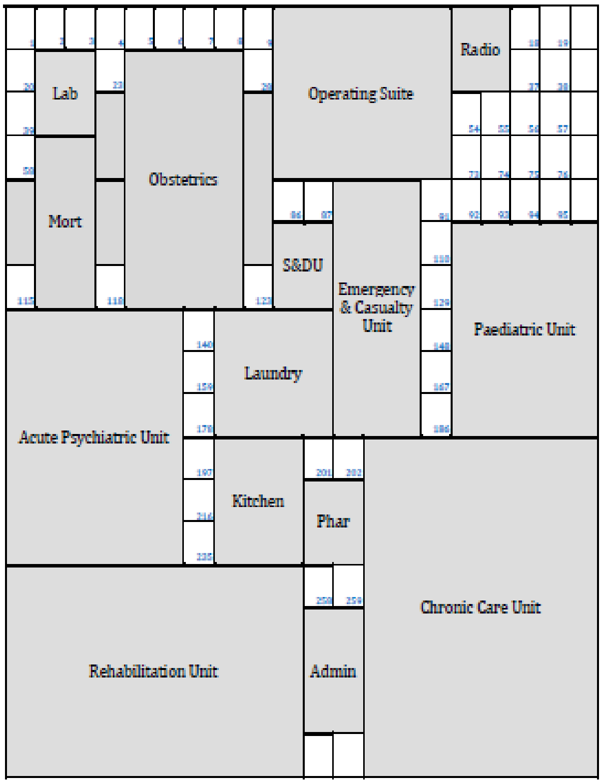

FIGURE 4: EXAMPLE 3 OUTPUT

EXAMPLE 4

The fourth example includes 15 hospital departments in the layout and the relationships between these are shown in Table 4. The output is provided in Figure 5.

TABLE 4: EXAMPLE 4 RELATIONSHIPS

	Admin	Obst	OS	Paed	Laun	Kitch	S&DU	Phar	Emer	Psych	CCU	Rehab	Mort	Lab	Radio	NICU	ICU	HCU
Admin	0	3	3	10	0	0	0	7	0	0	4	4	0	4	0	-	-	-
Obst	-	0	3	3	5	3	5	4	7	0	0	0	3	5	3	-	-	-
OS	-	-	0	4	5	0	6	2	6	0	3	3	4	5	5	-	-	-
Paed	-	-	-	0	5	3	5	4	3	0	0	0	3	5	3	-	-	-
Laun	-	-	-	-	0	0	0	0	3	3	5	4	0	0	0	-	-	-
Kitch	-	-	-	-	-	0	0	0	0	3	3	3	0	0	0	-	-	-
S&DU	-	-	-	-	-	-	0	0	7	0	5	3	0	1	0	-	-	-
Phar	-	-	-	-	-	-	-	0	3	3	3	3	0	0	0	-	-	-
Emer	-	-	-	-	-	-	-	-	0	0	3	0	4	6	6	-	-	-
Psych	-	-	-	-	-	-	-	-	-	0	0	3	0	6	4	-	-	-
CCU	-	-	-	-	-	-	-	-	-	-	0	1	3	5	3	-	-	-
Rehab	-	-	-	-	-	-	-	-	-	-	-	0	0	3	3	-	-	-
Mort	-	-	-	-	-	-	-	-	-	-	-	-	0	2	0	-	-	-
Lab	-	-	-	-	-	-	-	-	-	-	-	-	-	0	2	-	-	-
Radio	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	-	-	-
NICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ICU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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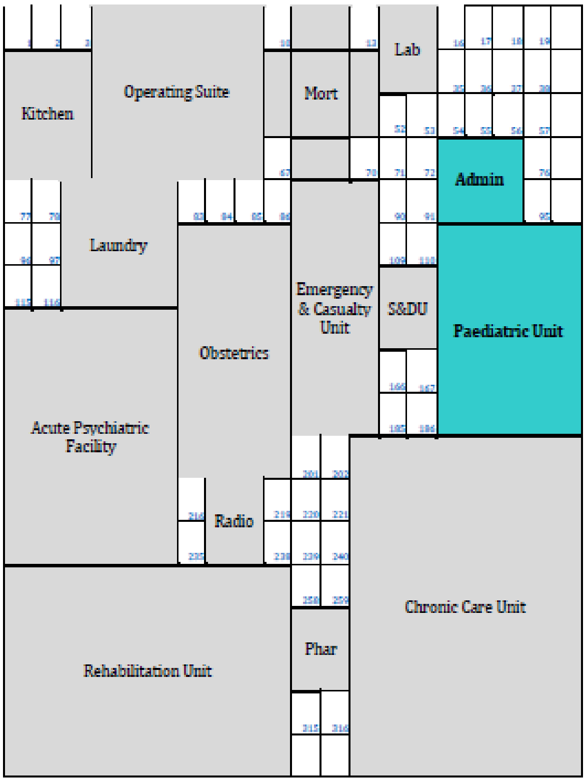
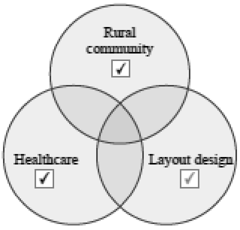


FIGURE 5: EXAMPLE 4 OUTPUT

D.3 EXPERT ANALYSIS FEEDBACK

VALIDATION QUESTIONS

Please indicate your area of expertise:

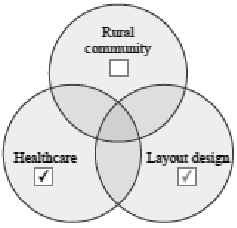


	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	◉ Yes ◯ No
2	Do you agree with the **rooms** included in each department?	◉ Yes ◯ No
3	Do you think the **relationship diagram** is realistic?	◉ Yes ◯ No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	◉ Yes ◯ No
4	Do you think the generated layout is **practical** from a healthcare point of view?	◉ Yes ◯ No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	◉ Yes ◯ No
	It will be even more helpful if other supporting factors such as IT will be considered.	
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	◯ Yes ◉ No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	◉ Yes ◯ No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	◯ Yes ◉ No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	◉ Yes ◯ No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards**?	◉ Yes ◯ No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	◉ Yes ◯ No
	Answers applicable to very high level stages of design.	
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	◉ Yes ◯ No

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	◉ Yes ◯ No
14	Are there any changes or additions to the framework that you think would be useful?	
	Include the impact of ICT (information communication technology)	

VALIDATION QUESTIONS

Please indicate your area of expertise:

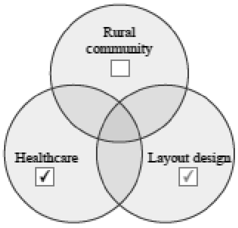


	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	◉ Yes ◯ No
2	Do you agree with the **rooms** included in each department?	◉ Yes ◯ No
3	Do you think the **relationship diagram** is realistic?	◉ Yes ◯ No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	◉ Yes ◯ No
4	Do you think the generated layout is **practical** from a healthcare point of view?	◉ Yes ◯ No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	◉ Yes ◯ No
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	◉ Yes ◯ No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	◉ Yes ◯ No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	◉ Yes ◯ No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	◉ Yes ◯ No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards?**	◉ Yes ◯ No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	◉ Yes ◯ No
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	◉ Yes ◯ No

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	◉ Yes ◯ No
14	Are there any changes or additions to the framework that you think would be useful?	

VALIDATION QUESTIONS

Please indicate your area of expertise:

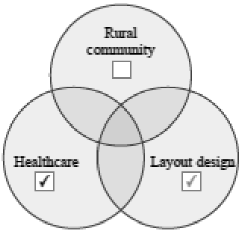


	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	◉ Yes ○ No
2	Do you agree with the **rooms** included in each department?	◉ Yes ○ No
3	Do you think the **relationship diagram** is realistic?	◉ Yes ○ No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	◉ Yes ○ No
4	Do you think the generated layout is **practical** from a healthcare point of view?	◉ Yes ○ No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	◉ Yes ○ No
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	◉ Yes ○ No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	◉ Yes ○ No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	◉ Yes ○ No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	◉ Yes ○ No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards**?	◉ Yes ○ No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	◉ Yes ○ No
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	◉ Yes ○ No

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	◉ Yes ○ No
14	Are there any changes or additions to the framework that you think would be useful?	
	No	

VALIDATION QUESTIONS

Please indicate your area of expertise:

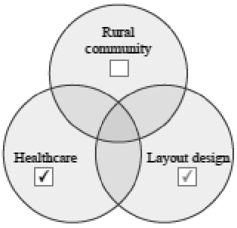


	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	(•) Yes ( ) No
2	Do you agree with the **rooms** included in each department?	(•) Yes ( ) No
3	Do you think the **relationship diagram** is realistic?	( ) Yes ( ) No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	( ) Yes ( ) No
4	Do you think the generated layout is **practical** from a healthcare point of view?	( ) Yes (•) No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	( ) Yes ( ) No
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	( ) Yes ( ) No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	(•) Yes ( ) No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	( ) Yes ( ) No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	( ) Yes ( ) No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards**?	( ) Yes (•) No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	( ) Yes ( ) No
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	( ) Yes (•) No

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	( ) Yes ( ) No
14	Are there any changes or additions to the framework that you think would be useful?	

VALIDATION QUESTIONS

Please indicate your area of expertise:

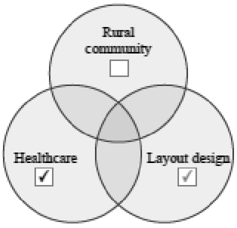


	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	(•) Yes ( ) No
2	Do you agree with the **rooms** included in each department?	(•) Yes ( ) No
3	Do you think the **relationship diagram** is realistic?	( ) Yes (•) No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	(•) Yes ( ) No
4	Do you think the generated layout is **practical** from a healthcare point of view?	( ) Yes (•) No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	(•) Yes ( ) No
	The initial inputs need to be supported by experience &/ precedent studies	
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	(•) Yes ( ) No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	(•) Yes ( ) No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	(•) Yes ( ) No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	(•) Yes ( ) No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards?**	(•) Yes ( ) No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	(•) Yes ( ) No
	I'm not too familiar with all laws and standards, but they do change and so the softwar	
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	( ) Yes (•) No
	A concept layout is informed by broader issues, e.g. size, location and form of the site.	

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	(•) Yes ( ) No
	Only if its outputs are comparable to current trusted methods, and faster to generate.	
14	Are there any changes or additions to the framework that you think would be useful?	
	Any framework will have limitations, so it is useful to add qualifications as necessary.	

VALIDATION QUESTIONS

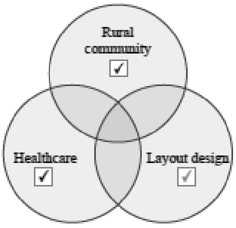
Please indicate your area of expertise:



	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	⦿ Yes ○ No
2	Do you agree with the **rooms** included in each department?	○ Yes ⦿ No
3	Do you think the **relationship diagram** is realistic?	○ Yes ⦿ No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	○ Yes ⦿ No
4	Do you think the generated layout is **practical** from a healthcare point of view?	○ Yes ○ No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	⦿ Yes ○ No
	On very initial stages only	
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	○ Yes ⦿ No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	○ Yes ⦿ No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	○ Yes ○ No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	○ Yes ○ No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards**?	○ Yes ⦿ No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	⦿ Yes ○ No
	IUSS guidelines need to be included. OOM estimator must be compared.	
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	⦿ Yes ○ No
	The model looks good on face value but needs to be tested.	
13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	⦿ Yes ○ No
	The model need to be tested but on face value it would seem usefull.	
14	Are there any changes or additions to the framework that you think would be useful?	
	Refer to previous comment	

VALIDATION QUESTIONS

Please indicate your area of expertise:

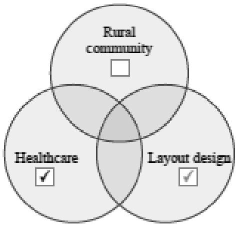


	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	(•) Yes ( ) No
2	Do you agree with the **rooms** included in each department?	(•) Yes ( ) No
3	Do you think the **relationship diagram** is realistic?	(•) Yes ( ) No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	(•) Yes ( ) No
4	Do you think the generated layout is **practical** from a healthcare point of view?	( ) Yes (•) No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	(•) Yes ( ) No
	A qualified yes, as a point of departure, yes.	
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	(•) Yes ( ) No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	(•) Yes ( ) No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	( ) Yes (•) No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	(•) Yes ( ) No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards**?	(•) Yes ( ) No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	(•) Yes ( ) No
	Yes, can be quite useful.	
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	(•) Yes ( ) No

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	(•) Yes ( ) No
14	Are there any changes or additions to the framework that you think would be useful?	
	Some flexibility regarding shape of the "frame" the output pattern need to fit into.	

VALIDATION QUESTIONS

Please indicate your area of expertise:

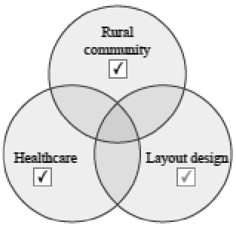


	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	◉ Yes ○ No
2	Do you agree with the **rooms** included in each department?	◉ Yes ○ No
3	Do you think the **relationship diagram** is realistic?	◉ Yes ○ No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	◉ Yes ○ No
4	Do you think the generated layout is **practical** from a healthcare point of view?	◉ Yes ○ No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	◉ Yes ○ No
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	○ Yes ◉ No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	◉ Yes ○ No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	○ Yes ◉ No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	◉ Yes ○ No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards**?	◉ Yes ○ No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	◉ Yes ○ No
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	◉ Yes ○ No

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	◉ Yes ○ No
14	Are there any changes or additions to the framework that you think would be useful?	

VALIDATION QUESTIONS

Please indicate your area of expertise:



	Healthcare	
1	Do you agree with the choice of **departments** included in the framework for designing a district hospital?	◉ Yes ○ No
2	Do you agree with the **rooms** included in each department?	◉ Yes ○ No
3	Do you think the **relationship diagram** is realistic?	◉ Yes ○ No
	And do you think this is a useful way to decide upon the placement of each hospital department relative to another?	◉ Yes ○ No
4	Do you think the generated layout is **practical** from a healthcare point of view?	○ Yes ◉ No
	Rural community	
5	Do you think the generated layout will be able to support the **healthcare needs** of the community or changed accordingly?	○ Yes ○ No
	I've left this blank because there are so many factors which support health care needs	
	Construction	
6	Do you think the framework can be useful for estimating the **initial costs** for a hospital that you are considering building?	◉ Yes ○ No
7	Do you think it can be useful for estimating the **initial size** of the hospital and its departments?	◉ Yes ○ No
8	Do you think the **cost estimation** is accurate enough to use during the initial planning phase of developing a new hospital?	○ Yes ◉ No
9	Do you think the methods used and calculations are appropriate for designing a hospital layout?	○ Yes ◉ No
	Laws and regulations	
10	Do you think the framework shows an accurate summary of the applicable **laws and standards?**	◉ Yes ○ No
11	Do you think the summary of these **guidelines** can be deemed **useful** for a person who needs to design a hospital?	◉ Yes ○ No
	As guidelines yes, this could be useful. Question 9 speaks of 'designing a layout' which	
	General	
12	Do you think the framework is useful for generating an initial **concept layout** that architects and other members of the design team can use as input for the design process?	◉ Yes ○ No
	Note the major difference between how this question is phrased and how number 9 is	

13	Would you be prepared to use this framework as an aid in the design phase of a rural hospital?	◉ Yes ○ No
	Would certainly be willing to try it out but would not rely on it for those with no exper	
14	Are there any changes or additions to the framework that you think would be useful?	

APPENDIX E: PROGRAM CODE

```
library("phonTools")
library("functional")
#takes a vector x of positions of departments
#and m is the number of possible positions
#returns the correct matrix version
vectorToMatrix <- function(x , m) {
  n <- length(x)
  q <- zeros(n,m)

  for(i in 1:n) {
    q[i,x[i]] = 1
  }
  return(q)
}

#takes the n by m matrix x and returns
#the vector version
matrixToVector <- function(x) {
  n <- nrow(x)
  m <- ncol(x)
  y <- c(0,0)

  for( i in 1:n) {
    for (j in 1:m) {
      if(x[i,j] == 1) {
        y[i] = j
      }
    }
  }
  return(y)
}

#returns false if all rotations of departments given by 3D
#array sizes don't fit in the space.
#width and height are width and height in blocks
#y is the vector of positions
BlockMatrixFull <- function(y,width,height,sizes) {
  #print(sizes)
  possibleRotations <- dim(sizes)[1]
  for(i in 1:possibleRotations) {
    if(BlockMatrixImproved(y,width,height,sizes[,,i])) {
      #print(i)
      return(TRUE)
    }
  }
  return(FALSE)
}


#returns false if any departments overlap or don't fit in the space.
#width and height are width and height in blocks
```

```
#sizes is a 2D array representing one combination of rotations for the departments
#y is the vector of positions
BlockMatrixImproved <- function(y,width,height,sizes) {
  #print(sizes)
  sizes_transpose = t(sizes)
  covered <- zeros(height,width) #an empty block matrix
  count_departments <- length(y)
  for (i in 1:count_departments) {
    value <- placeDepartment(covered,sizes_transpose[i,],y[i])

    if (value != FALSE || length(value) > 1) {
      covered = value
    } else {
      return(FALSE)
    }
    #print(covered)
  }

  return(TRUE)
}

#print(BlockMatrixImproved(c(4,3),4,4,array(c(3,2,2,2),dim = c(2,2))))
#print(BlockMatrixImproved(c(1,3),2,4,array(c(2,2,2,2),dim = c(2,2))))

#places a department of width and height given in sizeVector
# at point pointNumber in
# matrixBlock and returns the matrixBlock if it succeeds
# returns FALSE if it fails
placeDepartment <- function(matrixBlock,sizeVector,pointNumber) {
y_center <- floor(sizeVector[1] / 2)
x_center <- floor(sizeVector[2] / 2)
#print(y_center)
widthBlock <- ncol(matrixBlock)
heightBlock <- nrow(matrixBlock)

width <- widthBlock - 1
height <- heightBlock - 1

x_pos <- ((pointNumber - 1) %% width) + 1
y_pos <- floor((pointNumber - 1) / width) + 1
#print(y_pos)
columns <- sizeVector[1]
rows <- sizeVector[2]


for (i in 1:columns) {
  for (j in 1:rows) {
    y_point <- i + y_pos - y_center
    x_point <- j + x_pos - x_center
    if(y_point < 1 || x_point < 1 || y_point > heightBlock || x_point > widthBlock) {
      return(FALSE)
    }
    matrixBlock[y_point,x_point] = matrixBlock[y_point,x_point] + 1
```

```
      if (matrixBlock[y_point,x_point] >= 2) {
        return(FALSE)
      }
    }
  }
    return (matrixBlock)
}

#print(placeDepartment(matrix(c(0,0,0,0),nrow = 2, ncol = 2),c(2,2),1))#passes
#print(placeDepartment(matrix(c(0,0,0,0,0,0),nrow = 3, ncol = 2),c(2,2),2))#passes
#print(placeDepartment(matrix(c(0,0,0,0,0,0),nrow = 3, ncol = 2),c(3,2),1))#passes
#print(placeDepartment(matrix(c(0,0,0,0,0,0,0,0,0,0,0,0),nrow = 3, ncol = 4),c(2,2),5))#passes
#print(placeDepartment(matrix(c(0,0,0,0,0,0,0,0,0,0,0,0),nrow = 3, ncol = 4),c(3,2),3))

#Works out the QSCP value given number of departments n
#possible positions m as well as
#n*n matrix f
#m*m matrix d
# and the n*m matrix a (or is it m*n?)
FunctionQSCP <- function(y,n,m,f,d,a) {
  S <- 0
  print("Enter QSCP")
  x <- vectorToMatrix(y,m)
  #print(x)

  for (i in 1:n)
  {
    for(j in 1:m)
    {
      S = S + a[i,j] * x[i,j]
    }
  }
  for (i in 1:n){
    for(j in 1:m){
      for(k in 1:n) {
        for(l in 1:m){
          S = S + f[i,k]*d[j,l]*x[i,j]*x[k,l]
        }
      }
    }
  }
  print("Leave QSCP")
  return(S)
}
#exchange for any random other number not in the list
#or swap two of the numbers around
ChangeDepartments <- function(x,n,BlockMatrix) {
  m <- length(x)
  #z <- runif(3)

  good<- FALSE
  count_watch <- 0
  print("Enter Department Change")
```

```
 while(good == FALSE)
 {
  count_watch = count_watch + 1
  y <- x
  z <- runif(3)
  if (z[1] >= 0.5) {
   #exchange for number not on list
   q <- 1:n
   q = setdiff(q,x)
   #print(q)
   selection <- z[2] * (n - m)
   selection = floor(selection) + 1
   q[selection]
   #print(q[selection])

   y[floor(z[3] * m) + 1] = q[selection]
   #print(y)
   good = BlockMatrix(y)
  }
  else {
   index_a = floor(z[2] * m) + 1
   index_b = floor(z[3] * (m - 1)) + 1
   if(index_b >= index_a) {
    index_b = index_b + 1
   }
   swap = y[index_a]
   y[index_a] = y[index_b]
   y[index_b] = swap
   good = BlockMatrix(y)
   #swap two numbers around
  }
 }
 print("Leave Department Change")
 #print(count_watch)
 return(y)
 #return
}
gridPosition <- function(x,y,width) {
 #x_pos <- ((pointNumber - 1) %% width) + 1
 #y_pos <- floor((pointNumber - 1) / width) + 1
 return(((y - 1) * width) + x)
}
main <- function() {
 width_blocks <- 20
 height_blocks <- 25
 positions <- (width_blocks - 1) * (height_blocks - 1)
 number_departments <- 16

 f <- matrix(c(0,0,0,..., 0),nrow = number_departments,ncol = number_departments)
 d <- matrix(c(0,0,0,..., 20),nrow = positions, ncol = positions)
 size_array_3D <- array(c(4,4,7,..., 4),dim = c(2,16,65))
 #curry the BlockMatrixFull function to give a function that only depends on y
 BlockMatrix <- Curry(BlockMatrixFull,width=width_blocks,height=height_blocks,sizes=size_array_3D)
```

```
 #curry the ChangeDepartments function to give a function that only depends on y
 Change <- Curry(ChangeDepartments,n=positions,BlockMatrix=BlockMatrix)

  #curry the FunctionQSCPReady function to give a function that only depends on y
  FunctionQSCPReady <- Curry(FunctionQSCP,n=number_departments,m=positions,f=f,d=d,a=a)
  p = Curry(gridPosition,width=width_blocks - 1)
  first_guess<- c(p(18,16),...,p(5,13))
  #first_guess is a vector of positions of the departments that HAS to fit.
  #To be sure it fits, BlockMatrix(first_guess) HAS to equals true
   if(BlockMatrix(first_guess) == TRUE) {
     max_iterations = 500
     print(optim(first_guess,FunctionQSCPReady,Change,method = c("SANN"),control =    list(maxit =
             max_iterations)))
      } else {
       print("error! first guess does not fit!")
      }
}
main()
```

APPENDIX F: UPDATED FRAMEWORK

This section contains the outline of the developed framework after removing the step that pertains to calculating the optimal layout solution using the Branch and Bound Algorithm. The updated framework is shown in Figure 33.

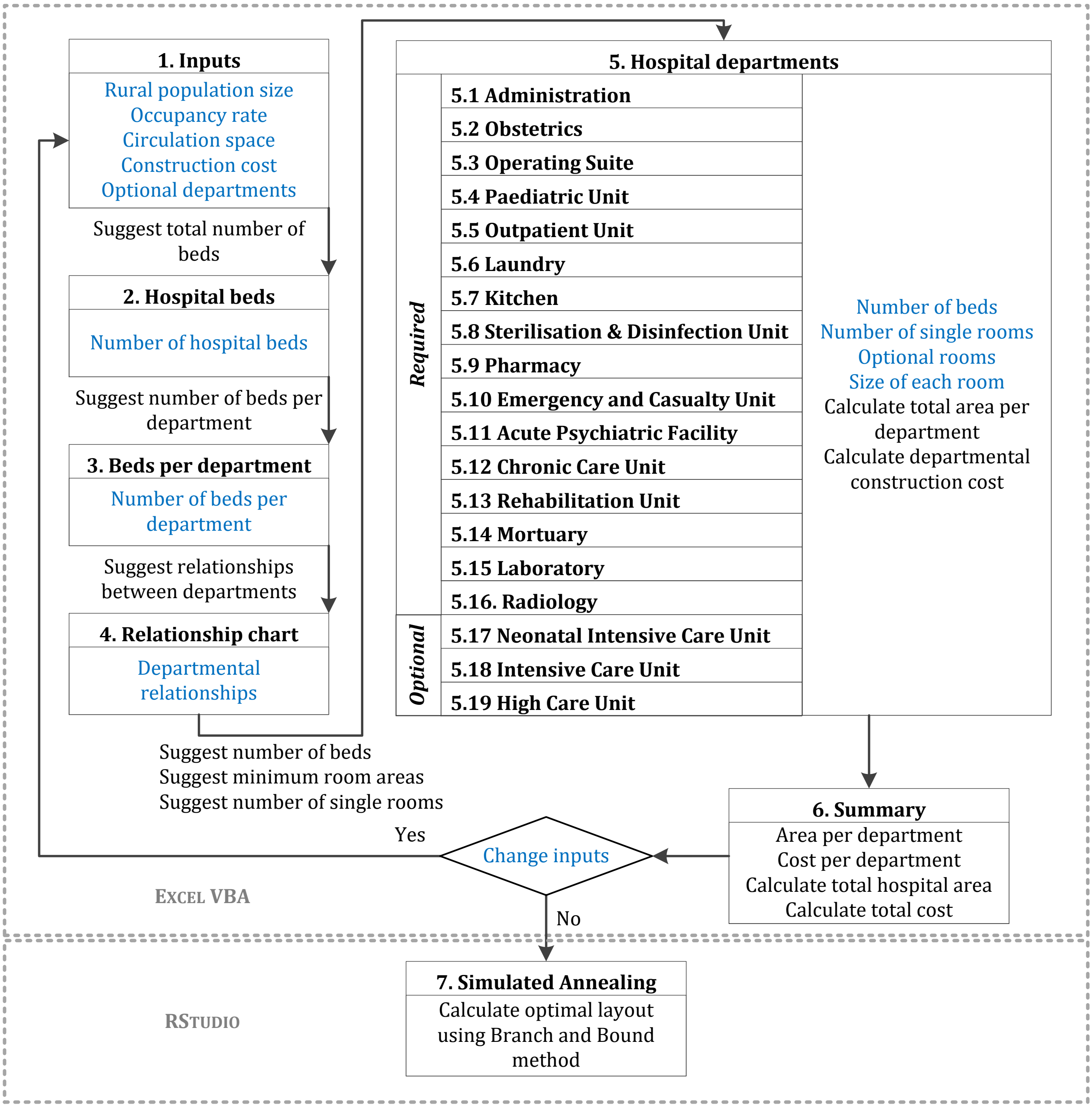


FIGURE 33: UPDATED FRAMEWORK