



OPTIMIZING OPERATING ROOMS' FACILITY LAYOUT DESIGN

By

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Biomedical Engineering

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Declaration

I declare that this thesis report, submitted to center of Biomedical Engineering at Addis Ababa Institute of Technology, Addis Ababa University in partial fulfillment of requirements for degree of Master of Science in Biomedical Engineering is entirely my own work with the exception of paraphrased or quoted work whose sources are appropriately cited and acknowledged in the references.

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Dedication

This thesis is dedicated to the strongest person I have ever known, my beloved mother Azeb G/Tsadik who passed away during the course of this thesis.

Abstract

In Low and Middle-Income Countries such as Ethiopia, most operating rooms (ORs) are built without the proper consideration given to the layout design of the room. This is one of the major causes for the spread of infection. According to WHO, this affects one third of surgical patients in these countries [1]. Research relates the highest bio-burden in an OR to the professionals working in it. This research thesis aims to develop an improved and optimized OR layout [2]. The objective is to maximize infection control by considering the flow patients and of the professionals.

Eight hospitals in Addis Ababa were selected for case study via a questionnaire. Literature review was done to study standards and guidelines requirement and recommendation on OR facility layout design and to investigate facility layout problems and modeling techniques. Based on the data collected from case studies and literature reviews on national and international standards, the flow of the professionals inside the OR was studied. It was then developed to an interaction adjacency matrix of the rooms inside the department. Then the OR layout model was created using graph theory technique which has shown to be the most successful modeling technique and the model was implemented on a MATLAB platform. The output was used to create alternative detailed OR designs for surgical center premise set up with minimum requirement and in a general and specialized hospital setups. Additionally, through the questionnaire, application of technologies in the OR facility and knowhow of the OR staff regarding facility layout design were studied.

A block layout with 85.6% optimization was acquired. The alternative detailed/architectural designs were made using this block layout. These met national and international standards. The study clearly revealed the possibility of infection control through optimized OR layout design. The research also indicated that there is lack in the application of technologies and in professionals training (regarding their OR facility layout design) within the selected hospital ORs.

This indicates that further in-depth research is necessary to collect input data that specifies a more detailed and accurate interaction between rooms in the OR department. In this case, using the developed MATLAB code, up to 96% optimization can be reached. As the staff and the technologies used have direct effect on infection control; on job training for the staff (to give awareness about the environment they work in) and implementation of technological advancements is essential.

Key words: Operating room, Infection control, Facility layout design, Standardize, Graph Theory, MATLAB, Optimization.

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List of Abbreviations

AS – Anesthesia Store

ASA – American Society of Anesthesiologists

CR/UR – Cleaner’s Room/ Utility Room

CUSS – Clean Utility Surgical Suite

CSR – Central Sterilization Room

DO/SO – Doctors’ Office/ Staff Office

DR – Duty Room

FF – Floating Facility

FLD – Facility Layout Design

FLP – Facility Layout Problem

FMHACA – Ethiopian Food, Medicine and Healthcare Administration and Control Authority

FMOH – Ethiopian Federal Ministry of Health

GTA – Graph Theoretical Approach

GTM – Graph Theoretical Method

HAI – Hospital Acquired Infections

HIC – High Income Countries

HLP – Hospital Layout Problem

iHFG – International Health Facility Guideline

LMIC – Low and Middle-Income Countries

MPWG – Maximal Planar Weighted Graph

MSF – Médecins Sans Frontiers

NS – Nurse Station

OR – Operating Room

OT – Operation Theater

OTES – OT Equipment Store

POPA – Pre-Operative Patient Area

PPE – Personal Protective Equipment

QAP – Quadratic Layout Problem

RF/PAC - Recovery Facilities/ Post Anesthesia Care

SA – Scrub Area

SaLTS – Saving Lives through Surgery

SCR – Staff Changing Room

SU – Soiled Utility/Sluice Room

SSI – Surgical Site Infections

SSS – Sterile Supply Store

WCO – Office Toilet

WCP– Patient Toilet

WCS – Staff Toilet

WHO – World Health Organization

Chapter One

Introduction

1.1 Back Ground

An operating room (OR) is a department within a hospital where surgical procedures are conducted in an aseptic environment. A surgical procedure involves “the incision, excision, manipulation or suturing of tissue that usually requires regional or general anesthesia or profound sedation to control pain” [3]. In designing of a facility within a hospital, special high focus should be given to critical departments such as operation rooms, where one break in proper protocol can lead to an infection.

Infections developed around the incision area are called Surgical Site Infections (SSI) [3]. There are three main sources of infectious pathogens in OR: the patient, the health care professional and the environment. Studies show that the highest bio-burden in an OR is the health care professional. [2] The surgical team has to follow aseptic practices and be in a constant state of high alert to prevent SSI and transmission of infectious microorganisms. Still SSI remains the second most hospital acquired infection (HAI) in high income countries (HIC) and the primary HAI affecting one in every three patients in low- and middle-income countries (LMICs) [4].

Collaboration of foundations and nonprofits in partnership with the Ethiopian Federal Ministry of Health (FMOH), Addis Ababa University, Mekelle University and Surgical Society of Ethiopia has been working together with a goal to reduce preventable deaths from surgically treatable conditions. With assistance from this Safe Surgery 2020 program FMOH has developed the Saving Lives Through Surgery (SaLTS) strategy with a focus to help transform the health system to ensure that every individual is able to access the surgical care they need quickly, safely, and affordably [5]. So far the focus areas have been on workforce development, leadership transformation program, national surgical planning, innovative infrastructure development (medical oxygen plant) and monitoring and evaluation. The program trained approaches to clean, disinfect and sterilize medical devices and pinpoint quality improvement projects to reduce SSI. Even so, less focus is given to standardize facility layout design and infrastructure of the actual OR to control SSI, yet this will have tremendous aid in the accomplishment of the goal.

For quality health care provision, departmental facility layout design should be integrated with hospital facility design. Facility layout design (FLD) is arrangement of everything within a facility (in our case the rooms within a department). The layout and design of a space significantly influence how the work is done as well as, the flow of work, materials and information through the system [6].

1.2 Statement of the Problem

In Ethiopia, most of the operating theatres are built without consideration of proper layout designs. One reason for this is, in Ethiopian standards, there is a requirement of what the operation room facility should comprise and the scale to which the rooms should minimally extend, but there is no layout design for the proximity of the facilities. This leads hospitals to allocating resources that should be in close proximity and integrated with the operation room to areas favorable to the designer, elsewhere within that building. This is one of the major causes for the spread of infections in ORs hindering effectiveness of staff. This in turn affects the quality of the healthcare provided.

Annually, millions of dollars (around 2,646 (million US dollars) in 2018) [7] is invested in health expenditures in Ethiopia. The lowest amount is spent on facility design of hospitals, without giving serious attention to the required equipment and technology and the impact on the quality and safety of patients and users. According to researches done on health care provision systems in other countries, a good amount of deadly hospital mistakes arises in relation to hospital facility and medical equipment. Therefore, it is mandatory to give attention to these areas.

In the current thesis research, possible solutions are suggested in regards to the optimal facility layout of an OR with an architectural design. Further, study has been done on the application of technological safeties for infection control in OR and exploration of the professionals knowhow related to this topic.

1.3 Objective

1.3.1 Main Objective

The main objective of this thesis is to design an improved and optimized OR layout for hospitals in accordance to Ethiopian and international standards and assessments conducted at selected hospitals in Addis Ababa.

1.3.2 Specific Objectives

The specific objectives of this thesis are:

- To study national and international standards and guidelines on OR facility layout design.
- To investigate the effect of the ORs and its facility's layout on patient care provision and infection control.
- To investigate design alteration methods.
- To analyze the application of technological safety for infection control in ORs found in selected hospitals.
- To explore the professional's knowledge related to infection control in their OR facility.
- To design and implement an optimal OR layout for two types of hospital setups (General and Specialized).

1.4 Scope

Due to budget and resource limitations, clinical validation is beyond the scope of this thesis.

1.5 Significance of the Study

The intention of this thesis research is to improve the facility's design of ORs in order to maximize infection control. Proper facility layout design in OR aids better patient care provision, maximizing the effectiveness of the health care professionals, hygiene considerations and better utilization of space, equipment and staff. It has also been proved that better healing occurs due to better hospital design, designed with more patient centered approach.

This research can be used to aid the design, planning and construction of newly opening hospital ORs facility layouts and the redesign consideration of existing hospital OR facility layouts.

Chapter Two

Literature Review

To most effectively explore all related issues and past studies on this subject both Theoretical and Empirical review has been done.

The theoretical literature review focuses on the topics of:-

- Surgical site infection,
- Infection control,
- National and international OR design standards and guidelines,

The empirical literature review focuses on the topics of:-

- Facility layout design and
- Prior works on hospital layout problem (HLP) and OR facility layout problem (FLP).

2.1 Surgical Site Infection

“Surgical Site Infection (SSI) is an infection that occurs in surgical patients at or near the site of operation” [4]. It causes morbidity, anxiety, discomfort, delay in recovery, an increased hospital stay and economic consequences [8, 9].

According to WHO, SSIs are the most frequent health care-associated infections (HAI) in LMICs affecting one third of surgical patients and the second most frequent type of HAI in HIC [1]. In HICs such as the USA, SSI is associated with a mortality rate of 3%, out of which 75% of deaths are directly attributable to it. Related to economy and prolong hospitalization, it is estimated to cost \$3.3 billion and 1 million additional inpatient-days annually [10].

2.1.1 Sources of Surgical Site Infections

There are three main sources of infections pathogens in OR: the patient, the health care professional and the environment. Hygienists in the 1990s argue that the previous mindset was that surgical areas were well enough secured from germs entering by airlocks in the environment. But studies show that the highest bio burden is due to the operating team, depending on their body-hygiene, clothes and movements. This is illustrated in Table 1 and Figure 1 below. The table shows the number of germs spread per hour from a single individual depending upon the individuals’ skin [2].

Germ spreading (every hour by small movements)	Normal Skin	After showering	After refitting/ Moistening
Naked	25,000-40,000	60,000-79,000	1,750-36,000
With Operating clothes	14,000-28,000	31,000-37,000	1,400-2,370
With clean room overall and high boots	780-2,240	2,900-5,400	117-340

Table 1: Spreading of germs from the body to the surrounding (10).

Figure 1 shows the emission of particles per second (particle size > 0.5µm) from an individual according to different clothes and movements [2]. As movement increases, so does the spread of infection.

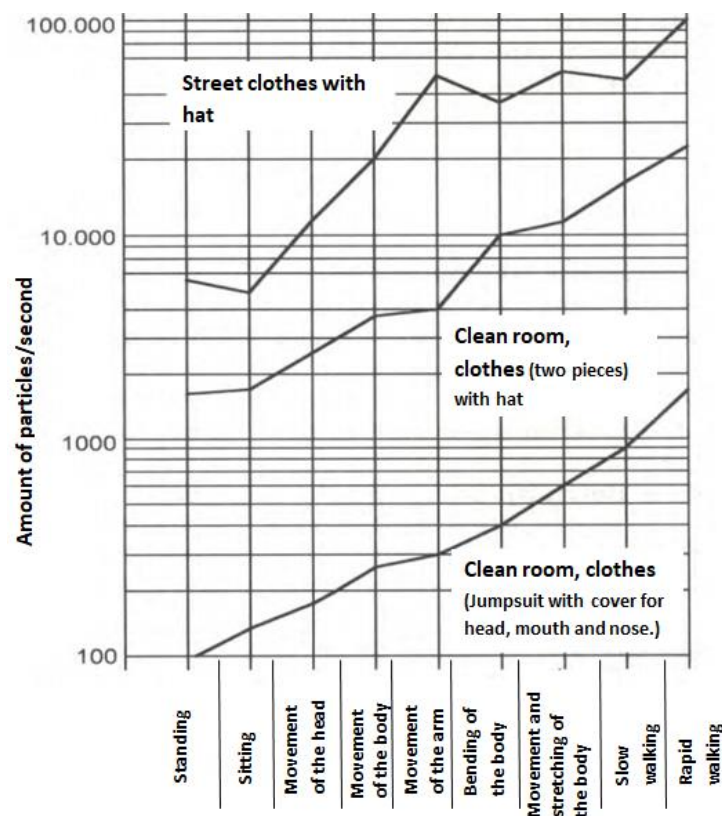


Figure 1: Emission of particles per human/sec.

2.2 Infection Control

Integration of different means of infection prevention techniques is required throughout a patient's journey of surgery [1]. Robert Koch Institute (RKI) 2000 states that, an effective prevention of infections is done by organizational, structural-functional and operative-technical means of prevention [2].

Organizationally, OR surgical team follows aseptic practices such as: wearing surgical attire/Personal Protective Equipment (PPE), using surgical hand and skin antiseptics and maintaining a sterile field to prevent SSI. Additionally hospitals can follow WHO global guidelines. These guidelines provide information in support of actions to improve organizational practices. Operative-technical means of prevention SSI are: minimize the amount of patient waiting time and integration of advanced equipment and technologies that aid with surgery in the OR [11].

Structural-functional means of preventing SSI is linked with effective, appropriate planning and forethought in the layout construction and design of an OR. It is essential that OR design be brought up-to standard and respect the concept of “progressive asepsis”. The asepsis standards increase as one goes in from the perimeter of the OR (access to operating department, auxiliary services) to the operating site (operating table, the surgical members of the team and the area around them) [12]. In OR design, there is no one, perfect solution and, each plan has to be done in collaboration with a hospital’s user, hygienists and planners [2].

2.3 National and International Standards

OR department is composed of the operating theater (OT) and supportive areas integrated to support and carry out its activities [12]. National and international standers and guidelines offer details of the departments’ composition, their spatial and functional relationship, general features and configurations.

2.3.1 Ethiopian Standards

Ethiopian standards only specify the requirements of what an OR facility should comprise, the scale to which the rooms should minimally extend and their interior construction. It requests an OR environment that is access restricted, organized and equipped allowing OR trafficking to be controlled and exercised over all persons and materials entering and leaving the area [13]. The composition of both general and specialized hospital OR departments requirements are the same. The major difference between the two is the number of operation theaters (OT) that are required. According to the standard, general hospitals are required to have minimum of three OTs and one septic OT while specialized hospitals are required to have a minimum of seven OTs. Two ORs can share a scrub station [14, 13].

Table 2 below summarizes the requirement of premises to set up a surgical center: what it is comprised of, with the amount and minimum scale of each facility.

Room Required	Quantity	Area
○ Operation Room		
– Operation Theater (OT)	2	60 m ²
– Scrub Area (SA)	1	12 m ²
– Clean Utility surgical suite (CUSS)	1	6 m ²
– Nurse station (NS)	1	12 m ²
– Anesthesia Store (AS)	1	8 m ²
– OR equipment store (OTES)	1	12 m ²
– Sterile supply store (SSS)	1	12 m ²
– Doctor’s office (DO)	1	12 m ²
– Duty Room (DR)	1	8 m ²
– Janitor’s Closet/Cleaner’s room/ Utility room (CR/UR)	1	6 m ²
– Soiled utility/ Sluice room (SU)	1	6 m ²
○ Staff Change room (SCR)	2	12 m ²
○ Toilet rooms with shower & hand washing basin (WCS)	2	12 m ²
○ Recovery room/ Post anesthesia care (with 2 beds)(RF/PAC)	2	16 m ²
○ Central Sterilization room (CSR)	1	6 m ²

Table 2: Premises set up for surgical center according to Ethiopian standard requirements (12).

To relate the structural-functional organization, the standard states location of SA to be outside but adjacent to OT, SU to be at the back of the OR, RF close to OR in semi-restricted area and for the NS to be integral part of the main patient corridor, the recovery area and the bed receiving area/ pre-operative patient area (POPA). It suggests NS be constructed and equipped so that it is possible for nursing staff to observe patients directly and where necessary to render assistance. Further to limit infection exposure to the OR, it requires SCR to have two doors one for entrance and the other to access the restricted areas.

2.3.2 International Standards and Guidelines

The American Society of Anesthesiologists (ASA) declare that it is appropriate to think of a building as another tool of the health care professionals whom it serves, because a great medical facility enables its staff, makes them more capable and makes their work more effective [15].

Guidelines such as “Medecins Sans Frontiers (MSF)” and “International Health Facility Guideline (iHFG)” state that asepsis must be considered a major criterion in design [12] [16]. MSF states that the setup and number of functional spaces will change according to the services provided, space availability, financial and human resources [12].

According to international guidelines, the location of OT and its supportive area in the OR is as follows:

- OT next to SA, close and easily accessible from POPA, close to SCR.
- SA next to the entrances of each OT.
- POPA immediately adjacent to OT, in the main access to the department and under visual control to NS.
- SCR adjacent to OT and in the entrance of the department.
- RF/PAC immediately adjacent to OT and in the main access to the department.
- DO close to OT and SCR.
- SSS and CUSS adjacent and easily accessible to OT and separated from SU.
- SU next to OT connected by wicket.
- CR/UR easily accessible from OT.

The WHO states that the internal layout should be based on the traffic flow within the department, as shown in Figure 2 below.

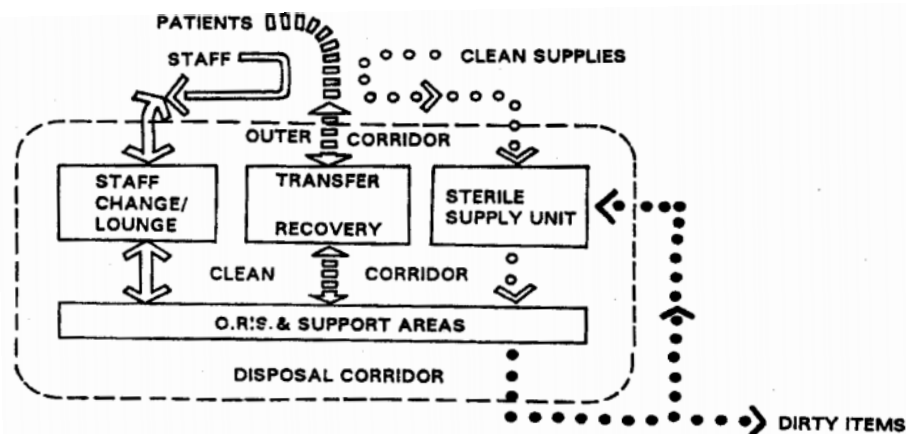


Figure 2: Traffic flow with in OR [17].

Rao (WHO, 2020), states these six points to be considered as objectives when planning an OR [9].

- 1) To control the concentration of pathogens;
- 2) To prevent infiltration of non-purified air into the operation theatre;
- 3) Air flow pattern that carries contaminated air away from the operating table;
- 4) Comfortable environment for the patient and operating team;
- 5) Convenient and uninterrupted personal movements inside the operation theater;
- 6) Safe zone creation in OT (for the safe location of sterile instruments and disposables).

2.3.2.1 Operation Department Area Distinction

There are three distinction areas of OR: restricted, semi-restricted and unrestricted. To achieve a high level of infection control, the asepsis standard is required to increase as one goes from unrestricted to restricted areas. The description of these areas is as follows:

2.3.2.1.1 Restricted Area

Restricted area is space contained within the semi-restricted area and accessible only through a semi-restricted area [18]. It includes the operating and other rooms that require aseptic field in which surgery or other invasive procedures are performed [19].

2.3.2.1.2 Semi-restricted Area

Semi-restricted area is the peripheral support area of the surgical suite. This area is entered directly from the unrestricted area past a nurse's station or from other area. The area includes: SA, SU, SSS, OTEs, CUSS, AS, CSR, corridors leading from the unrestricted area to restricted area of the surgical suite and the entrance to SCR, RF/PAC and sterile processing. The Ethiopian standard considers NS to be part of this area unlike other standards which considers it as part of unrestricted area.

2.3.2.1.3 Unrestricted Area

Unrestricted area is an area of the building that is not defined as semi-restricted or restricted [18]. This area includes a central control point for designated personnel to monitor the entrance of patients, personnel and materials into the semi-restricted area. This area includes: SCR, DO/SO, DR, RF/PAC, CR/UR, POPA and WCs.

2.4 Facility Layout Design

A facility is the space in which business activities built for specific purpose take place [6]. Facility layout design refers to the arrangement of everything within a facility (department, work-groups, machine, equipment and furnishings) after considering the various objectives of the facility [20]. Facility layout problems range in scale from the assignment of activities to cities, sites, campuses or buildings, to the location of equipment and personnel groups on a single floor of a building [21].

2.4.1 Problem Formulation

There are several types of models of formulating layout problems mathematically so that they can be solved. These models are generally used to suggest solutions to the layout problems, which most researchers consider as optimization problems, with either single or multiple objectives. [22]

2.4.2 Objective of Facility Layout Design

Approaches to evaluating FLPs pursue either of the two sets of objectives: quantitative or qualitative objectives. Quantitative objectives aim at minimization of the total MHC, rearrangement cost, backtracking and bypassing, and shape irregularities [23]. Qualitative objectives aim at maximization of the closeness between facilities. It places facilities that utilize common materials, personnel, or utilities adjacent to each other while separating the facilities for the reasons of safety, noise, or cleanliness [23]. Although the majority of researches focus on quantitative objective, minimization of material handling cost by designing facilities in best possible way, there are many other objectives to a FLD. Some of these objectives are summarized in Figure 3 below [6, 24, 22].

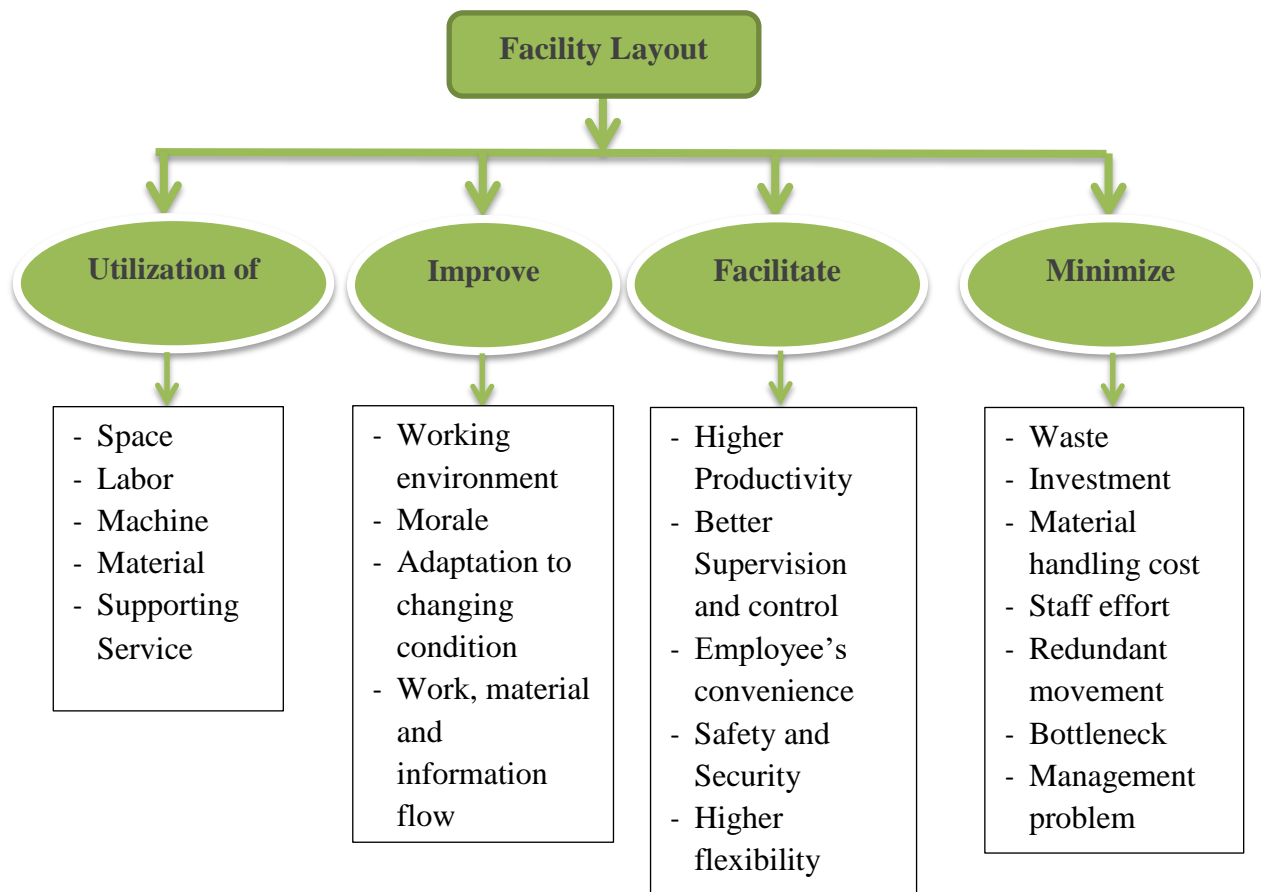


Figure 3: Objectives of facility layout.

2.4.2.1 Advantages of Optimum Design for Hospital Facility Layouts

Amol Shrikrishna in his research shared many advantages of designing optimal facility layouts for hospitals. He listed these advantages as follows [25]:

- The best possible location of the departments is achieved.

- The forecasting of future demand and capacity requirements can be analyzed with the help of a capacity model.
- The in-depth analysis of the interaction between the departments is obtained, which is useful in predicting the future course of action.
- For micro layouts, major workstations and instruments are placed in optimal work cells similar to macro layouts.
- Equipment clearances, human ergonomics, sample requirements and walking distances are optimized.

2.4.3 Modeling Facility Layout Problem

During the past six decades, different mathematical models have been developed for FLP. They can be divided into eight classes. These are Quadratic Assignment Problem (QAP), Quadratic set covering problem (QSP), Floating facilities Problem (FFP), Mixed Integer Problem (MIP), Graph Theory Problem (GTP), Linear Programming Problem (LPP), Integer Programming Problem (IPP) and Non-linear programming problem (NLP). Besides the eight classes, FLP can be modeled based on two categories named as certain layout problem and uncertain layout problem.

Certain layout problems: In this case objective functions and constraints are fixed, FLD optimization can be done in certain conditions. If all the input data are already known, operations research models can be used effectively [23].

Uncertain layout problems: In this case facility layout is done in uncertain condition. Despite in most models, transportation costs (Material handling cost (MHC)), the flow of materials, and the distances between facilities are considered independent and that no interaction exists between them; they are interdependent. The flow of materials is defined based on the product demand whose value is not predictable. To know demand products value it is necessary to know the price of a product which depends on material handling cost [23].

2.4.4 Constraints

Generally, constraints of facility layout problems are area, budget, and layout constraints, such as non-overlapping, pick up or drop off, orientation, and clearance between facilities [26, 23, 22].

2.4.5 Resolution Approaches

Operation researchers have formulated several approaches to address the different types of layout problems. They aim either at finding good solutions, which satisfy certain constraints

given by the decision-maker, or at searching for a global or local optimum solution given one or several performance objectives (single or multi objective). This has yielded heuristic-based methods or optimization algorithms and attempts of using artificial intelligence to address the layout problem. There are four approaches named Exact, Stochastic, Intelligent, and Approximate approaches.

2.4.5.1 Exact Approach

Exact methods are useful approaches to find optimal solutions for small-sized FLPs. Dynamic programming, branch and bound method, cutting plane algorithm, and semi-definite programming are examples of exact approaches [23].

2.4.5.2 Stochastic approach

Stochastic approaches are algorithms that produce near-optimal solutions with high probability. The Discrete event simulation approach is an example of stochastic approaches. [23]

2.4.5.3 Intelligent approach

Artificial intelligence approaches methods belong to a branch of computer science that simulates intelligent human behavior by machines. Expert systems and artificial neural networks are the most important subdivisions of artificial intelligence algorithms [23].

2.4.5.4 Approximate approach

These are approaches that can provide good suboptimal solutions for NP-complete problems that cannot be optimized with a reasonable amount of time when the facilities are more than 15 in number. [22] These approaches are widely classified as Constructive algorithms, Improvement algorithms, and meta-heuristic algorithms.

Constructive algorithms: Construction procedures build a layout from scratch by successively selecting and placing facilities until a completed layout is obtained. These methods have one drawback in common; that is, the final solution may be far from optimal because the methods generate only one layout. Well-known examples of construction algorithms are computerized relationship layout planning (CORELAP), automated layout design program (ALDEP), and programming layout analysis and evaluation technique (PLANET) [22, 23].

Improvement algorithms: Improvement methods start with an initial solution and attempt to improve it by swapping the locations of facilities. The swap that produces the best solution is

retained, and the procedure continues until the solution cannot be improved any further [22, 23]. Examples of these methods are pair-wise exchange, insertion neighborhood, Lin–Kernighan neighborhood, computerized relative allocation of facilities technique (CRAFT), computerized facility aided design (COFAD), etc.

Meta-heuristic algorithms: this is a higher-level procedure (heuristic design) designed to generate a good enough optimum result. Different meta-heuristics methods are presented to solve FLPs. The best known of these techniques are genetic algorithm, tabu search, simulated annealing, and ant colony optimization [23].

Throughout history, architectural designers have been responsible for creating architectural plans and designing facility structures. Since the question of optimality arose, operation researchers started modeling facility layout problems for industries. This was six decades ago and researchers argue that FLP is still in its initial stage and is an interesting field to work on.

2.5 Prior Works on OR FLD

As seen in the previous section, there are different heuristic methods that have been developed for solving FLPs for industrial purposes. Among these, there are only a few researches and projects made on hospital layout modeling. These HLPs were modeled as: Quadratic Assignment Problem (QAP), Floating Facilities (FF), Graph Theoretical Approach (GTA) and Systematic Layout Planning (SLP).

2.5.1 Quadratic Assignment Problem (QAP)

QAP is a mathematical model resembling the assignment problem statement. It considers the problem of allocating a set of facilities to a set of locations, with the objective to minimize the cost being a function of the distance and flow between the facilities, with costs associated with a facility being placed at a certain location [27, 28].

2.5.2 Floating Facilities (FF)

FF begins with defining a set of shapes in a Cartesian coordinate system. This includes the axis-aligned polygon, as the layout boundary and the spaces to be allocated, limited to the number of rooms. The rooms are represented with variables of the positions, the width, depth and labels as the names of each room. This technique proceeds through moving the rectangles which can assume any position around inside the boundary to find the optimal arrangement without overlapping [29].

2.5.3 Graph Theoretical Approach (GTA)

A GTA is an approach where the adjacency of each pair of facilities can be represented by a graph, in which nodes denote facilities and edges demonstrate the existence of flows or relationships between facilities [30, 26].

2.5.4 Systematic Layout Planning (SLP)

SLP is a step-by-step planning technique permitting identification, visualization and rating of the various activities, relationships, and alternatives involved in a layout project. Relationships, space and adjustment are the three fundamental areas of the technique. It combines quantitative measurement of materials movement with non-flow considerations such as noise, fumes, temperature, supervision, communication, personnel comfort and movement [31, 24].

When the number of activities is greater than fifteen, the time to solve the QAP increase exponentially and immeasurably as the size of the problem grows. Further QAP model, are weak at solving complex HLPs with dynamic demands, due to their approximate approaches. Thus QAP model is infeasible for hospitals design [29, 21].

A Floating Facilities technique is another modeling technique with more capabilities and freedom than a QAP model, such as working with unequal and usually dynamic room sizes and shapes [32]. Therefore, a further set of high-level constraints is usually defined, such as room area or room aspect ratio, to ensure that the outcome is architecturally viable [29].

“Foulds views the graph theoretic approach as more appropriate for the design of a new facility where there is more design freedom, while the QAP formulation is more useful in a structured situation” [21]. From the heuristic approaches developed, the most successful to the facility layout problem were based on GTA concepts [24, 33, 26].

GTA is primarily concerned with generating a layout that fulfills the immediate adjacency requirements between activities [21]. Three ordered steps are required to construct a layout using graph theory. These are development of maximal planar weighted graph (MPWG) according to interactions between the facilities, construction of the MPWGs dual and converting the dual into block layout [33]. (Exhaustive explanation of the idea of approach can be found in methodology section 3.7.5) Developing the maximal planar weighted graph is the keystone of the GTA [33, 34]. This problem is NP-hard and multiple researches have come up with different heuristic methods of developing it [34, 26]. Listed below are the sub-optimal solutions researchers have developed to acquire the MPWG.

1. Spiral Technique (manual traditional qualitative technique, calculate total closeness rating (TCR))
2. Planarity testing approach (planarity test preformed in each edge addition)
 - a. A maximal spanning tree
 - b. Branch and bound
3. Procedures which avoid planarity testing
 - a. String processing
 - b. Tetrahedron procedure
 - c. Wheel expansion

From these methods, the tetrahedron procedure showed high quality providing sum of the edge weights of the obtained graph lie between 92.4 and 99.8% of the upper bound on the optimal value [26]. Limitation of this method is in some cases rooms that have to be in middle of the setup might be located on the border. This has to be compensated for in the architectural design.

Another limitation of the Graph theoretical approach is the 2D block layout developed will not have area restriction. But this also leaves room for the architect to have freedom in the design and length and width selection ability based on minimum area required and amount of space available for the design.

Due to the complexity and diverse specialized function of hospitals, the design process is a collaborative work of different experienced expertise in order to meet the different requirements and constraints.

Now, more than ever, the impact that spread of infection produces is visible. An OR infection control rate is of utmost importance to a hospital critical care unit. In LMICs like Ethiopia, many means of infection control in an OR are overlooked in its facility layout design. As one means of solution to this problem, in this thesis an OR is designed using Graph theory model with a qualitative objective aimed at maximizing infection control in certain condition. As seen from the reviewed research SSI is directly related to movement of staff. Hence movement of staff within the department and structural and functional relation of the rooms from standards are taken as constrains. Tetrahedron heuristic algorithm resolution approach is used.

Chapter 3

Methodology

This thesis research intends to develop an optimization tool, where OR facility layout is designed in a way of maximizing infection control. Studies show that the main source of infection in an OR is movement of staff in the OR. Ethiopian standard requirement for OR design covers the issue of what the OR facility should comprise of but does not provide a layout design for the proximity of the different facilities. Because of this, architects/designers of a hospital allocate rooms which should be adjacent to each other, elsewhere in the hospital building. This increases movement of staff, hence the spread of infection.

In the current thesis research, a layout of an OR is built in order to limit the spread of infection from the staff, by designing rooms traveled frequently to-and-fro closer to each other. The design also considers the area distinction provided by standards and follows existing well known guidelines and recommendations on OR design.

In order to solve the facility layout problem, a Graph theory heuristics technique is used and implemented in a Matlab environment. This technique is chosen considering the fact that it is the most successful method in FLD and that facility adjacency is better modeled with this technique. Furthermore, this approach gives the architecture freedom in choosing dimensions. Another advantage of this procedure, following Arnolds and S. Nickel (2015), is that it is illustrative and visually presentable which makes it easier to convince the responsible hospital managers to apply the approach [26].

The method used in this thesis is a hybrid (mixed) method where the research data type is both qualitative and quantitative. To strengthen the reliability of the data, both primary and secondary data sources are used. Primary data are those collected directly from staff in the OR via questioners. Secondary data are those collected through literature review of both national and international standards and guidelines on OR design. In this thesis, descriptive survey method is used, as Gay (2000) said “it is a helpful method to show situations as they currently exist”.

The optimized output is then used to design actual 2D layout of a surgical center premise set-up with minimum requirement as per the Ethiopian standard and illustrate two other types of OR designs for general and specialized hospital.

This thesis also briefly analyzes through questionnaires the application of technological safety (HVAC, central gas supply systems and others) for better infection control, safety and effectiveness in the OR and explores the knowhow of the professionals related to the topic of infection control relative to OR FLD. Data from the questionnaires were analyzed and the outcomes are presented in the results and discussion section of this thesis document. Figure 4 presents a rough schematic of the proposed methodology.

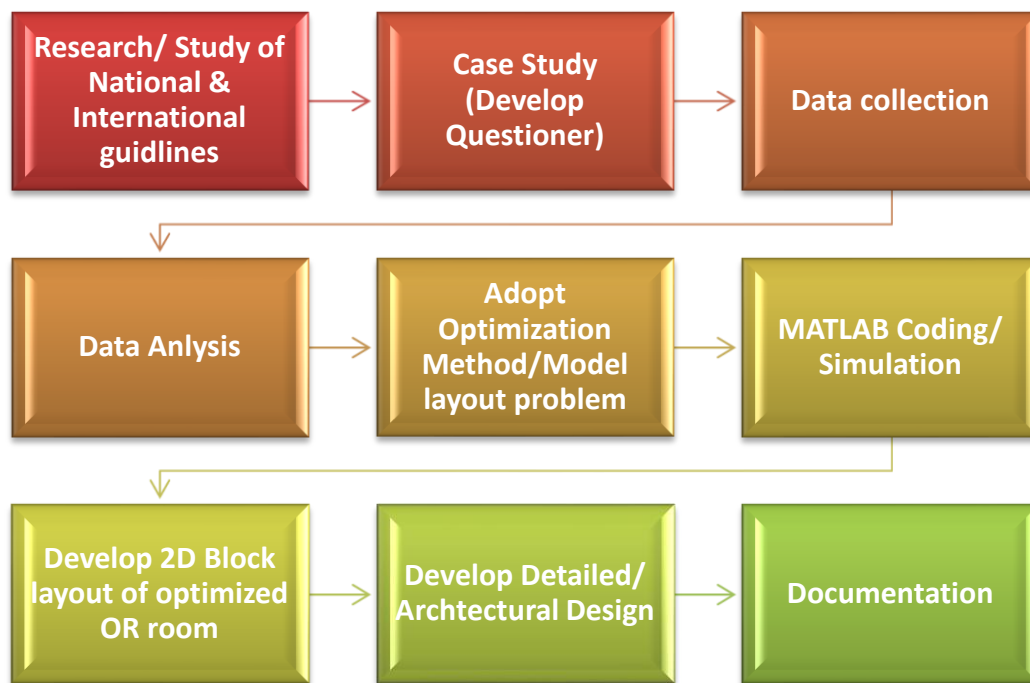


Figure 4: Methodology.

3.1 Ethical Considerations

The Center of Biomedical Engineering of the Addis Ababa Institute of Technology (AAiT), Addis Ababa University (AAU) approved that there are no ethical boundaries surpassed with this research. Further ethical clearance was acquired from the Addis Ababa Public Health Research and Emergency Management directorate (AAPHREM).

3.2 Data Collection Techniques and Procedures

Data for case study were collected mainly through questionnaires. Filling of questioners was self-administered unless help from the investigator is required. While on hospital visits data were collected through physical observation of the respective ORs, interview of the OR heads and staff which had difficulty filling out the questioner. The interview was filled on the questionnaires.

Besides the case study, study and review of the different national and international standards available in Ethiopia and worldwide was done. In order to develop an appropriate technique, research was done on current FLD optimization techniques as well as other methodologies used to solve facility layout problems. Selected materials such as books, articles, other publications and international standards and guidelines for this research were acquired from the internet. National standards were acquired from 5kilo AAiT campus library and national guidelines were acquired from Ethiopian food, medicine and health care administration and control authority (FMHACA), the now Ethiopian Food and Drug Administration (EFDA). Data from the internet search were more focused on hospital design with high emphasis on OR facility layout design. In each step, proper documentation was done.

3.3 Data Collection Quality Assurance

Some of the questions in the questioners were taken from previous similar research in the field. One of which is “Facility Questionnaire”, National Hospital Care Survey sponsored by Center for Disease Control and Prevention. The other questions were added in accordance with the need of the research and have been commented on by at least a member of the Health Care Facility Inspection team of the FMHACA.

3.4 Data Analysis

After collection of the questioners, the survey report was stored and analyzed on Google Forms. For this research the survey was done with actual questioner papers and filled questionnaires were manually inserted in the created Google Forms. The information is then collected and automatically presented in a graph, pie and bar charts. The quantitative data was used as the main input for the main objective of this thesis: optimization of OR FLD. The open ended questions were qualitatively analyzed.

3.5 Questionnaire Description

The questionnaire has a total of fifteen questions. There are two short answer questions, three multiple choice (one of which has a descriptive sub-question depending on the choice made), two yes/no questions (one of which has a descriptive sub-question depending on the yes or no reply), seven descriptive questions and one likert scale question. The likert scale question was the basic data used for optimization of the OR layout. The questionnaire came to an end with questions of respondents’ position in the organization, their signature and the date.

As described above, the method used in this research was a mixed method where the research data type was both qualitative and quantitative. The qualitative data collected by the questionnaire was to recognize the perspective and awareness of the professional (surgeons, anesthesiologists, nurse anesthetists, surgical technicians, registered nurses, biomedical professionals, etc...) regarding the OR facility layout. Also it is used to collect background information about their respective organization and OR department. Further, it intends to make analysis on the setup of the FLD of the ORs and the type of operation/surgery that is usually done. The survey also aimed to identify the need of the professionals with respect to their OR's layout design so that quality health care service is provided.

The quantitative part of the questionnaire was aimed to acquire knowledge about general flow of the staff in and out of the OR. This data was used as a basis to model the adjacency matrix which indicated interaction between two organizational units/rooms.

3.5.1 Content of Questionnaire

The first three questions are basic introductory questions aimed to identify the name and type of hospital/organization and the profession of the respondent. They were not numbered. To have a broader set of choices, four types of hospitals were picked: Public enterprise, Private hospital, Governmental hospital and Governmental health office.

- Public enterprise: an institute in the health sector which is publicly owned.
- Private Hospital: a privately owned hospital.
- Governmental Hospital: a hospital owned by the government.
- Governmental health office: a health office owned by the government.

Question number one and two ask the type/s of OR available in the hospital and the most usually practiced surgery type/s with its annual frequency, respectively. The purpose of these questions was to identify the types of ORs in the hospital. This is necessary to know for the design phase of an OR. The frequency can tell the necessity of the type of OR and to proximate the frequently used one from those rarely used.

Question number three asks the availability of certain technologies used in their OR facilities. The purpose of this question was to identify how many of the stated technologies are being used in their OR facility. The fourth question is a yes/no question which asks the availability of professionals/expertise responsible for their facility layout design. This question was used

to assess the availability of such professionals in their hospital and also gain the awareness of the staff member about it.

The fifth question straight on tries to identify if the professional has experienced any impact on patient care based on their current OR facility layout and to state the kind specifically. This question tries to directly pinpoint effects on patient care caused by facility layout design.

Question number six asks the professionals to evaluate their OR facility layout for quality patient care provision. There are three options for evaluation: It is effective and good as is, it is not effective and it is effective but need improvement. There are sub-questions that ask suggestions for improvement and the respondents' idea of what is important for their OR to deliver quality patient health care service.

Question number seven of the questionnaire was setup to give quantitative data as the major entity to the main objective of this thesis. It is a likert scale question that lists all mandatory rooms in an OR department according to the Ethiopian standard. And asks which of these rooms within the OR, respondents frequently visit from the OT. There are ranks from 1 to 5, which are described as follows;

- 1= not at all,
- 2= once or twice per day,
- 3= 3 to 4 times per day,
- 4= 5 to 8 times per day,
- 5= More often

The eighth question asks about the four parameters which are adjusted in order to control infection in the OT and increase quality of health care provision. Two of which should be more familiar to the professional than the other "Positive air" and "Temperature". The other two are "room size" and "patient and physician side lane". The aim of this question was to assess the knowledge of the professional with respect to these matters.

The ninth question asks how restricted and semi-restricted areas are differentiated in their OR. The expectation was for the professional to write their practices.

The tenth question asks the measures the professional use in order to have infection control in their OR.

The 11th and 12th questions ask the opinion/experience of the professional regards to maximize the infection control and minimize the turnaround time (the time starting from the patient entering the OR up to the time the patient leaves the OR) during surgery with regards to the OR facility layout.

3.6 Sampling

3.6.1 Sampling Strategy

The hospitals under study were general and specialized hospitals and health centers from both governmental and private sections. These sampled hospitals selection was based on whether or not they have an OR. Hospitals with OR were randomly selected for this research data collection.

3.6.2 Sampling Technique and Procedure

Currently, there are 29 private and governmental hospitals in Addis Ababa registered under the ministry of health. About 30% of these hospitals were included in the study, which made eight hospitals in total. 30% sample size is taken, as this is the size the health care facility inspection team of the FMOH used in their studies. To make the study inclusive of all hospitals, the selection of hospitals was done in such a way that four of the eight hospitals were governmental and the other four were private. The governmental hospitals were “Black Lion Hospital”, “Minilik II Hospital”, “Armed Forces Hospital (TorHiloch Hospital)” and “Saint Paul Hospital (Paulus Hospital)”. The private hospitals were “Myungsung Christian Medical Center (Korean Hospital)”, “Addis Hiwot Plc”, “Betezata General Hospital” and “Hayat Hospital”

The questionnaires were given out to and collected by the hospital’s head of biomedical department and/or OR department. Considering the work schedule of the professional that fills the questioner, answering of half of the questions in the questionnaire were considered complete. Name of the participant was not mandatory.

Survey was conducted in person. Participants were given two weeks to respond.

3.6.3 Sample Size

Sample size was based on estimation since data of staff of the hospitals could not be acquired due to confidentiality. Estimation of governmental hospital OR staff was 30 per hospital and for private was 15 per hospital. That made a total 180 respondents expected. Amount of respondents were 119, which was 33% off from the estimation.

It was not obligatory for the participants to fill out all the questions because it is voluntary. Unfortunately, due to their working hours and busy schedules it was not possible to get all the OR staff members of the respective hospitals to participate. Nevertheless, the questionnaires that were filled were satisfactory to the purpose of this study.

3.7 Graph Theory

Graph Theory is a branch of mathematics concerned with networks of points connected by lines [35].

3.7.1 Definitions

Graph: A graph is an ordered pair $G = (V, E)$ consisting of a nonempty set V (Vertices) and a set E (Edges) of two element subsets of V [36]. Vertices (V) are collection of dots and edges (E) are lines connecting those dots (see also Figure 5).

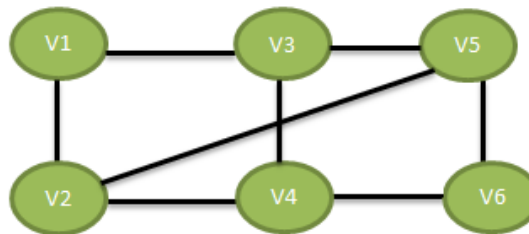


Figure 5: Undirected graph with 6 vertices and 8 edges.

Adjacency: When two vertices are connected by an edge, it is said they are adjacent.

Example: In Figure 5 above vertices $V1$ and $V2$ are adjacent, vertices $V2$ and $V3$ are not adjacent

Connected-Graph: A graph is said to be connected when there is a walk between every pair of vertices.

Walk: A walk is an alternating sequence of vertices & edges

$$W = v_0 e_1 v_1 \dots e_n v_n$$

$$\text{s.t. } j = 1: n, e_j = [v_{j-1}, v_j]$$

Simple Graph: A simple graph is a graph that has no self-loops or multi-edges.

Complete Graph: A graph is a complete graph if every pair of vertices is joined by an edge.

Planar Graph: When a connected graph can be drawn without any edges crossing, it is called planar [36]. A planar graph is called **maximally planar graph** if and only if the characteristic of planarity gets lost when adding a further edge [26]. Figure 6 depicts a planer graph with 9 nodes and 15 edges.

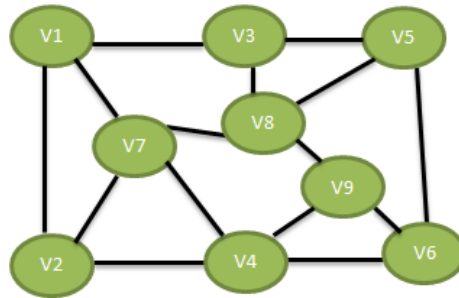


Figure 6: Planer graph with 9 nodes and 15 edges.

Facet (γ)/ Face: It is a subdivision of depicted graph plane.

- **Inner facet/Inner Face:** It is an area in the plane bounded by nodes & edges. Where the bounding nodes and edges form an elementary circle consisting only of different nodes and edges, pairwise interaction of two facets is empty and no subset of facet features the previous two characteristics [26].
- **Outer facet/Outer Face:** It is the area in the plane which is not covered by inner facet [26].

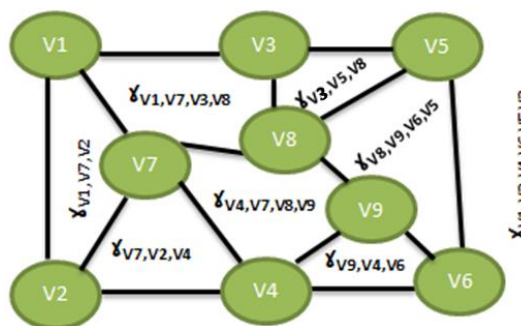


Figure 7: Inner and outer faces.

Dual Graph: The dual graph of a planer graph G is a graph that has a vertex for each face of G and has an edge whenever two faces of G are separated from each other by an edge and a self-loop when the same face appears on both sides of an edge. [26]

3.7.2 Basis for Application

As the main input, an interaction/adjacency matrix is required. In this regard, adjacency matrix obtained from quantitative data of questionnaires that describes the flow of the professionals in an OR and area distinction requirement from standards was used. Each entry of the matrix represents the number of interactions between two facilities. The principle followed in this research was; the higher the interaction weight between two facilities the higher the importance of their direct adjacency.

3.7.3 Objective

The objective is to **maximize the sum of the interaction weights** of the facilities that are adjacent in the resulting layout plan. This provides a layout in which the movement of staff is minimized leading to **maximization of infection control**.

3.7.4 Input Data

Flow matrix (the interaction between two facilities/rooms): The flow matrix was built out from the questionnaires and literature review done on department area-distinction.

- For interaction between the OT and other rooms weighing: the last column of data (result of most traveled) was taken from question number seven of the questionnaire. This data was binned using Matlab for further analysis. Binning is a process of taking continuous data and converting it to categorical.
- For other organizational unit interaction: weighing was done with respect to the case study data and operating department area-distinction relation from national and international standards and guidelines.

With the combination of both inputs, total weighed interaction matrix/adjacency matrix was developed on Excel sheet.

3.7.5 Idea of Approach

Two main steps are followed in GTA for layout planning. In the first step graph is constructed and then its planer graph version is driven. Planarity is required in order to derive a layout from the graph. In the second step dual graph is driven from the planar graph version. After construction of the dual graph, it is possible to extract a block layout from it. As a final output, 2D block layout design is obtained.

A Matlab code is generated to execute the first two steps. The technique used to develop a planar graph is the “Tetrahedron procedure”, which has proven to provide high quality output.

3.7.5.1 Graph construction

The nodes of the graph are the rooms in the OR and the edges are the interaction in between these rooms. By importing the adjacency matrix on the Excel sheet as input, the graph was constructed on Matlab.

3.7.5.2 Driving the planer Graph

Objective: To find planer graph in which the sum of edges weights, which represent the corresponding entries of the interaction matrix is maximized.

Output: Maximally planer weighted graphs (MPWG)/deltahedron

Using the techniques on construction of planar graph, a Matlab code was generated. This technique is briefed below with an example. The Matlab code generated to construct a planar graph from the initially constructed graph is presented in the appendix section.

Theorem: If a graph is a MPWG/deltahedron with n nodes & m edges then

$$m = 3n - 6$$

From this upper bound of sum of edge weights can be derived.

Given: Interaction matrix $A = (a_{ij})$, a simple, complete & undirected graph

$G = [V, E, A]$, with nodes $v \in V$, edge $e \in E$ weighted with the values in A.

Required: A maximally planer sub graph $G' = [V, E', A]$ of G with, $E' \subset E$ which has the highest sum of edge weights.

The upper bound of sum of edge weights (optimum value) can be calculated using the method below.

Decision variable: $x_{ij} = \begin{cases} 1, & \text{if edge } [i, j] \in E' \forall i, j \text{ with } i < j \\ 0, & \text{otherwise} \end{cases}$

Model

$$\text{Max } \sum_{i=1}^n \sum_{j=1}^n A_{ij} x_{ij}$$

subjected to $G' = [V, E', A]$ is a maximal planar graph

$$x_{ij} \in \{0, 1\} \forall i, j \text{ with } i < j$$

Since the problem is NP-hard, large instances cannot be solved to optimality so heuristic procedure such as the Tetrahedron procedure is developed to construct a maximally planar graph.

Solution: Tetrahedron procedure to construct a maximally planar graph

Step 1: Prerequisite

- Calculate the row sums of the interaction matrix.
- Sort them according to monotonically decreasing values.

Step 2: Initialization

- Choose four nodes with the highest row sums.
- Build an initial delthedron (in order to construct the initial deltahedron, one node has to be put in the center).

Step 3: Iteration

- Integrate the remaining nodes into the deltahedron in the order of decreasing row sums.
- Always connect the new node with the 3 existing nodes of the triangle where the objective function value is increased the most (thus, the new node is connected with the nodes of that triangle with which it has most interactions).
- Draw resulting graph.
- Iterate until all nodes are used.

If all nodes are inserted, the objective function value can be calculated by summing up the edge weights.

Example (Tetrahedron procedure to construct a maximally planar graph):

Given a simple complete graph below with six nodes and 15 weighted edges with interaction matrix A shown in Figure 8 and Table 3 below.

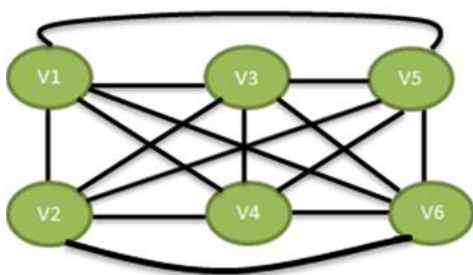


Figure 8: Simple complete graph.

A _{ij}	V1	V2	V3	V4	V5	V6
V1	-	5	3	1	4	9
V2	5	-	7	5	3	6
V3	3	7	-	10	8	2
V4	1	5	10	-	4	3
V5	4	3	8	4	-	1
V6	9	6	2	3	1	-

Table 3: Interaction matrix.

Required: maximally planar graph using tetrahedron procedure.

Solution:

Step 1: Prerequisite

- Calculating the row sums of the interaction matrix, Row sum a_i and sorting according to monotonically decreasing values as shown in Table 4.

Nodes	A_{ij}						a_i	Sorted Nodes	a_i
V1	-	5	V3	30	4	9	22	V3	30
V2	5	-	V2	26	3	6	26	V2	26
V3	3	7	V4	23	8	2	30	V4	23
V4	1	5	V1	22	4	3	23	V1	22
V5	4	3	V6	21	-	1	20	V6	21
V6	9	6	V5	20	1	-	21	V5	20

Table 4: Sorted row sum, example.

Step 2: Initialization

- Nodes with the highest row sums: Nodes $V' = \{1, 2, 3, 4\}$ have the highest row sums with values 30, 26, 23 and 22 respectively.
- Building an initial delthedron: Edges $E' = \{ [2,4], [2,1], [4,1] [3,4], [3,1], [3,2] \}$ as also seen on Figure 9.
- Faces/ Facet: $\{ \mathfrak{r}_{234}, \mathfrak{r}_{134}, \mathfrak{r}_{124} \}$
- Objective function value: $Z = 5 + 5 + 1+10 + 3 + 7 = 31$

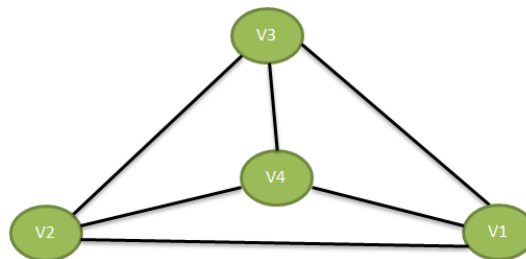


Figure 9: Example initial delthedron (resulting graph).

Step 3: Iteration

- Integrate remaining nodes, node 6 and 5 to the delthedron respectively.

1st iteration

- Node V6 is integrated first because it has higher node sum with value of 21.
- Choose interaction face in which the objective function is increased (see also Table 5).

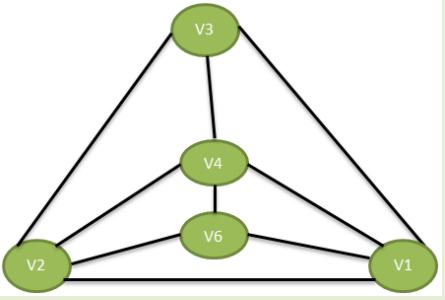
List of possible faces	Objective function value (with integrated node 6)	Resulting graph after integration of node 6
γ_{234}	$6 + 2 + 3 = 11$	
γ_{134}	$9 + 2 + 4 = 15$	
γ_{124}	$9 + 6 + 3 = 18$	
γ_{123}	$9 + 6 + 2 = 17$	
Highest value= 18 on face γ_{124}		

Table 5: Example 1st iteration.

2nd iteration

- Node V5 is integrated, as this is the last node of the initial graph, this is the final iteration.
- Choose interaction face in which the objective function is increased (see also Table 6)

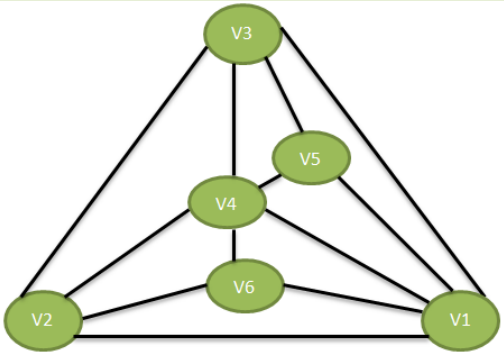
List of possible faces	Objective function value (with integrated node 5)	Resulting graph after integration of node 5
γ_{234}	$3 + 8 + 4 = 15$	
γ_{246}	$3 + 4 + 1 = 8$	
γ_{126}	$4 + 3 + 1 = 8$	
γ_{146}	$4 + 4 + 1 = 9$	
γ_{134}	$4 + 8 + 4 = 16$	
γ_{123}	$4 + 3 + 8 = 15$	
Highest value= 16 on face γ_{134}		

Table 6: Example 2nd iteration.

The resulting graph shown in Table 6 above is the final planar graph. Since all nodes are inserted the objective function value (Z) can be calculated.

Edges $E' = \{[2,1], [2,6], [2,4], [2,3], [1,3], [1,5], [1,4], [1,6], [3,5], [3,4], [4,5], [4,6]\}$

Upper bound on edge can be derived from the formula,
 $m = 3n - 6 \rightarrow m = 3 * 6 - 6 \rightarrow m = 12$, proves the graph is a MPWG/ deltahedron

$$Z = 5 + 6 + 5 + 7 + 3 + 4 + 1 + 9 + 8 + 10 + 4 + 3 = 65$$

3.7.5.3 Driving the Dual Graph

A Matlab code that create dual graph of a given planar graph is generated. Below is the technique of construction of dual graph from a planar graph.

Given: Simple, connected, undirected & planar graph.

Required: Dual graph.

Solution:

- i. Integrate additional node into the maximally planar graph (node represents the environment of the new building).
- ii. Connect node to all the nodes that formerly established the outer facet of the maximally planar graph. This node lies outside the dual graph.
- iii. Include exactly 1 node for each facet/face of the maximally planar graph (primal graph).
- iv. Include exactly one edge for each edge in the primal graph that separates two facets/faces. Connect two nodes in step 3 with the edge.

Example: Driving a dual graph given the planar graph in the figure shown in Table 6.

Steps 1 & 2: Integrate node V7 for the environment and connect it to the outer face nodes.

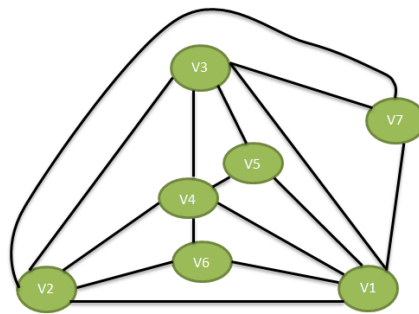


Figure 10: Step 1 & 2 dual graph formations.

Step 3: Include 1 node for each face (see Figure 11).

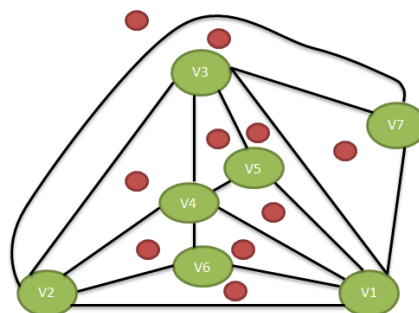


Figure 11: Step 3 dual graph formation.

Step 4: Connect included nodes with an edge passing the primal graph edge exactly once (see Figure 12).

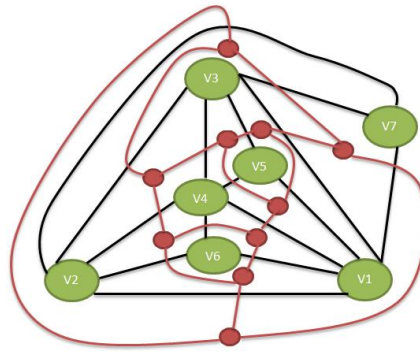


Figure 12: Step 4 dual graph formation.

By removing all of the primal graph edges and the additional node, the dual graph can be captured, as also seen on Figure 13.

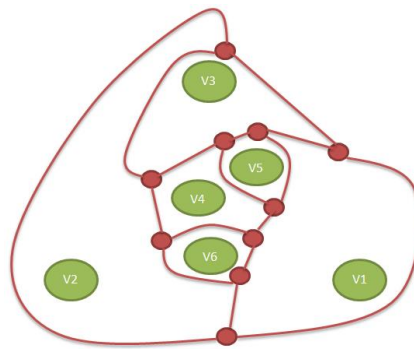


Figure 13: Formed dual graph.

3.7.6 Derive 2D Block Layout

Two dimensional block layout can be obtained from a dual graph. This is done manually: an artistic touch was required to develop an output. For example the 2D block layout for the dual graph shown in Figure 13 above can be visualized as shown in Figure 14 below.

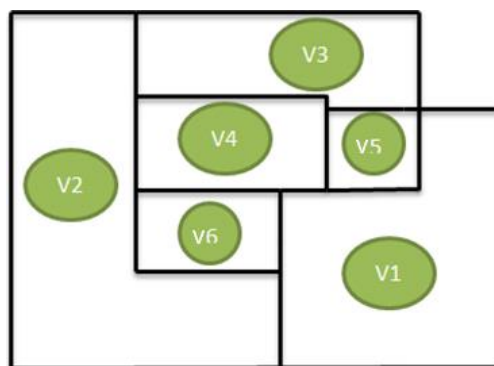


Figure 14: 2D block layout.

3.7.7 Derive the Detailed Layout (Architectural Design)

Due to the complex nature of the design, it is preferable to have interdisciplinary consultation. The 2D block layout formed from the dual graph was taken as a bubble

diagram/concept design. This was used as an input to construct a practical detailed layout with area restrictions. The detailed layout design is designed with consultations of an architect. In this layout, minimum area restriction from Ethiopian standards is used. The width for general access corridors was taken as 1.5m and patient transfer corridors were taken as 2.25m wide based on Neuferts Architects' Data [37] and MSF [12] guidelines.

Health Building Note (HBN) [38] standard suggest that for better visualization of tissue in OT, for healing progress and patient care and to keep staff energy and efficiency up, rooms such as the OT, RF and DR/staff rest room respectively have windows for natural light access. However, for some OTs as “laser surgery OT”, there might be a requirement of dark room. For this case, OTs in this detail designs are both designed with and without natural light access.

Architectural design depends on size, form, orientation, topography, and accessibility of the building plot area. The final outcome of these layouts is done considering building plots without limitation of these elements. Due to space limitations, consideration is made to design the layout with as minimum area usage as possible, but still keeping the integrity of the optimum block layout design. Buildings with these limitations or requirements can follow similar spatial arrangements by selecting different means of connection. Spaces can be connected through direct doors, wicket, walls, corridors, stairs, and elevators.

3.7.8 Construction of Detailed Layout for General and Specialized Hospitals

Similar to the detailed layout for a surgical center premise set-up with minimum requirement design, for general and specialized hospital too, it is constructed according to Ethiopian standards. In both cases, the number of OTs and scrub area is increased respectively. For a general hospital, there are four OTs required with a minimum of two scrub areas. For a specialized hospital, there are seven OTs required and a minimum of four scrub areas. Minimum requirement of scrub area is as such that one scrub area can be used by two OTs.

Chapter 4

Results and Discussion

This chapter has two sections. The first section (section 4.1) presents the findings from the questionnaire response. The second section (section 4.2) presents the process and final output of the optimization problem for OR FLD.

4.1 Questionnaire Responses and Analysis

4.1.1 Demographic Information

4.1.1.1 Name of Hospital/ Organization

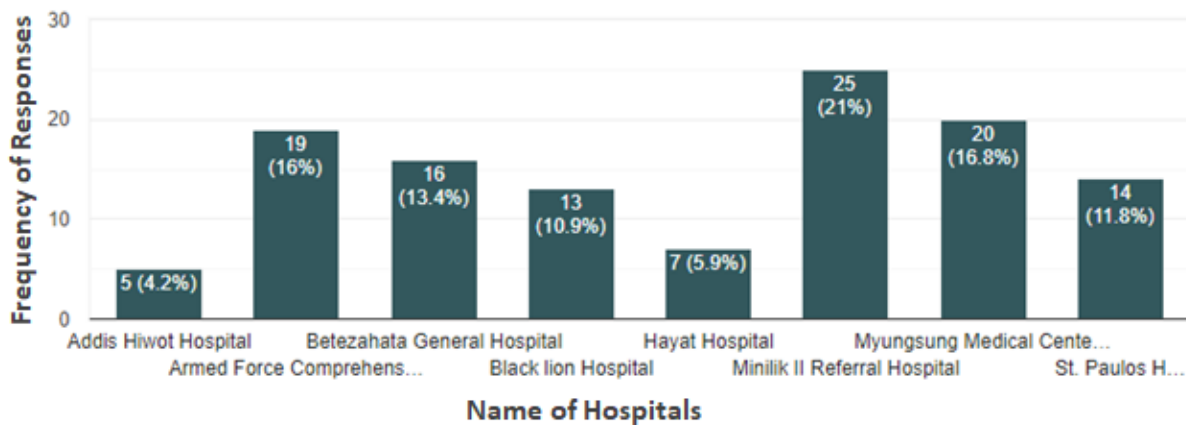


Figure 15: Name of Hospitals Chart.

The chart shown in Figure 15 above shows the eight hospitals involved in this survey with the amount of responses collected. From all eight hospitals, a total of 119 responses were collected.

4.1.1.2 Types of Hospitals

All 119 respondents responded to this question. They were asked to specify the type of hospital they worked and accordingly 71 (59.7%) of the respondents answered governmental, 46 (38.7%) answered private and 2 (1.7%) answered public enterprise as also indicated in the pie chart shown in Figure 16.

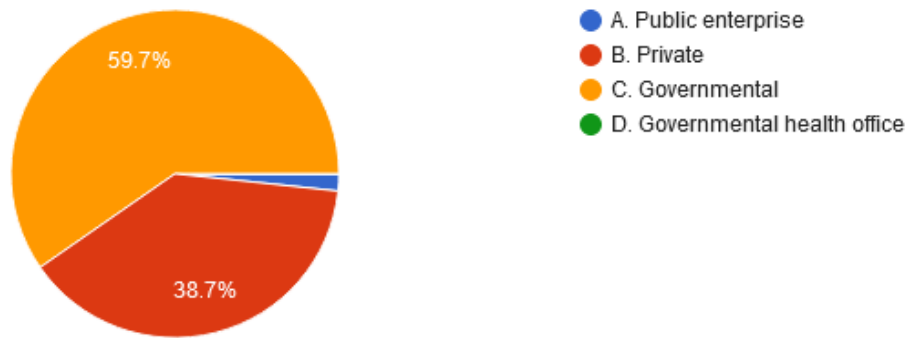


Figure 16: Types of Hospital.

From the responses of the “Name of Hospital” question above, it can be seen that 48 (40.3%) were from private hospitals and the rest 71 (59.7%) are from governmental hospitals. Comparing between the estimated numbers of responses to the actual number of responses collected, for governmental hospitals 60 % of the estimate was reached while for private hospital it was 80%.

4.1.1.3 Professional Position in the Organization

For this question, 94 responses were collected while the rest 25 responders left this question blank. 50% of the respondents were different specialty nurses. The variety of respondents’ position/profession can clearly be seen in the pie chart shown in the Figure 17 below.

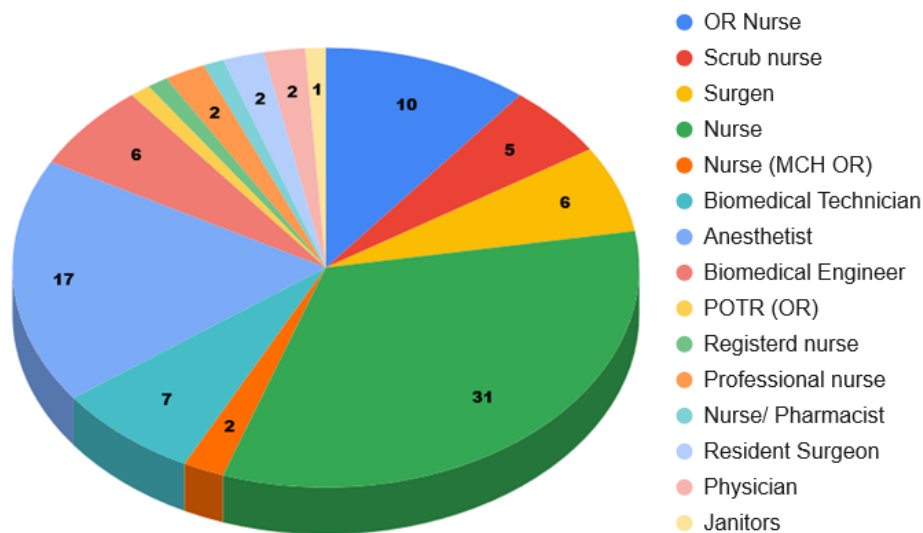


Figure 17: Position in the Hospital.

4.1.2 General Information

4.1.2.1 Types of Operation Rooms

Results show that most ORs are General ORs followed by Gynecological, Urology, Orthopedic and Spine. Nearly half of the respondents included that their hospitals also have Cardiac and Thoracic ORs. Other types of ORs have been raised by only few of the respondents.

4.1.2.2 Types of Surgeries

Types of surgery practice are correlated to the type of OR. The data analyzed show that the most frequent type of surgery done is caesarean section (CS) followed by other types of general surgery. Results also show that in some occasions surgeons come from abroad and do different types of surgeries. It was generally difficult for respondents to state the frequency of the surgeries they practice annually. This shows that there is less focus in documentation and follow up in the hospitals.

4.1.3 Technological Safety

4.1.3.1 HVAC system

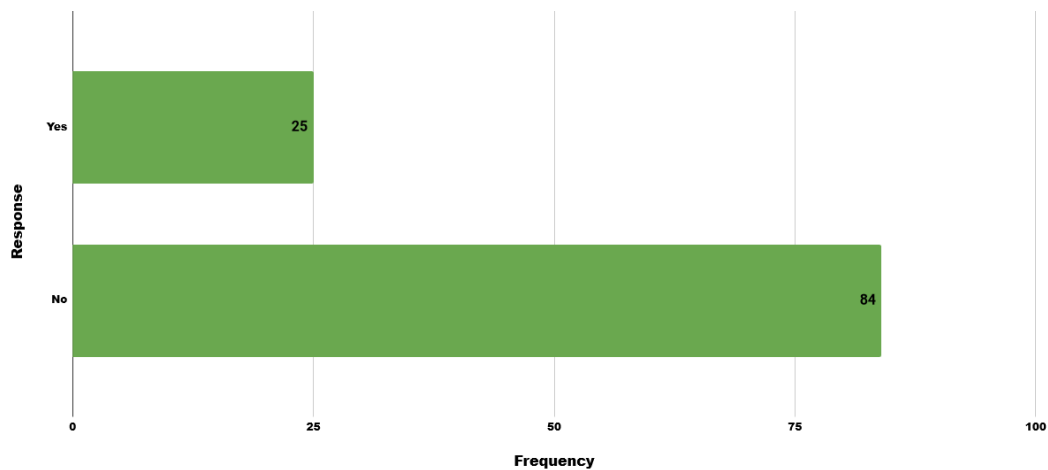


Figure 18: Availability of HVAC system.

A total of 109 responses were collected to the question whether the hospitals have a HVAC (heating ventilation and air conditioning) system in place or not. 25 (22.9%) replied “Yes” and 84 (77.1%) replied with “No”. The analysis shows most of the hospitals don’t have HVAC system see Figure 18.

4.1.3.2 Central gas supply pipeline

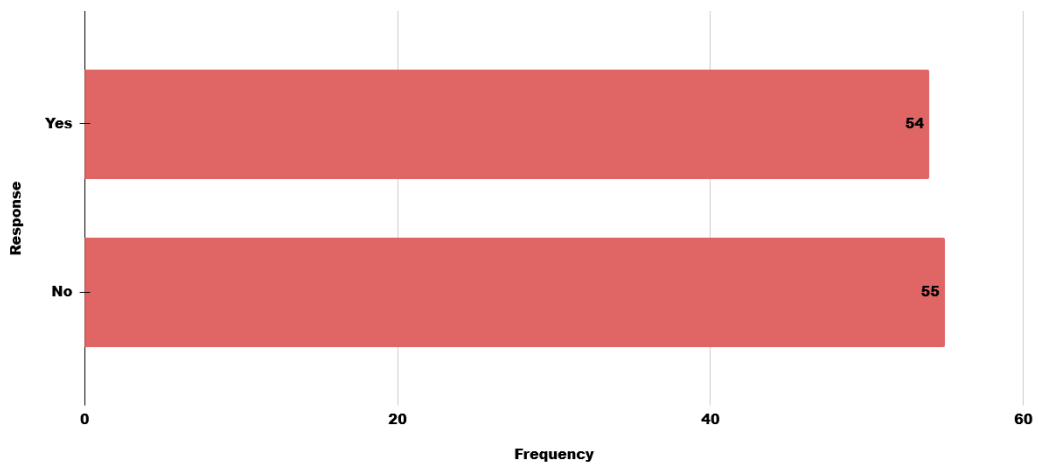


Figure 19: Availability of Central gas supply system.

A total of 109 responses were collected in this regard. 54 (49.5%) replied “Yes” and 55 (50.5%) replied with “No”. The analysis shows the availability of a central gas supply pipeline system is half and half. Although, during a physical observation, it was noted that in two of the hospitals the available system was not functional (see Figure 19).

4.1.3.3 General light

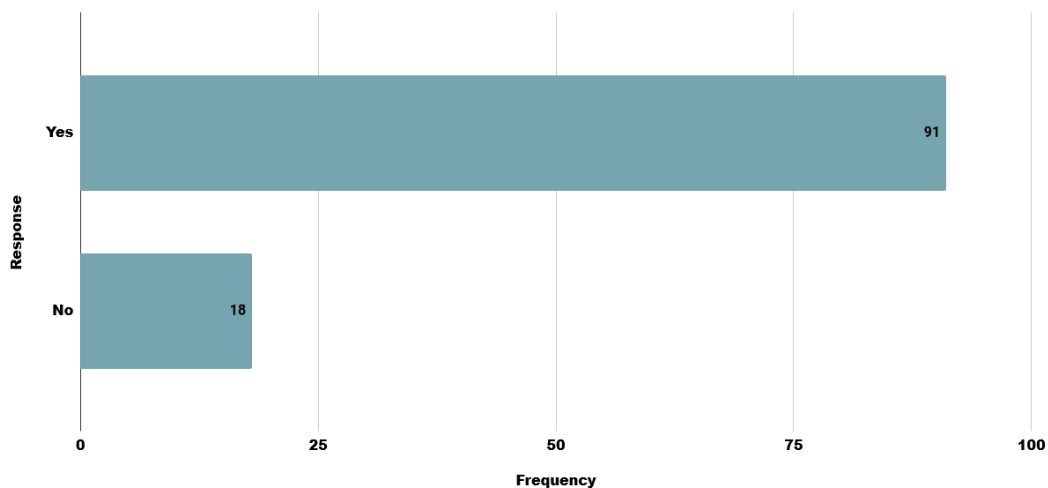


Figure 20: Availability of General lighting.

Again a total of 109 responses were collected: 91 (83.5%) replied “Yes” and 18 (16.5%) replied with “No”. The analysis shows most of the hospitals have general lighting and a small group responses indicated the lack of general lighting system in their OR (see Figure 20).

4.1.3.4 Power supply (backup)

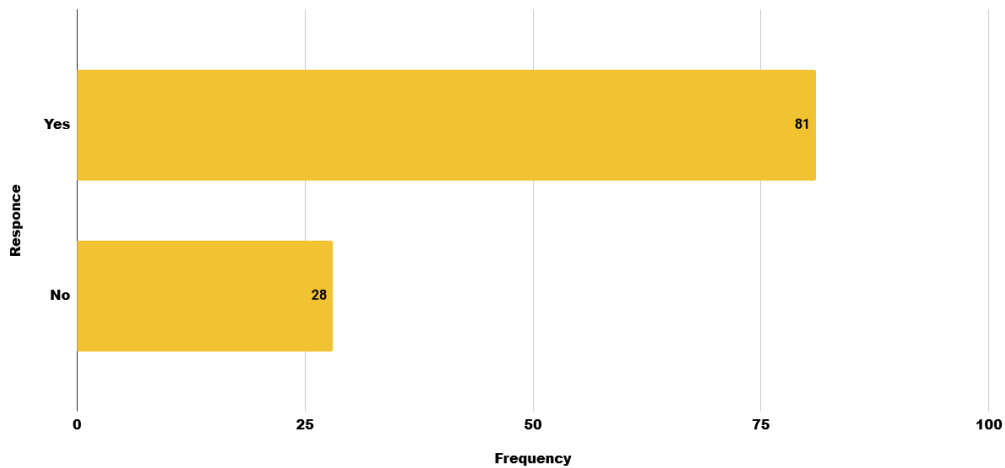


Figure 21: Availability of Backup Power Supply.

Out of a total of 109 responses collected, 81 (74.3%) replied “Yes” and 28 (25.7%) replied with “No”. The analysis shows most of the hospitals have backup power supply and a quarter of the hospitals do not have backup power supply in their OR (see Figure 21).

4.1.3.5 Power switching (away from operating area)

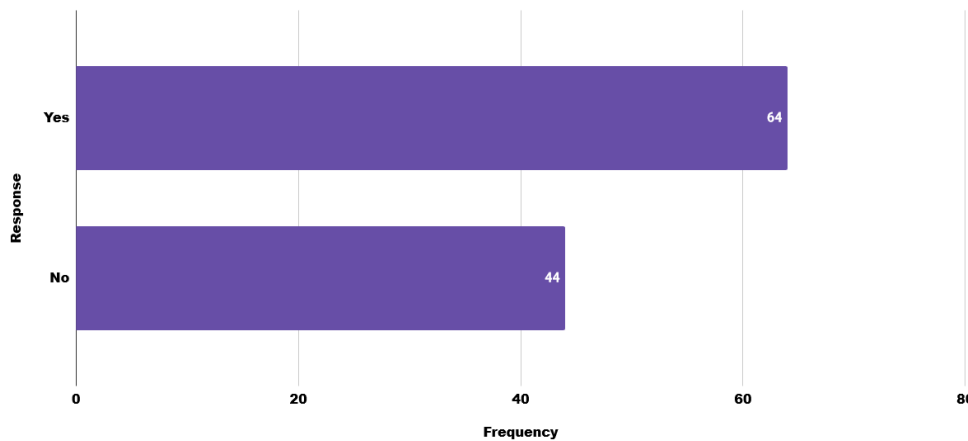


Figure 22: Availability of power switching (away from operating area).

A total of 108 responses were collected and 64 (59.3%) replied “Yes” and 44 (40.7%) replied with “No”. The analysis shows more than half of the professionals have a power switching (away from operating area) in their hospitals and less than half of the professionals’ do not have power switching (away from operating area) in their hospitals OR (see Figure 22).

4.1.3.6 Fire Safety

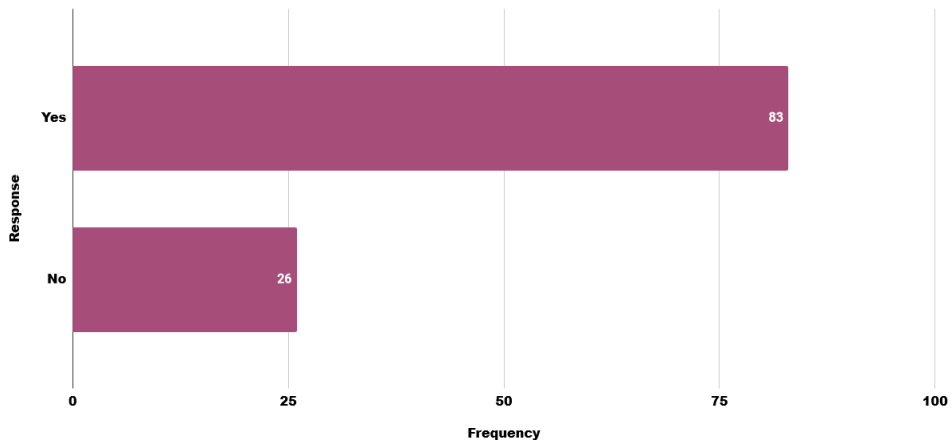


Figure 23: Availability of Fire Safety.

In total, 109 responses were collected and 83 (76.1%) replied “Yes” and 26 (23.9%) replied with “No”. The analysis shows most of the professionals have a fire safety system or tools in their hospitals and around a quarter of the professionals do not have fire safety tools or system in their hospitals OR (see Figure 23).

4.1.3.7 Operating light

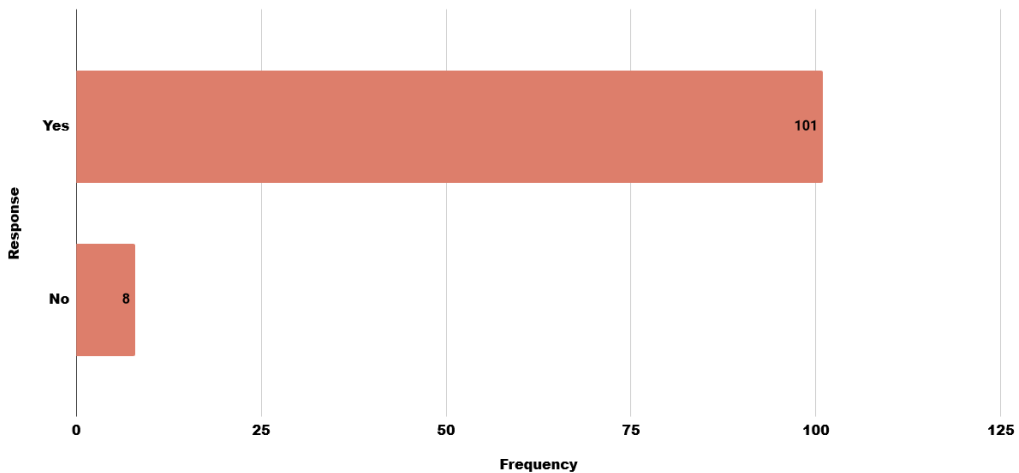


Figure 24: Availability of Operating light.

A total of 109 responses were collected in this case and 101 (92.7%) replied “Yes” and 8 (7.3%) replied with “No”. The analysis shows majority of the professionals have operating light in their OR and few of the professionals’ do not have operating light in their hospitals OR (see Figure 24).

4.1.3.8 Grounding/ Earthling

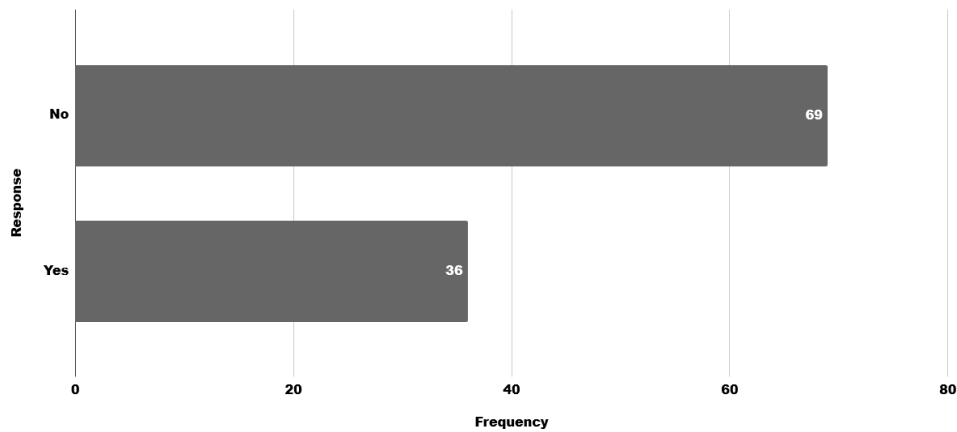


Figure 25: Availability of Grounding (earthling) system.

Out of a total of 105 responses collected, 69 (65.7%) replied “No” and 36 (34.3%) replied with “Yes”. The analysis shows more than half of the professionals do not have grounding in their hospitals and more than a quarter of the professionals have grounding in their hospitals OR (see Figure 25).

4.1.4 Current Facility Layout Design

4.1.4.1 Responsible professional/expertise

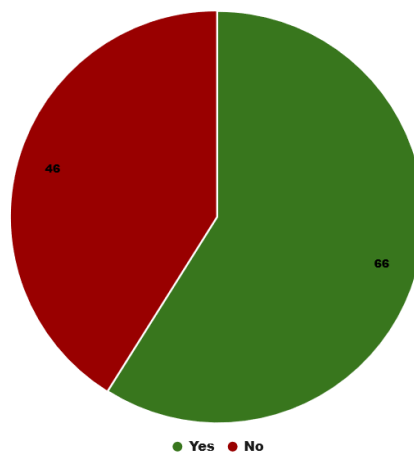


Figure 26: Availability of professional responsible for FLD.

When asked about the availability of a professionals/expertise responsible for their OR facility layout design, 66 (58.9%) of 112 respondents answered “Yes” and 46 (41.1%) answered “No”. This shows a positive sign towards the acceptance of the need of facility layout design for ORs (see Figure 26).

4.1.4.2 Impact on patient care

A total of 107 respondents replied when asked if they have come across any impact on patient care due to the facility layout of their OR and Figure 27 shows their responses.

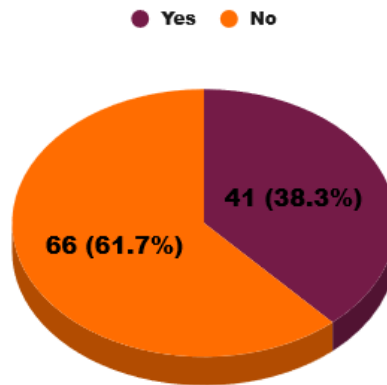


Figure 27: Impact on patient care.

Respondents that replied with a yes were asked to specify. Their responses were related not only to the facility layout impact on patient care but also impacts on patient care created by absence, misuse and shortage of medical supply, equipment and technology and with relation to members of the staff practices. Statements have been made about re-operation being common due to improper infection control, sterility breach and hospital acquired infections.

Listed below are some impacts raised due to the facility layout design:

- Cross contamination due to distance from Scrub area to OR;
- High temperature due to direct sunlight to OR;
- Inconvenience pathway for transporting patients;
- Insufficient room space;
- Similar pathway for transfer of waste and patients/visitors travel;
- Absence of proper changing area for both patients and professionals;
- Absence of rest rooms and nurse stations and
- Poor drainage system.

4.1.4.3 Evaluation for quality patient care provision

Professionals were asked to rate their current facility layout design for quality patient care provision with options: It is effective and good as is, it is not effective and it is effective but needs improvement. A total of 115 professionals responded to this question. Their response is provided in the pie chart given in Figure 28 below.

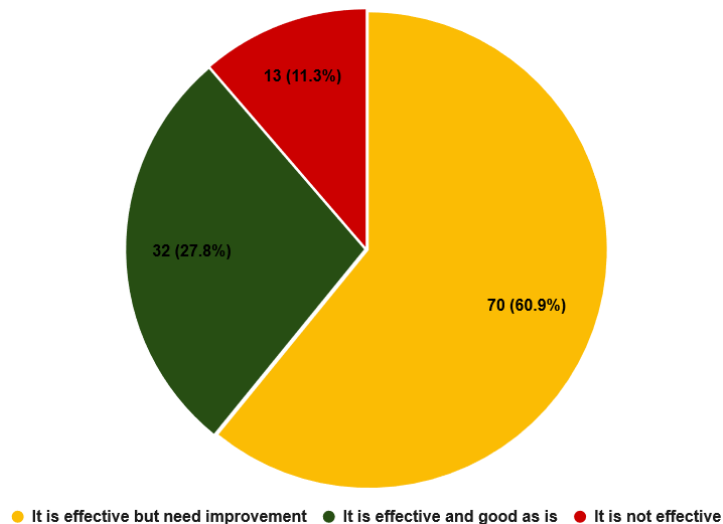


Figure 28: Facility layout effectiveness evaluation.

Professionals were asked for their suggestions for the improvement and 81 of them responded. Presented below are some of the suggestions:

- Re-design, improve/ upgrade the OR design;
- Integrate material cabinet together with the OR wall;
- Provide sufficient space;
- Consider environment, like sunlight in OR room design;
- Add quality service and functional infrastructures;
- Involve medical professionals while designing the layout;
- Design smooth and straight pathway for patient safety, and
- Separate rooms for OR and Recovery (PACU).

Professionals were asked to further elaborate what they think is important to deliver quality patient health care services in their OR. A total of 86 professionals replied to this question in relation to facility layout, equipment and professional practices. The responses in relation to facility layout are to follow national policies, to design wider room, design OR including all necessary rooms, improve recovery facility and to educate the staff about OR facility layout and technologies.

4.1.5 Staff Frequency of Travel

Given 12 rooms that an OR must incorporate, professionals were asked which of these rooms within the OR unit they frequently visit from the operation theatre. They rank it from 1 to 5 depending on their frequency of travel on daily bases. The summarized answers are provided in Table 7 below.

Frequency of travel From OT to OR rooms					
OR Rooms	1	2	3	4	5
Scrub area	14	16	26	19	34
Stuff change room	10	40	25	17	15
Clean utility room	19	34	16	19	17
Soiled utility room	33	31	21	7	7
Nurse station	24	20	21	15	23
Anesthesia store	49	20	12	12	13
OR equipment store	24	25	26	12	21
Sterile supply room	27	23	23	15	18
Doctor's office	41	29	9	11	14
Duty room	29	35	12	15	16
Janitor's closet	49	23	14	4	6
Toilet rooms	9	58	19	10	13

Table 7: Frequency of travel in OR.

4.1.6 Professional Opinion/Experience

4.1.6.1 For infection control and quality health care provision

This section was targeted to analyze the understanding of the OR staff professionals and the consideration they take on parameters that need to be controlled in an OR. The purpose of controlling these parameters is to control spread of infection and provide quality health care. Provided below are their responses per each subject.

4.1.6.1.1 Positive Air

A total of 70 professionals responded to this question and 13 professionals described only the advantages and importance of having positive air to reduce infection and gas pollution in the OT although one professional argues that it is not good for operation. Few suggested installation of a HVAC or AC system and it should be according to the WHO standard. 6 professionals shared their knowhow on the work process involved in achieving positive air. 3 professionals shared practices that should be implemented to maintain positive air in OT such as; close windows, avoid crowding and monitor patient flow. 1 suggested work to be done on FLD to aid staff in proper usage.

Others replied that they don't know about it, some just replied "yes", "good", "Adequate", "No", "Avoid air", "Should be important", "It doesn't exist", "Should be install" and

“Environment air”. Most professionals argue that they don’t have a system of controlling the air pressure in their OR and suggested its availability.

4.1.6.1.2 Temperature

A total of 82 professionals responded to this question. Most responders stated their opinion on the parameter of temperature in the OT. The stated parameters were: “18⁰C”, “20⁰C”, “24⁰C”, “25⁰C”, “26⁰C”, “37⁰C”, “18-26⁰C”, “20-25⁰C”, “21-24⁰C”, “27-33⁰C”, “35-37⁰C”, “Not more than 39⁰C” and normal room temperature. Others state that the adjustment of temperature in OR depends on: the need of surgeons and health professionals’ preference, the type of surgery and according to standard.

Few stated that there should be AC and temperature monitoring system in the OR but that it is not available in their OR. 1 said that this is cause for downtime in noon day time in their OR. 2 related this question to infant warmer, water heater, and electrical blanket. Others have replied as follows: “yes”, “I don’t know”, “I have no idea”, “No”, “Temperature control system”, “Cold”, “Optimum”, “maintain T 0C”, “Good temperature control system”, “There is no indicator” “not known”, “Good if possible”, “the normal temperature for health service is used”, “AC”, “It can't be control”, “Good”, “cold area”, “No temperature” and “Not have indicator”.

4.1.6.1.3 Room Size

A total of 82 responses were collected on this subject. Most respondents argued that it is related to ventilation and is important factor to avoid cross contamination, prevention of infection in an OR and effectiveness of professionals working inside the OR. The stated statements are that it should be: “according to WHO standard”, “comfortable for traffic flow”, “adequate to accommodate staff, patient and equipment”, “roof height must be able to allow OR light to be far from OR table”, “square shaped”, “is good as is” and “some rooms are small”. Some stated the parameter OR room size should be: “5m by 5m (25m²)”, “8*8(8*10) m²”, “400-600 foot”, “400 m²”, “4*5 m”, “4*4”, “18*30 in(ft.)”, “10*10 cm”, “10 by 10 m”, “5*6”, “600 m²”, “5/6 or 5/7” and “4 * 6”.

The suggested practices are: “avoid unused materials from the room”, “well organization” and “close rooms and avoid frequently use of the corridor”. 1 said that “The room size is enough but number of population is high”. Others have replied as follows: “I don't Know”, “Good”, “Adequate”, “I have no idea”, “good size”, “Ok”, “I haven't idea about size”, “Good size”, “It is null designed”, “Ophthalmic OR need improvement”, “Must be

bigger/large”, “Fair”, “Adequate air ventilation room”, “to narrow”, “Is good as it is”, and “Appropriate size”.

4.1.6.1.4 Patient and physician side lane

A total of 45 responses were collected for this subject. Some of the responses are that it should be: “According to WHO standard”, “different and free traffic”, “marked and separated”, “equipped or designed in a way to prevent infection and contamination”, “one way/ different entry and exit” and “3 ft. space between physician/OR staff and patient”. Few expressed the importance of separation of patient and physician side lane for infection control.

Others have replied as follows: “Good if available/possible”, “Yes”, “Adequate”, “Good”, “Normal passageway”, “It must be wide”, “Optimal”, “Wide as much as possible”, “Enough place to talk each other”, “I don't know about this”, “no/ non”, “rail on walls (barrier plastic)” and “It is okay”.

The responses of most of the professionals for this section show that they are not well informed about these subject matters even if they know their importance if implemented. Some have raised issues with many professionals gathering in the OT when surgery is conducted, this problem was also observed during the physical visits. This does not only limit the size of the room but also increase spread of infection and the temperature in the room.

4.1.6.2 OR area distinction

Professionals were asked how they differentiate between restricted and semi-restricted areas in their OR. A total of 108 responses were collected for this question. Below are the collected answers.

Responses with respect to restricted area are as follows: “is sterile area where the operation is held and where health practitioners who changed cloth stay at (the surgeon, scrub nurse assistant)”, “is totally restricted area”, “include OR rooms, work room and physician scrub”, “strict zone where traffic should be limited”, “limited access without responsible person and surgical attires”, “access for only sterile person and material” and “A designated space contained within the semi-restricted area”.

Responses with respect to semi- restricted area are as follows: “area away from operation site (the anesthetist, runner/circulatory nurse)”, “is between the restricted and non-restricted area”, “include recovery room, changing room or clothing room”, “access zone, patient hair

must be covered”, “limited to traffic properly attar” and “peripheral support area of the surgical site”.

The majority of the respondents (58 professionals), said with painted colored green and red line and labeling (green for semi-restricted or restricted, red for restricted and some said yellow for semi-restricted). Others have replied as follows: “By identifying with partition floor”, “Restricted areas are demarked by large carton”, “There is no standard way implemented”, “No restriction”, “not applied here”, “By door”, “I don't see any differentiate in our OR”, “It is differentiated by design”, “Not clearly”, “Restricted, surgery sight”, “Semi-restricted- Anesthetics, circulate area”, “No idea”, “Its own area” and “Use doors and color lines”.

From these responses, it can be seen that some hospitals don't implement the area distinction rule and that there are some professionals with difficulty of differentiating the restricted area and semi-restricted area.

4.1.6.3 Measures taken for infection control

The professionals were asked about the measures they take for infection control in their OR and asked to focus on the subject of facility layout design. A total of 98 responses were collected. Only two responded with respect to the facility layout saying “By changing the room design and positive air” and “Reduce traffic”. Most replied with similar concept of cleaning, disinfection and sterilization. Others have replied with respect to product that should be used and practice they follow as professional within the OR.

Others have responded as follows: “There is no adequate infection control method here”, “good infection system control”, “By patient progress and wound heals”, “Awareness creation and training”, “West disposal using”, “allow ventilation”, “Infection prevention process”, “Awareness creation” and “Protect patient and professionals from air infection”.

From the number of responses made related to the OR facility layout, it can be clearly seen that the professionals do not have awareness about the environment they work in.

4.1.6.4 Maximization of infection control

Professionals were asked to share their opinion and experience on maximizing infection control with regards to the OR facility layout. A total of 79 professionals responded to this question. 8 responded in regards to the facility layout as follows: “standardize facility”, “separate restricted and semi-restricted area”, “The structure of building is not made to use

like OR it is an adaptation, there is no bathroom, there are some places that had leakage after raining, this should be maintained”, “Change the OR door to slide-able and close all the time”, “widen rooms” and “change OR design”.

Some responses were related to practice (keeping sterility, sterility check, proper discard of waste, regular checkup of infection control, hand washing, wearing proper surgical attires, scheduled cleaning and disinfection of OR and improve equipment management) and product (install HVAC system, Sterilizers, UV radiators).

A number of the respondents suggested that training should be given to create awareness and change the mind set of professionals about infection prevention, cleaning and use of equipment and instruments. Four of the respondents raised sterility breach issue concerning the high number of people inside the OR while conducting operation due to students, residents and unnecessary health professionals entering the OR.

Same thing as the section above can be seen here; few of the professionals reflect infection control to the environment and room layout they work in. It can also be seen that they have knowhow of its importance and are open to take training.

4.1.6.5 Minimization of turnaround time

With regards to OR facility layout, the professionals were asked to specify the measures they take to minimize turnaround time for surgery. In this case a total of 58 respondents shared their opinion and experience. None of the responses were related to the facility layout. Most are redundant answers as previous questions. New answer on this section is that they prepare every instrument that is needed before arrival of patients to the OR and that it is hard to tell the amount of time taken for surgery because it depends on the type of surgery and surgeon.

4.2 Optimized OR Facility Layout Design

The proposed graph theory based tool used to optimize the layout design of an OR was implemented in a Matlab environment. As discussed in the methodology section, graph theory is a method of arranging each room in a facility in accordance to its interaction with other rooms in the facility. The facility layout was designed based on the room adjacency weight. In this case, the weight was driven from the flow of staff collected from the questionnaire/case study and OR design related standards and guidelines. Highest adjacency rated rooms (rooms the staff travel back and forth the most) are designed closer in the layout

and the lowest adjacency rated rooms (rooms the staff travel back and forth the least) are designed farther away from each other. The steps employed in using this method have been clearly stated in Chapter 3, Section 3.7 of this document with detailed explanation of each term including few examples.

After the development of the 2D block layout for surgical center premise set-up with minimum requirement using the Matlab code, the detailed layout of the design was designed for simulation with an architect. In this section, the works done and results acquired to optimize and improve the layout design of an OR are described in detail.

4.2.1 Objective

The objective was to design an OR with a maximized infection control layout by controlling the spread of infection due to flow (staff/professional frequency of travel). A layout with 85.6% optimality was acquired (this is 6.8-14.2% off from the expected result using the tetrahedron procedure whose output lie between 92.4-99.8%), with it an improved detailed layout design for 3 types of OR was designed.

4.2.2 Input Data

The input data for the design of the 2D block layout with graph theory was an Adjacency matrix. It contains all of the rooms an OR should comprise and the interaction relationship amongst each other.

According to standards there are a total of eighteen facilities an operation room should comprise together with toilet for the SCR (WCS), office (WCO) and patient (WCP). Interaction relation between an OT and the other rooms in the OR department was extracted from the questionnaire. The last column of data (result of most traveled) was taken from question number 7. This indicated the number of staff that make the highest travel back and forth from the OT to the other areas of the OR department. This data was binned (between 0 and 1) for further analysis. This was done with a Matlab code; the output can be seen in Table 8 below.

	SA	SCR	CUSS	SU	NS	AS	OTES	SSS	DO/SO	DR	CR/UR	WC
OT	34	15	17	7	23	13	21	18	14	16	6	13
Same data after binning												
OT	1	0.4	0.5	0.2	0.7	0.4	0.6	0.5	0.4	0.5	0.1	0.4

Table 8: Highest staffs travel frequency.

For other rooms interaction amongst each other, weighing was constructed in relation to the binned data and national and international standards. According to national and international guidelines an OR has three area-distinctions: Restricted, Semi-restricted and Unrestricted as also been explained in Chapter 2, Section 2.3.2.1. Guidelines categorize the rooms of an OR department to the three areas in the OR. Below are the lists of rooms which an OR should comprise according to the area they belong in accordance to the guidelines.

Restricted area (RA): OT

Semi-restricted area (SRA):

SA	OTES	AS
SU	CUSS	CSR
SSS	NS	

Unrestricted area (UA):

SCR	RF/PAC	WCO
DO/SO	CR/UR	WCP
DR	POPA	WCS

The restricted area can only be accessed through the semi-restricted area and the semi-restricted area is accessed through the unrestricted area. This relationship can be seen in Figures 29 and 30 below.



Figure 29: OR area distinction relationship.

From the OR area distinction relationship shown in Figure 29 above it can be seen that rooms in RA are adjacent to rooms in SRA, rooms in SRA are adjacent to rooms in UA and rooms in UA and RA are not adjacent and are twice far away from each other compared to their relationship with SRA (see Figure 30).

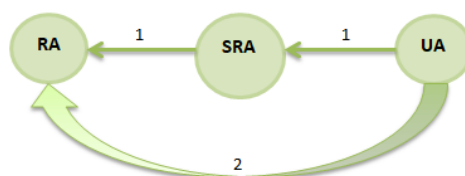


Figure 30: OR area distinction distance relationship.

Based on this distance relationship the interaction of the rooms in the OR can be derived. They are weighted from 0 to 1. The highest weight is 1, this shows most adjacent units and the lowest weight is 0 showing no adjacency at all. The range of the weight describes the adjacency rate of the department (see Figure 31).

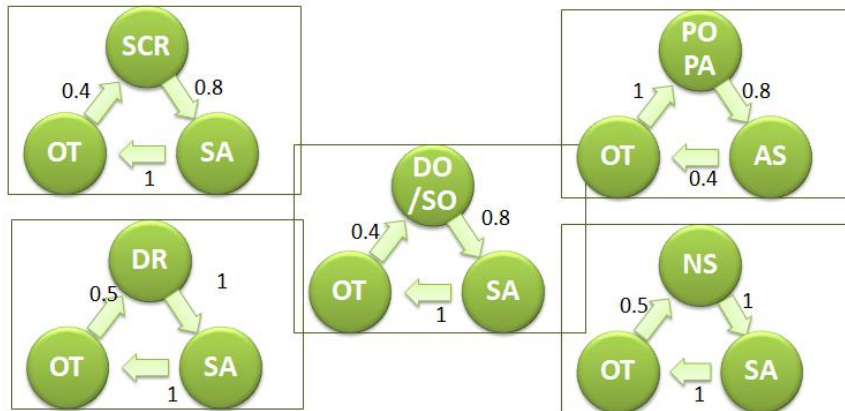


Figure 31: OR rooms interactions and weight.

Based on the guidelines, the recommended setup of OT to rooms CSR, SU and SSS is as shown in Figure 32 below. This is the relationship setup used to make the interaction relation on this thesis. There is no direct relationship between OR and CSR.

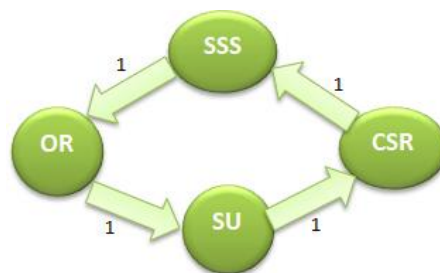


Figure 32: Interaction between OT and sterilization rooms.

Sterile supply store has direct adjacency to clean utility supply store so that sterilized materials can be transported from the SSS to CUSS with minimum probability of infection exposure. The recommended setup of these two rooms is shown in Figure 33 below.



Figure 33: Interaction between SSS and CUSS rooms.

Ideally, staffs of the OR enter in to the department through the staff changing room (SCR). From SCR staffs travel to different rooms in the unrestricted area zone, specifically they have

to get direct access to the duty room (DR), the offices (DO/SO). Shown below in Figure 34 is the interaction between SCR with DR and DO/SO.

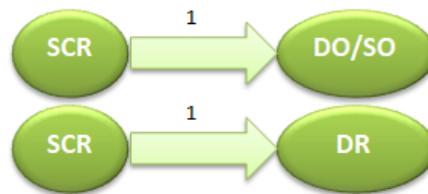


Figure 34: Interaction between SCR with DO/SO and DR.

Since DR and DO/SO are in the same area zone they are close with each other. Considering the high probably of staff travel in between these rooms the interaction is high. It is shown as in Figure 35 below.



Figure 35: Interaction between DR and DO/SO.

Nurses have to keep a close contact with patients in both pre and post operation state of the patients; hence there should be a direct access from the nurse station to the rooms where patients occupy. Additionally, staffs have to get close access from their resting area and office to the nurse station. Shown on Figures 36 and 37 below are the interactions of NS with areas the patients occupy and with areas for the staff.



Figure 36: Interaction of NS with patient rooms.

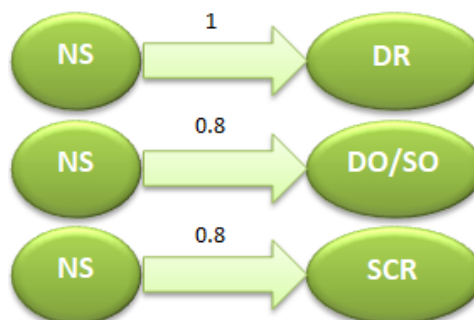


Figure 37: Interaction of NS with staff rooms.

The area used to store cleaning and disinfecting materials and equipment should have some connection to areas occupied by patients. The access should be close enough for the janitor to

directly come to the area to clean up in times of accident and far enough to limit the spread of infection. Shown below in Figure 38 is the estimated interaction between CR/UR with areas the patients occupy.

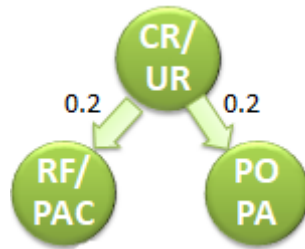


Figure 38: Interaction of CR/UR with patient rooms.

In this OR layout design there are 3 toilets. WCS is toilet for the staff and it is connected to SCR and DR, WCO is toilet in doctor/staff office and WCP is toilet for patients prior to surgery. Shown below in Figure 39 is the interaction of the toilet rooms with the rooms adjacent to them.



Figure 39: Interaction of toilet with their adjacent rooms.

From the interaction relationship the adjacency matrix was constructed as shown in Table 9 below. The surgical center premise set-up with minimum requirement layout is designed considering the minimum requirement by Ethiopian standard agency for OR design. Hence, there are two OTs in the adjacency matrix. For the SCR and the pre and post anesthetic patient areas, there is one of these rooms in the adjacency matrix but they will be divided into two (for male and female) in the designed layout, as there is no distinction of these rooms beside it being for both gender.

Rooms	OT1	OT2	SA	SU	SSS	RF/PAC	POPA	CR/UR	OTES	CUSS	SCR	DO/SO	DR	NS	CSR	AS	WCS	WCO	WCP
OT1	—	1	1	1	1	1	1	0.1	0.6	0.5	0.4	0.4	0.5	0.7	0	0.4	0	0	0
OT2	1	—	1	1	1	1	1	0.1	0.6	0.5	0.4	0.4	0.5	0.7	0	0.4	0	0	0
SA	1	1	—	0	0	0	0	0	0	0	0.8	0.8	1	1	0	0	0	0	0
SU	1	1	0	—	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
SSS	1	1	0	0	—	0	0	0	0	1	0	0	0	0	1	0	0	0	0
RF/ PAC	1	1	0	0	0	—	0	0.2	0	0	0	0	0	1	0	0	0	0	0
POPA	1	1	0	0	0	0	—	0.2	0	0	0	0	0	1	0	0.8	0	0	1
CR/UR	0.1	0.1	0	0	0	0.2	0.2	—	0	0	0	0	0	0	0	0	0	0	0
OTES	0.6	0.6	0	0	0	0	0	0	—	0	0	0	0	0	0	0	0	0	0
CUSS	0.5	0.5	0	0	1	0	0	0	0	—	0	0	0	0	0	0	0	0	0
SCR	0.4	0.4	0.8	0	0	0	0	0	0	0	—	1	1	0.8	0	0	1	0	0
DO/SO	0.4	0.4	0.8	0	0	0	0	0	0	0	1	—	1	0.8	0	0	0	1	0
DR	0.5	0.5	1	0	0	0	0	0	0	0	1	1	—	1	0	0	1	0	0
NS	0.7	0.7	1	0	0	1	1	0	0	0	0.8	0.8	1	—	0	0	0	0	0
CSR	0	0	0	1	1	0	0	0	0	0	0	0	0	0	—	0	0	0	0
AS	0.4	0.4	0	0	0	0	0.8	0	0	0	0	0	0	0	0	—	0	0	0
WCS	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	—	0	0
WCO	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	—	0
WCP	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	—

Table 9: Adjacency Matrix of OR department

Another input data to design the final detailed layout design was the requirement of premise setup surgical center has with the amount and minimum scale of each facility. This was obtained from Ethiopian standards (ES 3619:2012 First edition) as also been indicated in Chapter 2, Section 2.3.1 of this document.

4.2.3 Graph Construction

The Initial Graph was constructed on Matlab using the syntax for undirected edges graph “graph”. There are two inputs. The first input was names of the rooms in the OR, which were a 1 by 19 cell array. The second input was the Adjacency/ Interaction matrix imported from an Excel file.

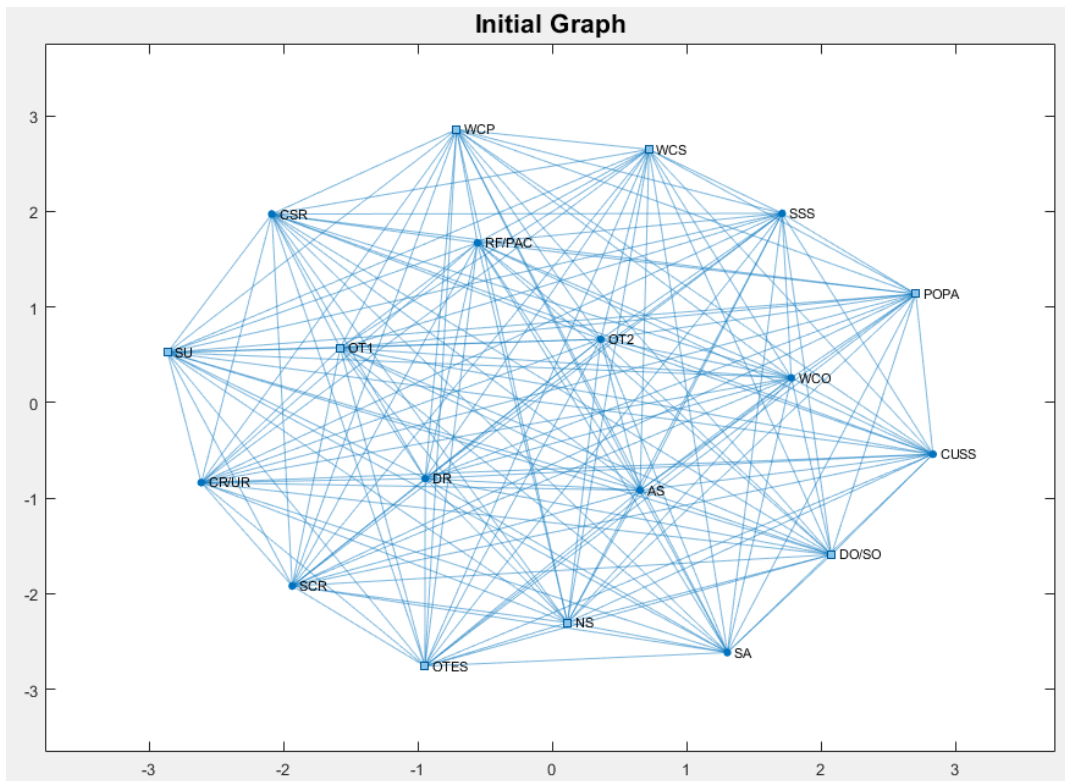


Figure 40: Initial Graph.

The output of the initial graph construction code is a simple, connected and complete graph with 19 nodes. Nodes are described by a blue dot followed by the abbreviation of the room. Edges are described by blue lines; there are a total of 171 edges (see Figure 40).

4.2.4 Planer Graph Construction

The Matlab code generated use a tetrahedron heuristic procedure to execute this problem. In the first step (prerequisite) each row weight is summed and sorted in descending order. Table 10 below shows the result of sorted row sum according to monotonically descending values.

Node Names	Row sum
'OT1'	9.6000
'OT2'	9.6000
'NS'	7
'DR'	6
'SA'	5.6000
'SCR'	5.4000
'DO/SO'	5.4000
'POPA'	5
'SSS'	4
'RF/PAC'	3.2000

'SU'	3
'WCS'	2
'CUSS'	2
'CSR'	2
'AS'	1.6000
'OTES'	1.2000
'WCO'	1
'WCP'	1
'CR/UR'	0.6000

Table 10: Sorted row sum.

Next step (Initialization), is to choose four of the highest row sums and build the initial Delthedron as sub-graph of the initial-graph.

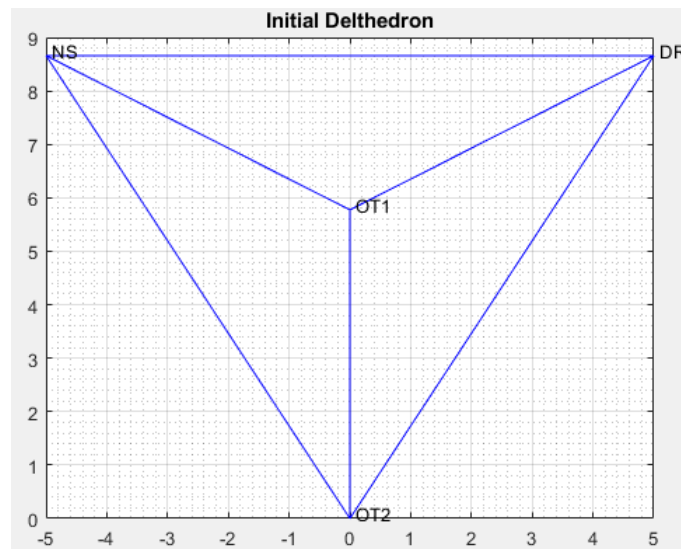


Figure 41: Initial Delthedron.

The output is a Delaunay triangulation with three inner faces/ facets and one outer face as shown in Figure 41.

The last step is iteration stage; remaining nodes are integrated into the Deltahedron in the order of decreasing row sums and designed as a sub graph of the initial graph. These nodes are inserted in the face where they have higher sum of edge weights. In some iteration, the new node can have equal interaction (similar value of sum of edge weights) to two or more faces; in this case user is requested to make a decision to choose the most feasible interaction.

The end result is dependent on the user's choice and the value might deviate from the required objective function value, but it gives possibility of examining different swaps

without requiring much time. The layout with more feasibility to implement in the real world application is selected.

There were 15 iterations for the 2 OR inputs (also presented in the Appendix section). From multiple trials/swaps, the selected input decisions made in the case of similar sum of edge weights are 3, 10, 3, 14, 7, 14, 7, 17, 8 and 13, respectively. Figure 42 presents the resulting planar graphs as new nodes are added in consecutive iteration.

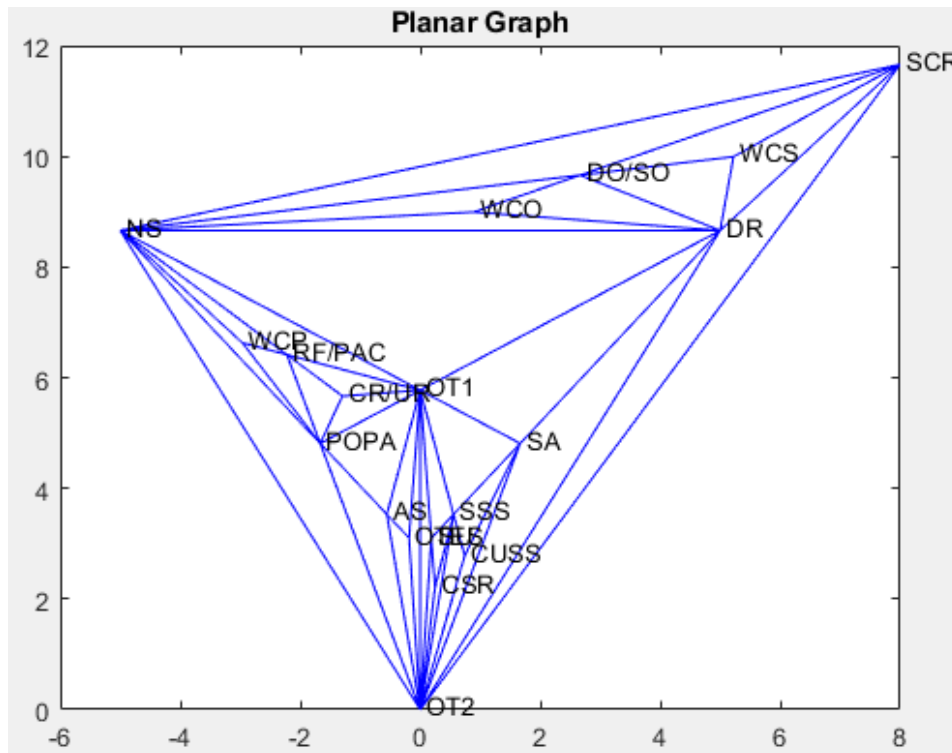


Figure 42: Planar Graph for 2 OT OR.

The upper bound of sum of edge weights derived from this maximal planar graph is equal to $3(n)-6$, n being the number of nodes/ rooms in the OR department. This proves that maximal planar graph is acquired.

The highest sum of edge weights for the acquired planar graph is 32.2; this is 85.6% of the upper bound of the sum of edge weights.

4.2.5 Dual Graph Construction

After construction of the planar graph, the dual graph is constructed. The first and second steps in construction dual graphs are the integration of an additional node for the environment (free boundary of the Delaunay triangle) and connect it to all the nodes that establish the outer face. The result is shown in Figure 43 below.

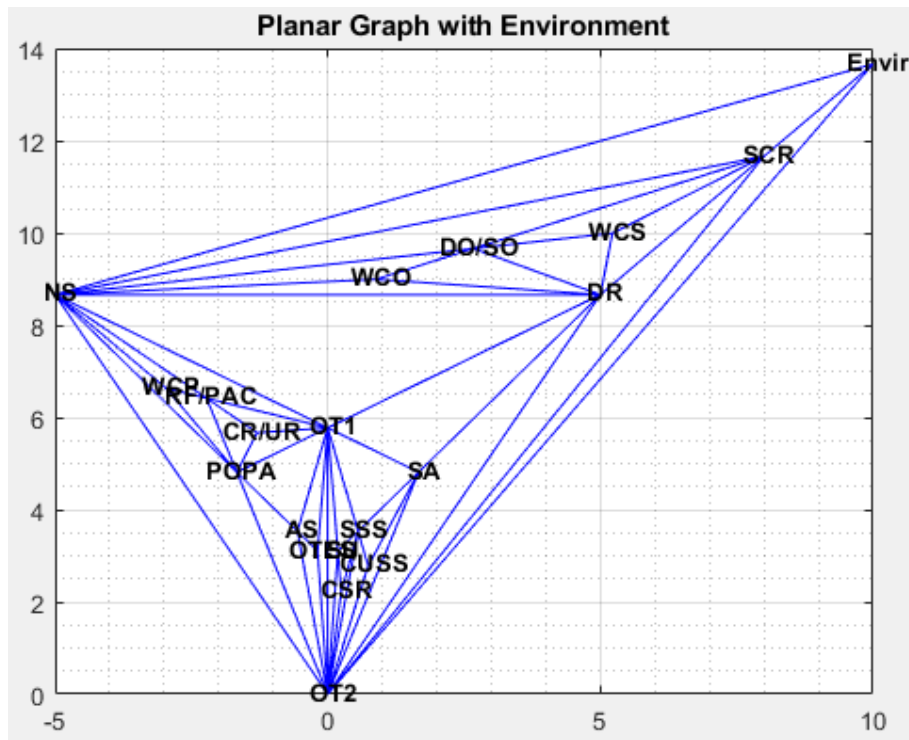


Figure 43: Planar graph with environment.

In step three, a node is included in each faces of the planar graph including the outer face. These points are indicated with red circles on the plot. The result is shown in Figure 44 below.

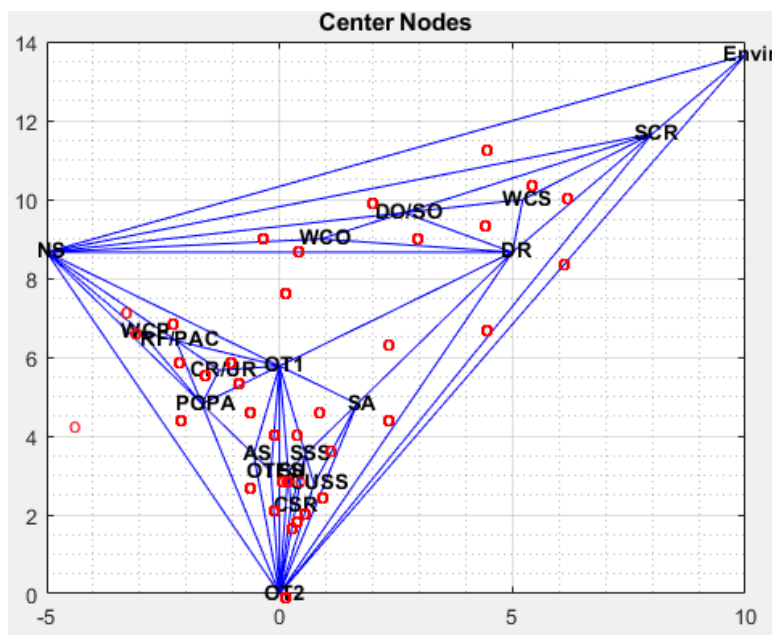


Figure 44: Center nodes of planar graph face.

In last stage, the center nodes in the faces are connected by edges that pass the edges of the primal graph once. This is indicated by red lines. There is exactly one edge included for each

edge of the planar graph. The result gives the dual graph of the planar graph and presented in Figures 45 and 46 below.

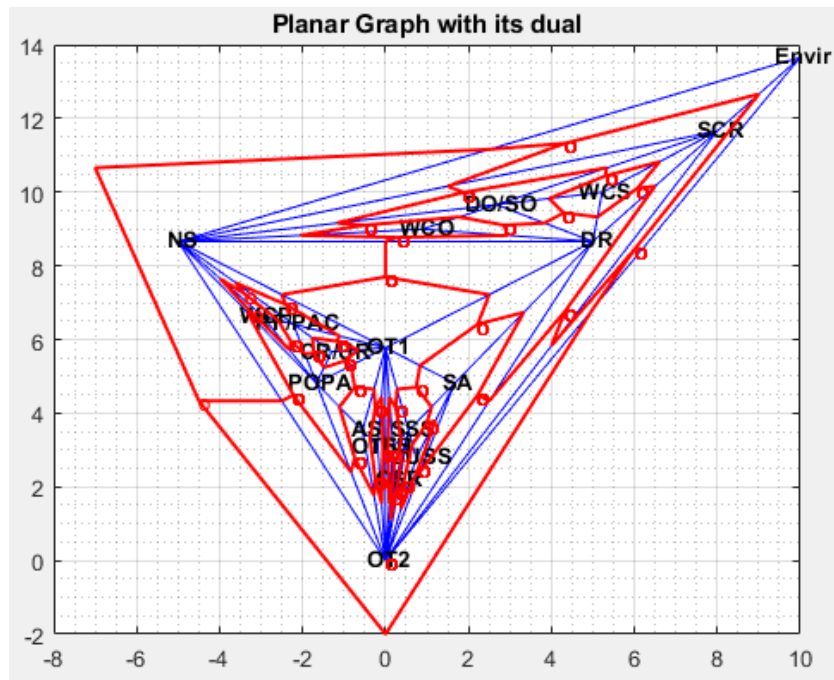


Figure 45: Planar graph with its dual.

The extracted dual graph is shown in Figure 46 below.

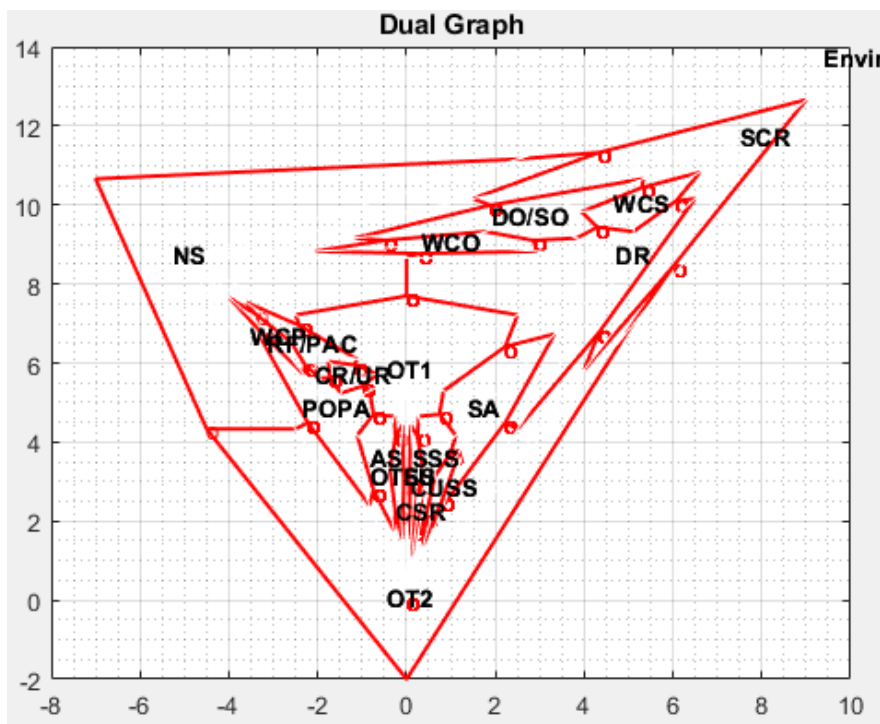


Figure 46: Dual Graph

4.2.6 2D Block Layout

From the above dual graph, a 2D block layout is formed. Figure 47 below shows the result.

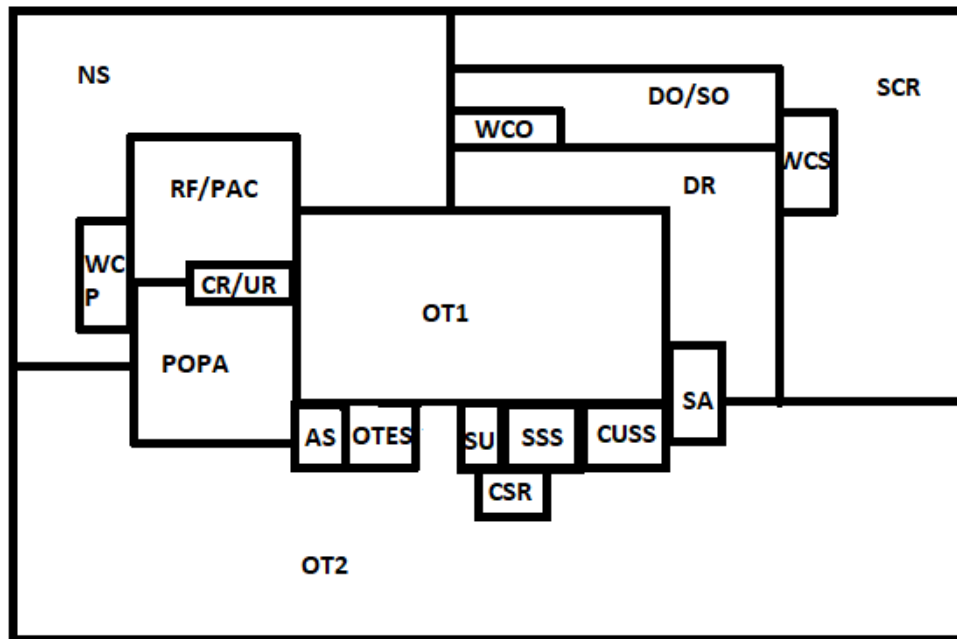


Figure 47: 2D block layout.

In the block layout above area-distinction is conformed. It can be seen that two OTs share the support of auxiliary/supportive rooms, the rooms in the semi-restricted area zone can be seen in the same position except NS. As was stated in the literature review section, one limitation of this procedure is that it might position rooms that need to be in the middle of the layout on the border of the layout. This has to be compensated in the architectural design/detailed layout version. The rooms in unrestricted area zone can also be seen in the same position of the block layout. This assures that the design compliments recommendations of standards.

4.2.7 Detailed Layout (Architectural Design)

There are different possible outcomes to design a detailed layout from a block layout, two alternatives of each type of OR are done here. The basic difference between the two alternative designs is that in the first design there is no difference between staff and patient entrance and exit, this reduces the floor area required. In the second setup, SCR has two doors (main entrance and access to the other supportive areas) and patient entrance and exit are different, giving even better infection control design setup. The two alternative layouts for a surgical center premise set up with minimum requirement are depicted in Figure 48 and Figure 49 below.

4.2.7.1 Surgical Center Premise Set-up with Minimum Requirement

Legend

- RESTRICTED
- SEMI RESTRICTED
- UNRESTRICTED



Figure 48: 2 OR Detailed Layout Alternative A.

Legend

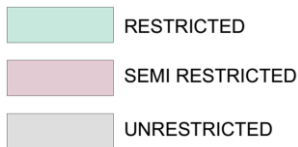


Figure 49: 2 OR detailed layout alternative B.

In both alternative designs, the integrity of the block diagram adjacency is retained. The corridor system is separated into staff corridors with links to the functional rooms and pre and post-operative patient corridor. As WHO recommendations, it is designed in a way to separate pathways of staff, patient and material (Infected/dirty utility from the sterile once) [17]. All rooms that require natural lighting have windows. Considering setups where air

vents cannot be installed, toilets also have windows for ventilation purpose. Separation of staff, patient and material flow can be clearly seen in the design.

The minimum area requirement of each facility is made as per Ethiopian standards. Space usage is limited. The output simulated final layout designs for a surgical center premise set up with minimum requirement which provides capability to control infection.

4.2.7.2 General Hospital OR

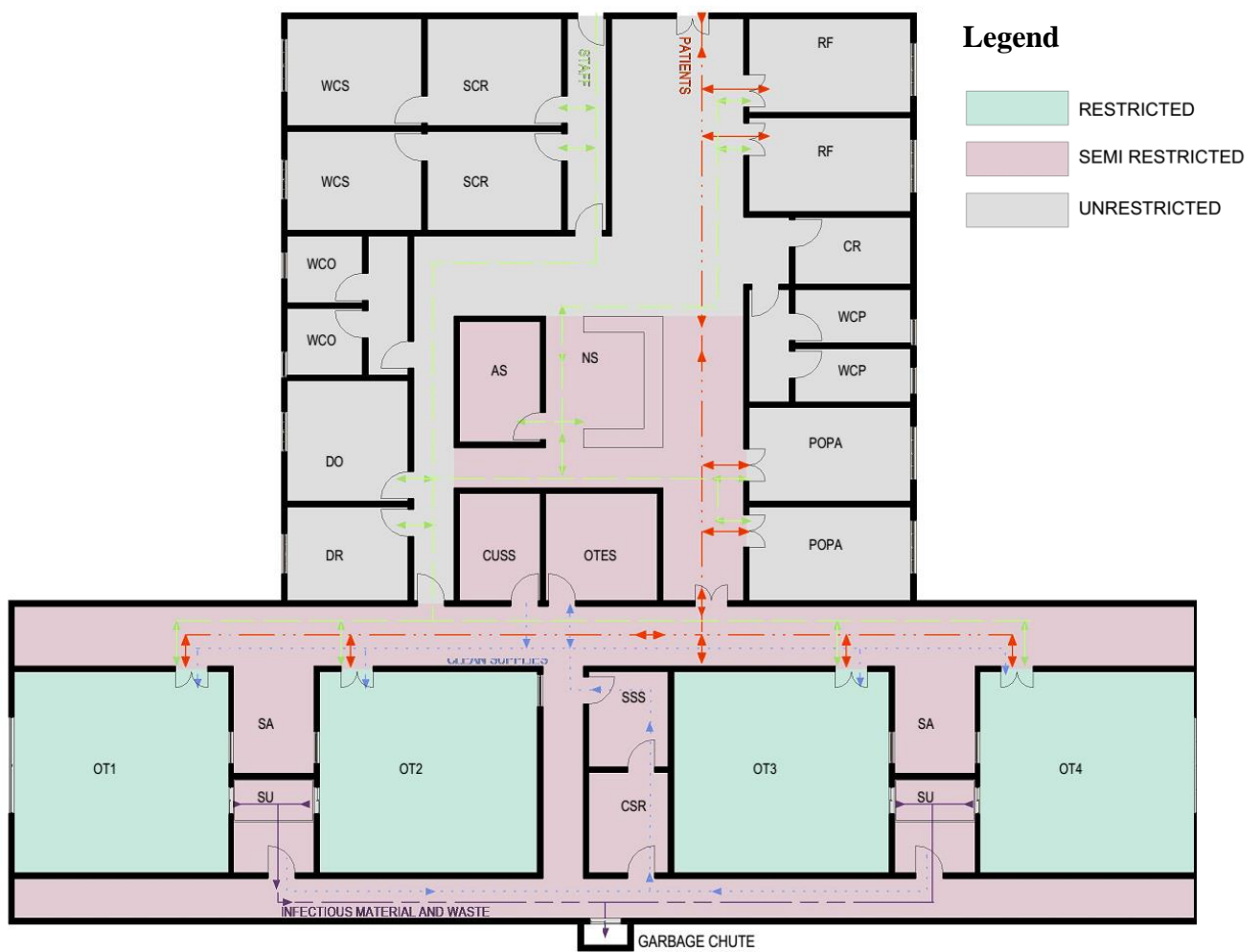


Figure 50: General Hospital OR detailed layout alternative A.



Figure 51: General Hospital OR detailed layout alternative B.

General hospital OR setup has four OTs with two SA and SU shared in between them. The integrity of the block layout adjacency is kept in both designs as well. Clear separation of staff, patient and material flow can be seen. The two alternatives for a General Hospital setup are indicated in Figure 50 and Figure 51.

4.2.7.3 Specialized Hospital OR



Figure 52: Specialized Hospital OR detailed layout alternative A.

Specialized hospital OR setup has seven OTs with four SA and SU shared in between them. The integrity of the block layout adjacency is kept in both alternative setup designs. The two alternatives for a Specialized Hospital setup are indicated in Figure 52 and Figure 53.

Chapter 5

Conclusion and Recommendation

This thesis aimed at designing an improved and optimized operation room layout in order to maximize infection control. It was implemented in accordance to Ethiopian and International standards, guidelines and assessment conducted from hospitals. The optimization was achieved based on graph theory method.

One approach to infection-control in ORs is limiting the flow of traffic in the department. This is accomplished by making rooms with high flow adjacent to each other. Thus graph theory was the ideal method. Up to 96% optimality is anticipated using the written code but 85% optimality was reached. This is possibly due to the data collected and used as input constraint. If an in-depth research goes in-to the data collection, there is likelihood of having an input data that specifies a more detailed and accurate interaction between rooms in the department. If so, there might be less possibility of user interference in the program. This can guaranty high accuracy of output near to the optimality level that the used method can reach.

Recommendation to FMOH

Ethiopia's major attention in health care is on increasing the number of health care professionals and expansion of both governmental and private hospitals and health care centers. These hospitals and healthcare centers must consider proper facilities design in order to provide quality health care. For integrated practical result, the health care professionals must have full knowledge about the facility they work in.

Recommendation to FMOH and Hospitals

Integration, regular inspection, updating and maintenance of technologies into the OR setup and layout (such as Lighting, HVAC system and centralized gas supply system) is advised as it aid with infection control and effective work flow. Local industries might be involved in the advancement of these technologies if they are deemed essential and required in Ethiopian standards.

In order to achieve the ultimate optimum value of infection control in the layout design, it is also advantageous if healthcare professionals are well educated and skilled with the technologies they use and about the environment they work in. Therefore, the professionals

should have on job training. Answers from the questioners have indicated that they are in need of and open to it.

Recommendation for University Hospitals

For hospitals integrated with university or college, the OR layout design should incorporate technologies which capacitate the students to attain and visualize surgeries in OT without direct interaction to the patients in mass, as this increases the likelihood of SSI.

This research is yet another proof that facility layout problem can be applied to hospital designs. Since the work flow in hospitals can be known and estimated in advance, it has advantages of having more uniform constraints unlike manufacturing industries. Hence the output of the design is more relevant, beneficial and futuristic. With the developed Matlab code (also presented in the Appendix), optimum design can be obtained provided well synthesized constraints. This research can be used to aid with the design planning and construction of newly opening hospital ORs. It not only aids in designing an OR facility with maximized infection control but also saves time and money spent on designing a concept design layout.

Chapter 6

Future Improvements

Future research is required to not only gather more data (such as through questioners) but also long term detailed observation of professionals flow through the OR. Merging other design consideration such as architectural, automation, lightning and technology in the input constraint is also advantageous. Consideration should also be made to form interdisciplinary collaboration with all essential expertise (Operation researchers, Biomedical Engineers, Architects, Hygienist, physician etc.) beginning from the planning stage of hospital design. This is helpful in the decision making and attainment of practically applicable optimum design.

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Appendix

Questioner



Addis Ababa University
Institute of technology
Center of Biomedical engineering
Master thesis questionnaire on improving operation room facility layout design

Thank you for participating in this survey. The purpose of this questioner is to recognize the perspective of the professional (surgeons, anesthesiologists, nurse anesthetists, surgical technicians, registered nurses, biomedical professionals etc...) regarding the operation room facility. It is intended to make analysis on the setup of the facility layout design in operation rooms and to conduct an assessment of the type of operation/surgery that is usually done. The survey also aims to identify the need of the professionals with respect to their operation room's layout design so that quality health care service is provided.

If you have questions as you complete this form, please contact Ms. Meba Hailu at +251920887467 or email mebahb@gmail.com

Assurance of confidentiality - All information which permits identification of any individual, a practice, or an establishment will be held confidential and will be used only by Ms. Meba Hailu for the purpose of this thesis. It will not be disclosed or released to other persons without the consent of the individual or the establishment.

Name of the Hospital/ Organization _____

Profession _____

Type of hospital

- Public enterprise
- Private
- Governmental
- Governmental health office

1. What type/s of OR do you have in your hospital (General, Orthopedic, Gynecological, Spine, Urology, Cardiac/Thoracic...)

2. What type of surgery/surgeries do you frequently do? State in number annually if possible?

3. Do you have the following technologies at your OR facilities (Put a mark on those relevant)

- | | | | |
|--------------------------|---|--------------------------|-----------------|
| <input type="checkbox"/> | HVAC system (Air flow control system, Temperature control system, Positive pressure ventilation, Humidity control system and HEPA filter) | <input type="checkbox"/> | Fire Safety |
| <input type="checkbox"/> | Central gas supply pipeline | <input type="checkbox"/> | Operating light |
| <input type="checkbox"/> | General light | <input type="checkbox"/> | Earthing |
| <input type="checkbox"/> | Power supply (backup) | <input type="checkbox"/> | |
| <input type="checkbox"/> | Power switching (away from operating area) | | |

4. Do you have a professional/expertise responsible for your facility layout design?

- Yes No

5. Based on your current OR facility layout, have you come across any impact on patient care at your hospital/clinic?

- Yes No

5.1 If yes please specify

6. How do you evaluate the OR facility layout in your hospital for quality patient care provision?

- It is effective and good as is
- It is not effective
- It is effective but need improvement

6.1 What is your suggestion for improvement?

6.2 What do you think are important for your OR to deliver quality patient health care service?

7. Which of these rooms within the OR unit do you frequently visit from the operation theatre on daily bases?

(Please tick, as appropriate, by ranking from 1= not at all, 2= once or twice per day, 3= 3 to 4 times per day, 4= 5 to 8 times per day, 5= More often)

No.	Rooms	1	2	3	4	5
1	Scrub area					
2	Stuff change room					
3	Clean utility room					
4	Soiled utility room					
5	Nurse station					
6	Anesthesia store					
7	OR equipment store					
8	Sterile supply room					
9	Doctor's office					
10	Duty room					
11	Janitor's closet					
12	Toilet rooms					

8. In your opinion/ from your experience what consideration should be followed with the following issues with respect to infection control and quality of health care provision in the OR?

8.1 Positive air

8.2 Temperature

8.3 Room Size

8.4 Patient and physician side lane

9. How do you differentiate between restricted and semi-restricted areas in your OR?

10. Which measures do you take in your OR for infection control?

11. In your opinion/ from your experience what would maximize the infection control in your OR (with regards to the OR facility layout)?

12. In your opinion/ from your experience what measures could minimize the turnaround time during surgery (with regards to the OR facility layout)?

Position in the organization

Signature

Date:

Information sheet

Master thesis questionnaire on improving operation room facility design layout

Dear Participant,

I invite you to participate in a research study entitled Optimization/ improving operation room facility design layout. I am currently enrolled in the Center of Biomedical Department at Addis Ababa University in the institute of technology, and I am in the process of writing my Master's Thesis. The purpose of this questioner is to recognize the perspective of the professional (surgeons, anesthesiologists, nurse anesthetists, surgical technicians, registered nurses, biomedical professionals etc...) regarding the operation room facility.

The enclosed questionnaire has been designed to collect information on the setup of the facility layout design in operation rooms and to conduct an assessment of the type of operation/surgery that is usually done. It also aims to identify the need of the professionals with respect to their operation room's design layout so that quality health care service is provided.

Your participation in this research project is completely voluntary. You may decline altogether, or leave blank any questions you don't wish to answer. There are no known risks to participation beyond those encountered in everyday life. Your responses will remain confidential and anonymous. Data from this research will be kept under lock and key and reported only as a collective combined total. No one other than the researchers will know your individual answers to this questionnaire.

If you agree to participate in this project, please answer the questions on the questionnaire as best you can. It should take approximately 30 minutes to complete. Please return the questionnaire as soon as possible to the person that provided it for you.

If you have any questions about this project, feel free to contact Ms. Meba Hailu at +251920887467 or email mebahb@gmail.com.

Thank you for your assistance in this important endeavor.

Sincerely yours,

Meba Hailu

MATLAB Code

A. Data Binning

```
data=[34,15,17,7,23,13,21,18,14,16,6,13];%insert data
edges=1:3:34; % partition the data / distribute the numbers into 3 equally
spaced bins
y=discretize(data,edges);% group numeric values into discrete bins
A=y/max(y); % divide binned data with max value to gain results 0-1
```

B. Graph Construction

```
close all
clc
%~Input attributes (Nodes (names) and Edges(Adjecency/ interaction
matrix)).
names=
{'OT1','OT2','SA','SU','SSS','RF/PAC','POPA','CR/UR','OTES','CUSS','SCR','
DO/SO','DR','NS','CSR','AS','WCS','WCO','WCP'}; % Input node names
A=xlsread('Excel Adjacency matrix-2OR.xlsx'); % Export Adjacency matrix
data from Excel.
A(A==0) = eps; %Change zero element to eps (2^(-52)): make the graph
connected.
%~Output (initial graph)
Graph_initial=graph(A,names,'upper','OmitSelfLoops'); % Define an
undirected graph (with name "Graph_initial") make it simple by omitting
any self loops.
Graph_initial.Edges; % View edge table of the graph.
Graph_initial.Nodes; % View node table of the graph.
plot (Graph_initial) % Plot the graph.
title ('Initial Graph') % Give title to the plot.
```

C. Planar Graph Code

```
%% Step1: Prerequisite
A_rowsum=sum (A,2); % Calculate row sums of interaction matrix
namesT= transpose (names); % Change row vector of names to column
RS=table (namesT,A_rowsum,'VariableNames',{'NodeName' 'RowSum'}); %
Creat table with list of row sum ("A_rowsum") and node names("namesT")
%~Sort row sum in descending values
R=sortrows(RS,2,'descend'); % Sort row to monotonic decreasing values

%% Step2: Initialization
%~Extract four nodes with the highest row sums
B= R(1:4,:);% Choose four nodes in R with the highest row sums
%~Extract the row with node names
Names= B(:,1);% Choose first row of B
Names_cell=table2cell(Names); % Convert the class of Names to cell
Names_cellT= transpose(Names_cell); % Change to row vector
%~Creat a subgraph containing the four nodes from the initial graph
K = findnode(Graph_initial,Names_cellT); % Find the node names in
Name_cellT; in the initial graph Graph_initial
H= subgraph (Graph_initial,K'); % Creat a subgraph of the initial graph
with nodes in k,
H.Edges;
H.Nodes;
InitialDelthedronWeight=sum(H.Edges.Weight);
```

```

%~Creat a delaunay triangles and plot the subgraph (H)
a=5;
xx=[0;-a;a];
xxx=mean(xx);
yy=[0;sqrt(3)*a;sqrt(3)*a];
yyy=mean(yy);
x= [xxx;xx]; % Specify x axis for H.
y= [yyy;yy]; % Specify y axis for H.
[sOut,tOut]=findedge(H); % Locate all edges in H, assign the source and
tagret nodeIDs to "sOut" and "tOut" respectively.
C= [sOut tOut]; % Creat a 2-column matrix assigned "C" with rows of sOut
and tOut. C defines the start and end Vertex IDs of constained edges for a
delaunay triangulation.
DT=delaunayTriangulation(x,y,C); %Creat a delaunary triangulation object,
with input arguments "x", "y" and "C".
figure, triplot(DT)% plot DT.
% axis ([-10 10 -3 15])
title ('Initial Delthedron') % Give title to the plot.
grid on
grid minor
%Label the vertices with node name.
NN=table2cell(H.Nodes);
dx=0.1;
dy=0.1;
BB=cellstr(NN);
hold on
text(x+dx, y+dy,BB)

%% Step3: Iteration
MaxofAddedEW=zeros(1,size(K,1).^2);% Creat a one column matrix named.
%~Add new node step by step with for loop.
for m=5:size(names,2)
B2=R(1:m,:); % Choose first m nodes in R and assign it to "B2".
Names2=B2(:,1); % Choose first row of B2 and assign it to "Names2"
(extract node names).
Names_cell2=table2cell(Names2); % Convert the class of Names2 from table
to cell and assign it to "Names_cell2".
Names_cell2T=transpose(Names_cell2); % Change column vector of Names_cell2
to row vector by transposing and assign it to "Names_cell2T".

k2=findnode(Graph_initial,Names_cell2T);% Find the node names in
Name_cell2T; in the initial graph Graph_initial and assign value to "k2".
H2=subgraph(Graph_initial,k2'); %Create a subgraph of the initial graph
with nodes in k2, assign it to "H2".
H2.Edges;
H2.Nodes;

% Integret new node in each face/triangle in the previous plot and
identify which makes the highest edge sum.
AddedEW=zeros(1,size(DT,1)+1); % Create a column matrix of 0s,to allocate
the weight sum of each face interaction. Assign value to AddedEW.
IterationSum=0;
AnotherRespectiveNodes=cell(3,size(DT,1)+1);
for n=1:size(DT,1)
H2i=subgraph(H2,[DT(n,:) m]); %Create a subgraph of H2 with nodeIDs in
the nth row of DT("n"th face/triangle) and the new nodeID m. Assign it to
"H2i".

```

```

[eid,nid]=outedges (H2i,Names_cell2(end,end)); % Extract the outgoing
edges and the successor nodes from the new node, assign it to "eid" and
"nid" respectively.
EW=H2i.Edges.Weight(eid,:);% Identify all the weight of edges in "eid"
and assign it to "EW".
AddedEW(n)=sum(EW);% Add all the edge weights and assing to
"AddedEW(n)"
% Compare values of AddedEW(n) to IterationSum
% If current value in AddedEW is greater than the value in
IterationSum,
% Assign the current value in AddedEW to IterationSum and
% Assign the values in nid to "RespectiveNodes"
if AddedEW(n)>IterationSum
    IterationSum=AddedEW(n);
    RespectiveNodes=nid;
end
% Compare values of AddedEW(n) to IterationSum
% If current value in AddedEW is equal to the value in IterationSum,
% Assign the current value in AddedEW to SameIterationSum and
% Assign the values in nid to "AnotherRespectiveNodes"
if AddedEW(n)==IterationSum
    SameIterationSum=AddedEW(n);
    AnotherRespectiveNodes(:,n)=nid;
end
% When the value of n equals the row size of DT
% Extract the outer vertices in the boundary of DT and assign it to
"F".
% Create a subgraph of H2 with nodeIDs in the rows of F and the new
nodeID m. Assign it to "H2i".
% Extract the outgoing edges and the successor nodes from the new
node, assign it to "eid" and "nid" respectively.
% Identify all the weight of edges in "eid" and assign it to "EW".
% Add all the edge weights and assing to "AddedEW(n+1)"
if n==size(DT,1)
    F=freeBoundary(DT);
    H2i=subgraph(H2,[F(:,1)' m]);
    [eid,nid]=outedges (H2i,Names_cell2(end,end));
    EW=H2i.Edges.Weight(eid,:);
    AddedEW(n+1)=sum(EW);
end
% Compare values of AddedEW(n+1) to IterationSum
% If current value in AddedEW is greater than the value in
IterationSum,
% Assign the current value in AddedEW to IterationSum and
% Assign the values in nid to "RespectiveNodes"
if AddedEW(n+1)>IterationSum
    IterationSum=AddedEW(n+1);
    RespectiveNodes=nid;
end
% Compare values of AddedEW(n+1) to IterationSum
% If current value in AddedEW is equal to the value in IterationSum,
% Assign the current value in AddedEW to SameIterationSum and
% Assign the values in nid to "AnotherRespectiveNodes"
if AddedEW(n+1)==IterationSum
    SameIterationSum=AddedEW(n);
    AnotherRespectiveNodes(:,n+1)=nid;
end

```

```

    % If current value of the added weight sum is not the highest change
    % the value of the current nodes to the nodes with the highest
interaction sum.
    % Compare values of AddedEW(n+1) to IterationSum
    % If current value in AddedEW is less than the value in IterationSum,
    % Assign the value in RespectiveNodes to nid
    if AddedEW(n+1)<IterationSum
        nid=RespectiveNodes;
    end

end

MaxofAddedEW(m)=max(AddedEW); % Identify the maximum value in AddedEW
assign it to current value of MaxofAddedEW(m).

%~Display the value of the highest sum in the current iteration
NewNode=table2cell(H2.Nodes(end,end));
Z=['Current iteration highest sum and new node
are:',num2str(IterationSum),'and', NewNode];
disp(Z)

%~If there are two iterations with equal highest sum,
% Allow user to choice which node iteration to pass
% Display node of high interaction

if IterationSum==SameIterationSum
    HEY=find(AddedEW==IterationSum);
    LIST=AnotherRespectiveNodes(:,HEY);
    if size(HEY)==[1 1]
        disp('Current iteration node should be placed in between:')
        disp(LIST)
        ChoosenJJ=HEY;
    else
        disp('You have these choices to place your current node:')
        disp(LIST)
        disp('These are the column number')
        disp(HEY)
        Promptn='Select the column number of the list of nodes you
prefer: ';
        ChoosenJJ=input(Promptn);
    end
    for jj=ChoosenJJ
        nid=AnotherRespectiveNodes(:,jj);
    end
else
    disp('Current iteration node should be placed in between:')
    disp(RespectiveNodes)
end

%~Connect the new node with the nodes it has high interaction with
H3=subgraph(H2,nid); %Create a subgraph of H2 with node in nid(highest
interaction nodes). Assign it to "H3".
H3.Nodes;
H3.Edges;
% Add the new node in the previous planer graph
H=addnode(H,H2.Nodes(end,end));

```

```

% Add the edges from the new node to the respective node with high
interaction
H2NodesA=table2array(H2.Nodes); % convert table of graph H2 nodes to array
H3NodesA=table2array(H3.Nodes); % convert table of graph H3 nodes to array
NewEdges=table([H2NodesA(end,end) H3NodesA(1,1); H2NodesA(end,end)
H3NodesA(2,1); H2NodesA(end,end) H3NodesA(3,1)], EW ,
'VariableNames',{'EndNodes','Weight'});
H=addedge(H,NewEdges);
H.Edges;
H.Nodes;

%~Creat a delaunay triangles and plot the graph
KK=findnode(H,nid);
FB=freeBoundary(DT);
if KK==FB(:,1)
    xnew=x(KK(2))+ 3;
    ynew=y(KK(2))+ 3;
else
    xnew=sum(x(KK))/3;
    ynew=sum(y(KK))/3;
end
x= [x; xnew]; %With the input from used specify x axis for the new node in
H
y= [y; ynew]; %With the input from used specify y axis for the new node in
H
[sOut,tOut]=findedge(H);
C= [sOut tOut];
DT=delaunayTriangulation(x,y,C);
figure, triplot(DT)
% axis ([0 15 0 20])
grid on
grid minor
%label the vertices with node name
NN=table2cell(H.Nodes);
dx=0.1;
dy=0.1;
BB=cellstr(NN);
hold on
text(x+dx, y+dy,BB)
end

%% Prove the aquired graph is planar graph {maximally planar graph/
deltahedron}
% "If a graph is a deltahedron with nn nodes and mm edges, then this
holds:
% mm=3nn-6
NumberOfEdges=numedges(H); % Identify the number of edges in the aquired
graph
nn=numnodes(H); % Identify the number of nodes in the graph, assign it to
'nn'.
mm=3*nn-6;
if NumberOfEdges==mm
    disp ('Maximal Planar graph is aquired!')
else
    disp('Planar graph is not aquired.')
end
end

```

```

SumofMaxofAddedEW=sum(MaxofAddedEW)+InitialDelthedronWeight;
W=['Highest sum of edge weight is: ',num2str(SumofMaxofAddedEW)];
disp(W)

%% Save variables for further analysis
XAXSIS=x;
YAXSIS=y;
Conectivity=C;
NodeNames=NN;

```

D. Dual Graph Code

```

%% Dual Graph
% Call variables in the planar graph.
XAXSIS;
YAXSIS;
Conectivity;
NodeNames;
%Creat the Planar Graph and plot it.
DT=delaunayTriangulation(XAXSIS,YAXSIS,Conectivity); %Creat a delaunary
triangulation object, with input arguments "x", "y" and "C".
figure, triplot(DT) % Plot DT.
title ('Planar Graph') % Give title to the plot.
%Label the vertices with node name.
dx=0.1;
dy=0.1;
BB=cellstr(NodeNames);
hold on
text(XAXSIS+dx, YAXSIS+dy,BB)
hold off

%% Step 1: Integrate additional node && Step 2: Connect node in step 1 to
all the nodes that formerly established the outer facet.
F = freeBoundary(DT); % Query free boundary facets.
% Creat axis of new node with respect to the middle node of F.
xNew=XAXSIS(F(2,1))+ 2;
yNew=YAXSIS(F(2,1))+ 2;
% Creat a new x and y axis containing all node axis and new node axis.
x=[XAXSIS;xNew];
y=[YAXSIS;yNew];

% Set the Connection of new node to the boundary node(creat Edges)
% Instant conectivity (Edges) between the outer nodes and the environment
% is accived in delaunay Triangulation after setting of the x and y axis
of
% the added node...here is another method of creating the connectivity
% C=[Conectivity; zeros(3,2)];
% for k=1:3
%     j=size(Conectivity,1)+k;
%     C(j,1)=size(x,1);
%     C(j,2)=F(k,1);
% end

% Re-plot the planar graph with the added environment node
DT=delaunayTriangulation(x,y,Conectivity); %Creat a delaunary
triangulation object, with the added node.

```

```

figure, triplot(DT) % Plot DT.
title ('Planar Graph with Environment') % Give title to the plot.
grid on
grid minor
%Label the vertices with node name (call the new node "Envir" for
Environment).
NODNE=size(NodeNames);
NodeN=NodeNames;
NodeN(NODNE(1)+1,1)={'Envir'};
dx=0.1;
dy=0.1;
BB=cellstr(NodeN);
hold on
text(x+dx,
y+dy,BB, 'FontWeight', 'bold', 'HorizontalAlignment', 'center', 'Color', 'black'
)
hold off

%% Step 3:Include exactly 1 node for each facet/ face.
DT=delaunayTriangulation(x,y,Conectivity); %Creat a delaunary
triangulation object, with input arguments "x", "y" and "C".
figure, triplot(DT) % Plot DT.
title ('Center Nodes') % Give title to the plot.
grid on
grid minor
%Label the vertices with node name.
text(x+dx,
y+dy,BB, 'FontWeight', 'bold', 'HorizontalAlignment', 'center', 'Color', 'black'
)
%Extract the center point (midpoint) of each facet.
Center= zeros(size(DT,1)+1,2); % Create a variable named "Center" to locate
the midpoint of the facet.
for n=1:size(DT,1)
    O=DT(n,:);
    MidPointx=((x(O(1))+ x(O(2))+x(O(3))))/3;
    MidPointy=((y(O(1))+ y(O(2))+y(O(3))))/3;
    Center(n,:)= [MidPointx,MidPointy];
    % For the outer facet, create a point away from the outer nodes 1&3
(the other nodes besides the environment)
    if n==size(DT,1)
        F=freeBoundary(DT);
        MidPointx=(x(F(1,1))+x(F(3,1)))/2-2;
        MidPointy=(y(F(1,1))+y(F(3,1)))/2;
        Center(n+1,:)= [MidPointx,MidPointy];
    end
    Center;
    hold on
    text(Center(:,1),Center(:,2), 'o', 'Color', 'red');
end

%% Step 4:Include exactly one edge for each edge in the primal graph that
separates two facets/ faces.
% Connect two nodes in step 3 with the edge.
% WAK=size(edges(DT));
% Median=zeros(WAK);

for n=1:size(DT,1)
    M=DT(n,:);

```

```

Medianx=((x(M(1))+ x(M(2))))/2;
Mediany=((y(M(1))+ y(M(2))))/2;
MedPoint=[Medianx,Mediany];
QQ=[Center(n,1),MedPoint(1)];
RR=[Center(n,2),MedPoint(2)];

line (QQ,RR,'Color','red','LineWidth',1.5)

Medianx=((x(M(1))+ x(M(3))))/2;
Mediany=((y(M(1))+ y(M(3))))/2;
MedPoint=[Medianx,Mediany];
QQ=[Center(n,1),MedPoint(1)];
RR=[Center(n,2),MedPoint(2)];

line (QQ,RR,'Color','red','LineWidth',1.5)

Medianx=((x(M(2))+ x(M(3))))/2;
Mediany=((y(M(2))+ y(M(3))))/2;
MedPoint=[Medianx,Mediany];
QQ=[Center(n,1),MedPoint(1)];
RR=[Center(n,2),MedPoint(2)];

line (QQ,RR,'Color','red','LineWidth',1.5)

end

% Create a line from the center point of environment to midline of node (2
and 3).
Medianx=(x(F(1,1))+x(F(3,1)))/2;
Mediany=(y(F(1,1))+y(F(3,1)))/2;
MedPoint=[Medianx,Mediany];
QQ=[Center(n+1,1),MedPoint(1)];
RR=[Center(n+1,2),MedPoint(2)];

line (QQ,RR,'Color','red','LineWidth',1.5)
% Extend the line over node 3 and to the midpoint of 3 and the
environment.
Medianx=(x(F(2,1))+x(F(3,1)))/2;
Mediany=(y(F(2,1))+y(F(3,1)))/2;
MedPoint=[Medianx,Mediany];
QQ=[MedPoint(1),x(F(3,1))-2, Center(n+1,1)];
RR=[MedPoint(2),y(F(3,1))+2,Center(n+1,2)];
line (QQ,RR,'Color','red','LineWidth',1.5)
% Extend the line under node 2 and to the midpoint of 2 and the
environment.
Medianx=(x(F(2,1))+x(F(1,1)))/2;
Mediany=(y(F(2,1))+y(F(1,1)))/2;
MedPoint=[Medianx,Mediany];
QQ=[MedPoint(1),x(F(1,1)), Center(n+1,1)];
RR=[MedPoint(2),y(F(1,1))-2, Center(n+1,2)];
line (QQ,RR,'Color','red','LineWidth',1.5)
title ('Planar Graph with its dual') % Give title to the plot.
%% Extract the dual graph
tripplot(DT,'color','white')
title ('Dual Graph')

```

```

text(x+dx,
y+dy, BB, 'FontWeight', 'bold', 'HorizontalAlignment', 'center', 'Color', 'black'
)
hold off

```

E. Optimization Percent Calculator

```

A=xlsread('Excel Adjacency matrix-2OR.xlsx');
X= zeros(size(A));
B= zeros(size(A));
for i=1:size(A,1)
    for j=1:size(A,2)
        if i<j
            X(i,j)=1;
        else
            X(i,j)=0;
        end
        B(i,j)=(A(i,j)*X(i,j));
        OF=max(sum(sum(B)));
    end
end
W=['The Upper bound of sum of edge weight is: ',num2str(OF)];
disp(W)

Percent=(SumofMaxofAddedEW*100)/OF;
Y=['The aquired result is ',num2str(Percent),'% of the upper bound of sum
of edge weight'];
disp(Y)

```

F. Iteration Outputs

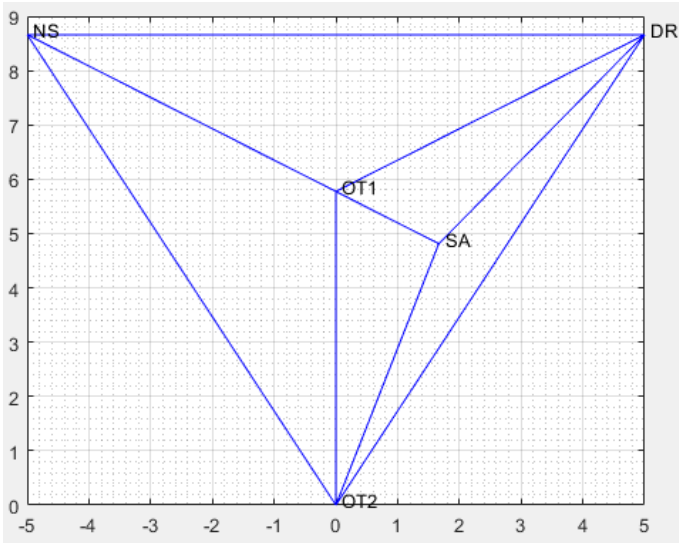


Figure: Iteration #1

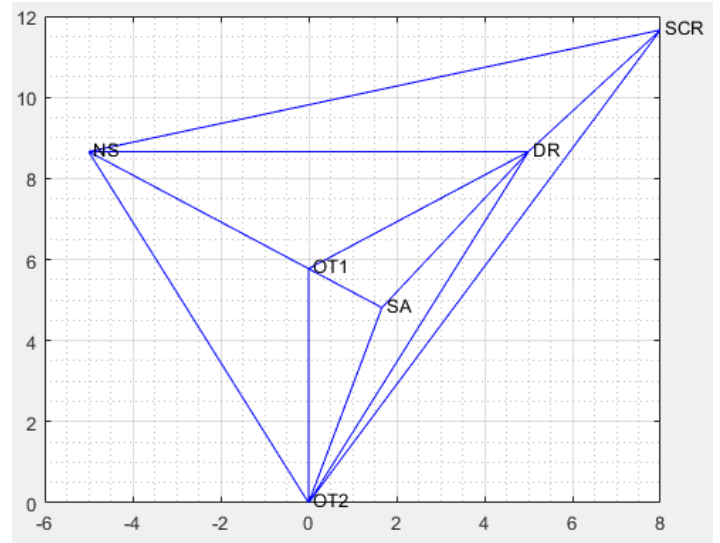


Figure: Iteration #2

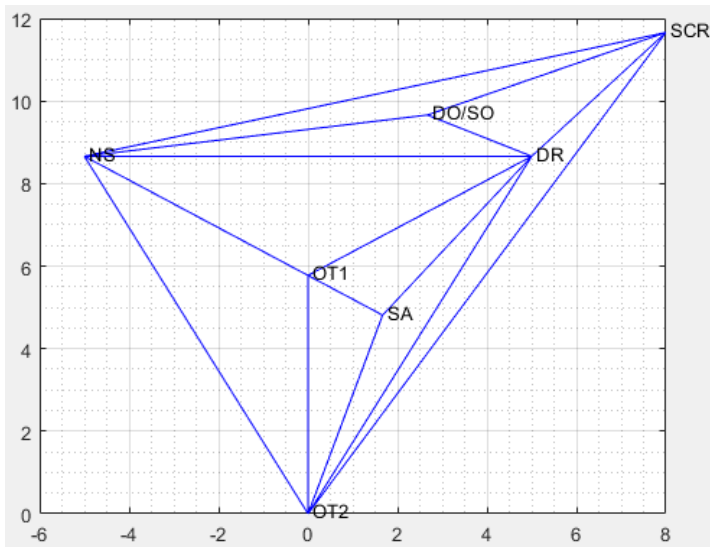


Figure: Iteration#3

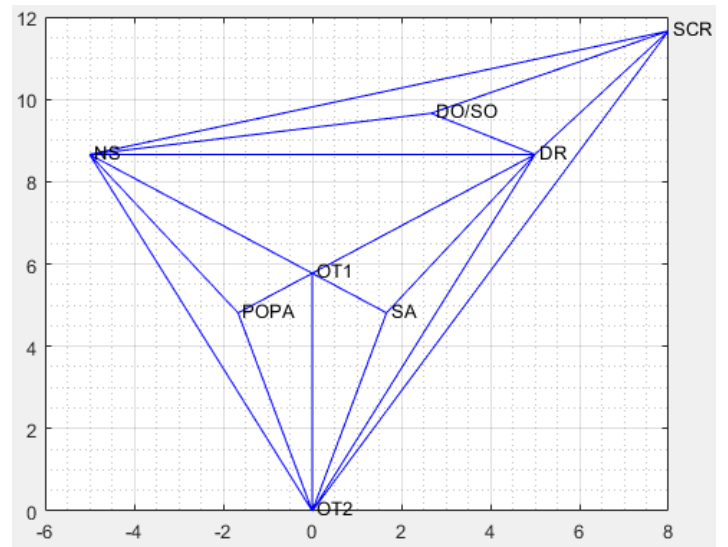


Figure: Iteration#4

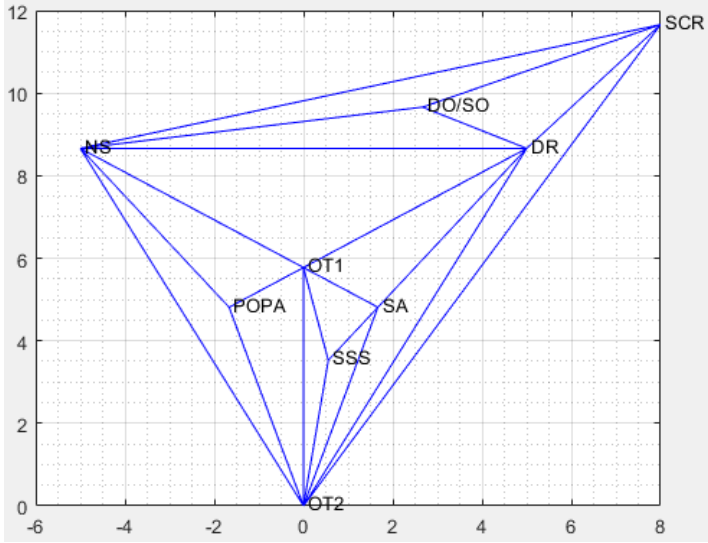


Figure: Iteration #5

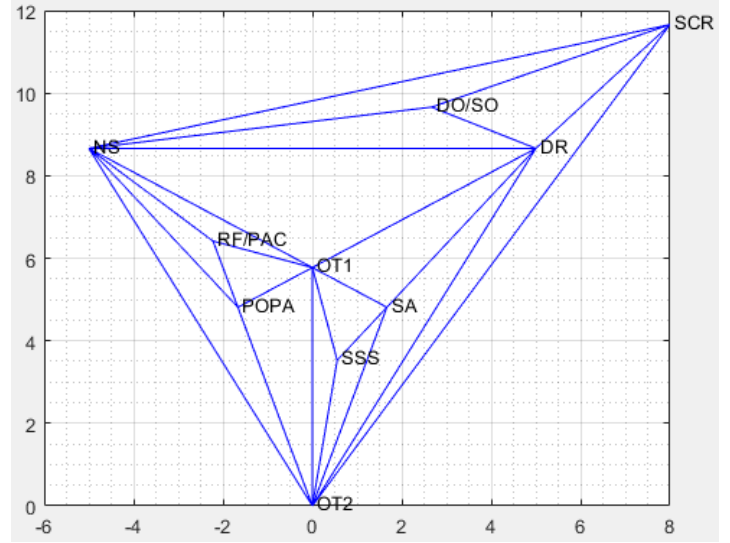


Figure: Iteration #6

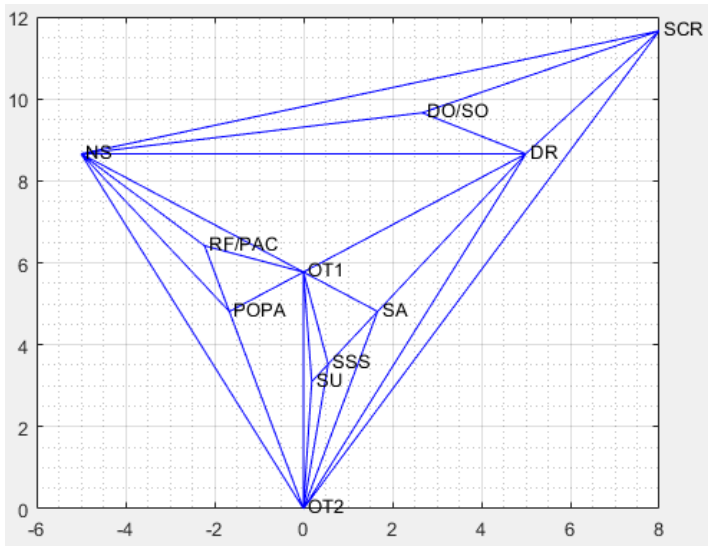


Figure: Iteration #7

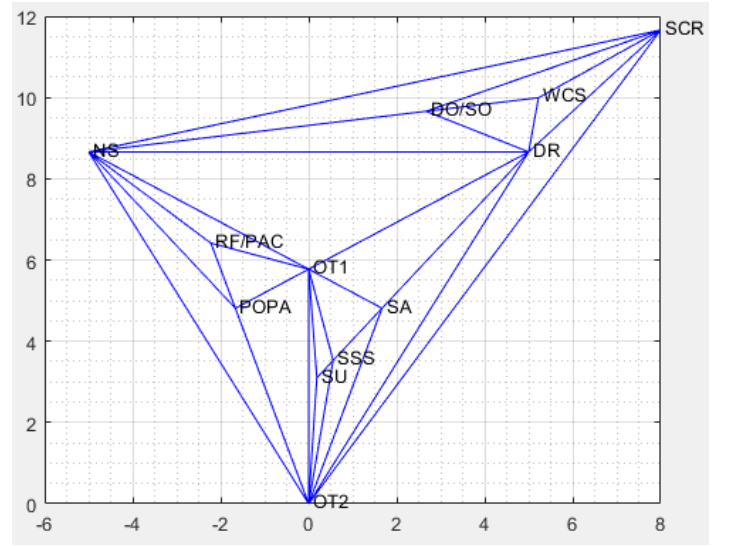


Figure: Iteration #8

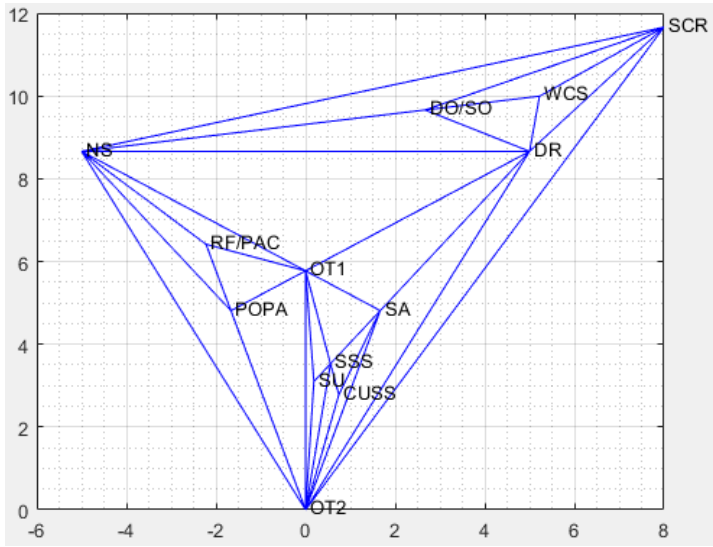


Figure: Iteration #9

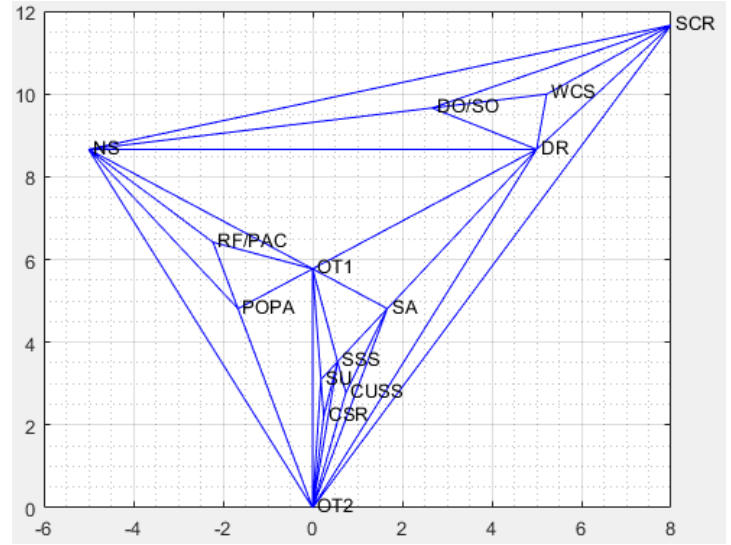


Figure: Iteration #10

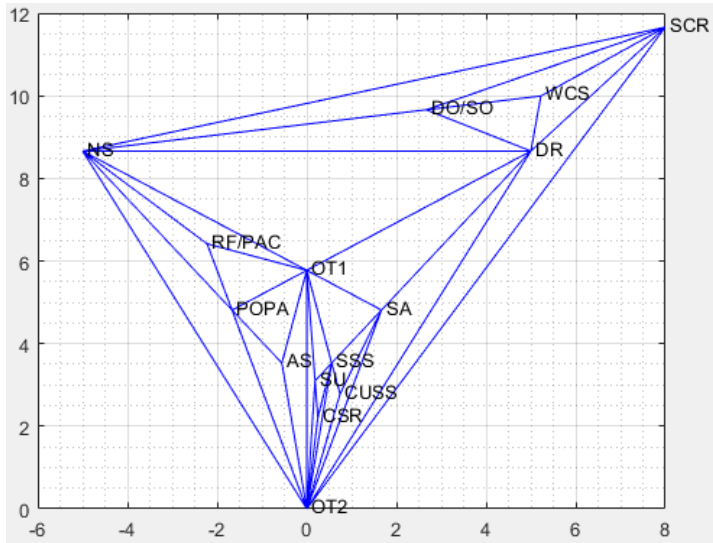


Figure: Iteration #11

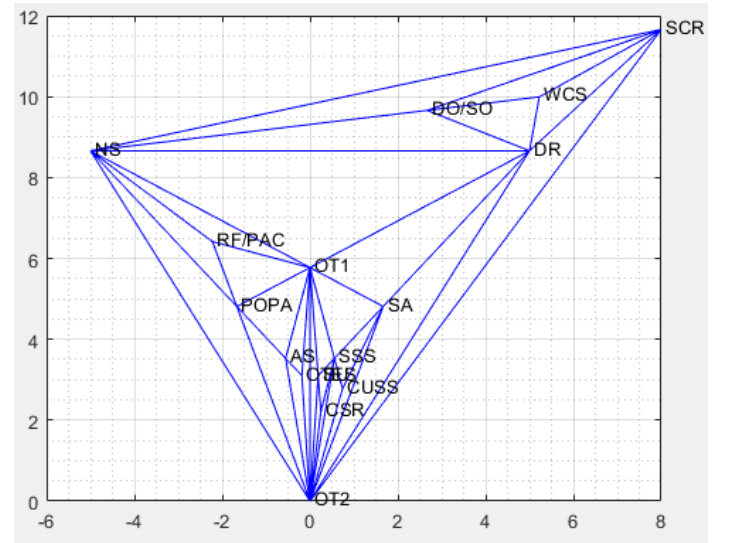


Figure: Iteration #12

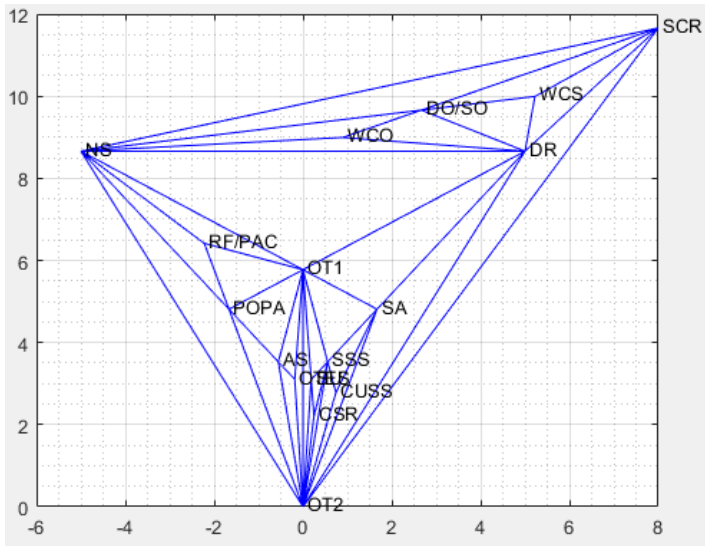


Figure: Iteration #13

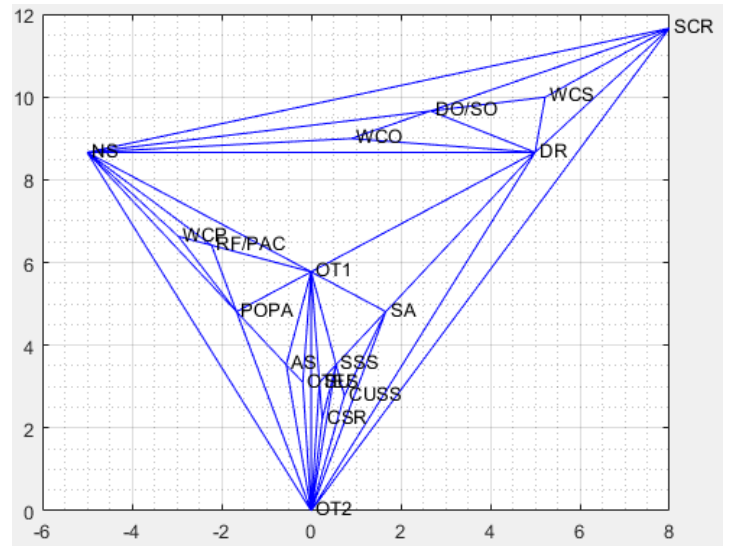


Figure: Iteration #14

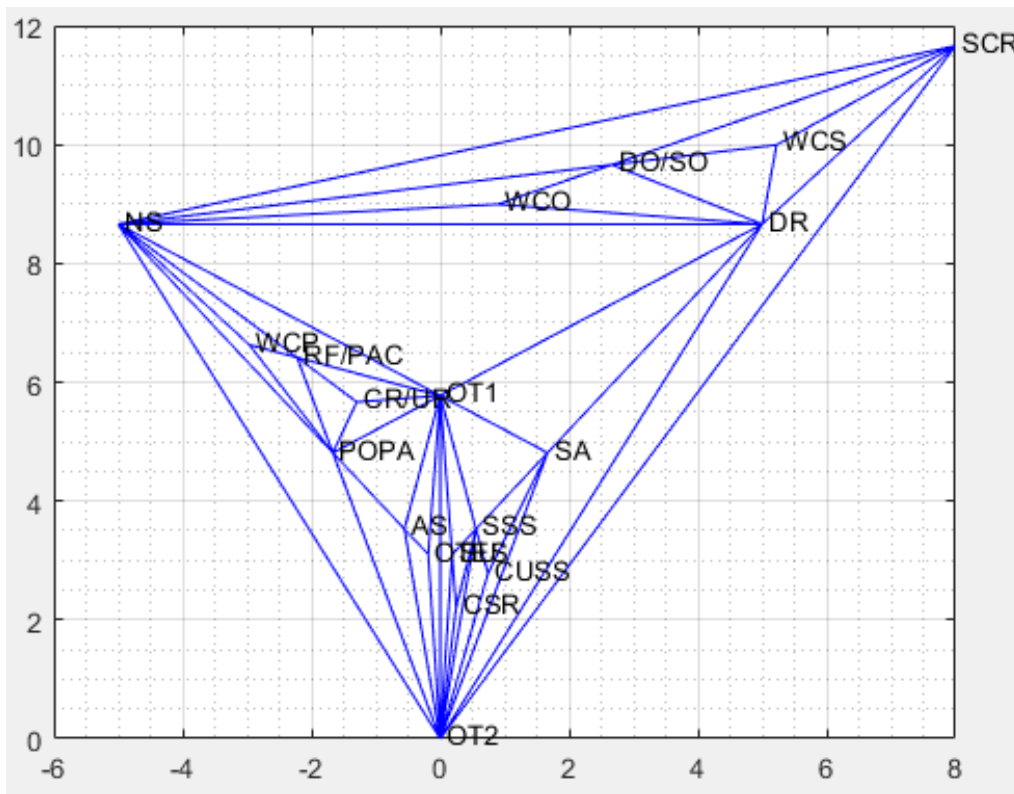


Figure: Iteration # 15