A NEW FRAMEWORK CONSIDERING UNCERTAINTY FOR FACILITY LAYOUT PROBLEM

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

$F(i,j)$	Total flow between a pair of departments
$d(i,j,\Pi)$	Rectilinear distance between department i and department j in the layout Π.
C	Cost to transport one unit of flow for one unit of distance.
μ	Mean of a normal random variable
σ^2	Variance of a normal random variable
$F_{stochastic}\lfloor x_{ij} \rfloor$	Matrix of stochastic variables that are normally distributed with mean μ and variance σ^2 respectively.
f_{15}	Flow of materials between department 1 and 5
x_{ij}	Stochastic variable between department i and j
$\sigma_{ij}^{\ 2}$	Variance of the total flow between department i and department j.
μ_{ij}	Mean of the total flow between department i and department j.
d_{ij}	Rectilinear distance between department i and department j
$d^2{}_{ij}$	Squared Euclidean distance between department i and department j
$F\ \lfloor u_{ij} \rfloor$	Expected value matrix of product demand forecast
$F\ \lfloor \sigma^2{}_{ij} \rfloor$	Variance matrix of product demand forecast
a	A lower limit of the triangular distribution
m	Mode of the triangular distribution
b	An upper limit of the triangular distribution
$\sum_{p=1}^{p} C_p^{\ Robust}$	Material handling cost when robust layout is applied to period p
$\sum_{p=1}^{p} C_p^{\ Optimal}$	Material handling cost of optimal layout of period p
$X^s{}_{ij}$	If facility i is assigned to location j for scenario s otherwise 0
c_{ij}	Fixed location cost associated with assigning facility i to location j

d_{jm}	Distance between site j and site m
f^{s}_{jk}	Flow of materials between facilities j and k for scenario s.
s	Number of scenarios or states
n	Number of departments
P_s	Probability of occurrence for each scenario
F_s	Flow matrix for each scenario
f_{ij}	Flow of material between department i and department j

LIST OF ABBREVIATIONS

ALDEP	Automated layout design program
AV	Average
AC	Ant colony
Arena	Arena simulation software to measure system strategies for optimized performance
BETAINV	An excel function to generate Beta random variables
BLOCPLAN	Block Plan
B&B	Branch and Bound
CDFLP	Constraint dynamic facility layout problem
CLMLP	Close loop machine layout problem
COFAD-F	Computerized facility design flexible
CORELAP	Computerized relationship layout planning
CRAFT	Computerized relative allocation facility technique
CP	Cutting plane
CPLEX	IBM IL OG CPLEX OPTIMIMZATION studio
CSP	Constrained shortest path
CT	Cut trees
D	Deviation from best known results
DFBC	Dynamic from between chart
DFLP	Dynamic facility layout problem
DHOPE	Dynamic heuristically operated placement evolution
DP	Dynamic programming
FACOPT	Facility optimization
FDMS	Fuzzy decision making system
FLP	Facility layout problem
FMS	Flexible manufacturing system
FRLP	Facility re layout problem
GA	Genetic algorithm
HAS	Hybrid ant systems
LayOPT	Layout optimization
LCRI	Layout configuration robust index

LINGO	Software designed to solve linear, nonlinear and integer optimization models
LOGIC	Layout optimization with guillotine cuts
LMLP	Loop machine layout problem
MCS	Monte carlo simulation
MFLAP	Multi objective facility layout planning
MHC	Material handling cost when PDF matrix is applied and average total MHC when mean matrix is applied
MHS	Material handling system
MIP	Mixed integer programming
MLP	Machine layout problem
MOFLP	Multi objective facility layout problem
MFP	Master facility plan
MULTI-HOPE	Multi floor heuristically operated placement evolution
MULTIPLE	Multi -floor plant layout evaluation
NLT	Non linear technique
NORMINV	An excel function to generate normal random variables
OFMLP	Open field machine layout problem
PDF	Product demand forecast
PLANET	Plant layout analysis and evaluation techniques
PROMODEL	Discrete event simulation software
QAP	Quadratic assignment problem
RAND()+	An excel function to generate a uniformly distributed random number between 0 and 1
REL	Relationship chart
SA	Simulated Annealing
SABLE	Simulated Annealing based layout evaluation
SD	Standard deviation of total material handling cost
SFLP	Static facility layout problem
SRMLP	Single row machine layout problem
Stochastic FLP	Stochastic facility layout problem
TCF	Time complexity function
TFP	Total facility penalty

TPC	Total penalty cost
VAR of layout	Variance of the total material handling cost of the layout configuration
VIPPLANOPT	Visually interfaced package of PLAN Layout OPTimization

ABSTRACT

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In today's dynamic environment, where product demands are highly volatile and unstable, the ability to design and operate manufacturing facilities that are robust with respect to uncertainty and variability is becoming increasingly important to the success of any manufacturing firm in order to operate effectively in such an environment. Hence manufacturing facilities must be able to exhibit high levels of robustness and stability in order to deal with changing market demands. In general, Facility Layout Problem (FLP) is concerned with the allocation of the departments or machines in a facility with an objective to minimize the total material handling cost (MHC) of moving the required materials between pairs of departments. Most FLP approaches assume the flow between departments is deterministic, certain and constant over the entire time planning horizon. Changes in product demand and product mix in a dynamic environment invalidate these assumptions. Therefore there is a need for stochastic FLP approaches that aim to assess the impact of uncertainty and accommodate any possible changes in future product demands.

This research focuses on stochastic FLP with an objective to present a methodology in the form of a framework that allows the layout designer to incorporate uncertainty in product demands into the design of a facility. In order to accomplish this objective, a measure of impact of this uncertainty is required. Two solution methods for single and multi period stochastic FLPs are presented to quantify the impact of product demand uncertainty to facility layout designs in terms of robustness (MHC) and variability (standard deviation). In the first method, a hybrid (simulation) approach which considers the development of a simulation model and integration of this model with the VIPPLANOPT 2006 algorithm is presented. In the second method, mathematical formulations of analytic robust and stable indices are developed along with the use of VIPPLANOPT for solution procedure. Several case studies are developed along with numerical examples and case studies from the literature are used to demonstrate the proposed methodology and the application of the two methods to address different aspects of stochastic FLP both analytically and via the simulation method. Through experimentation, the proposed framework with solution approaches has proven to be effective in evaluating the robustness and stability of facility layout designs with practical assumptions such as deletion and expansion of departments in a stochastic environment and in applying the analysis results of the analytic and simulation indices to reduce the impact of errors and make better decisions.

DECLARATION

I hereby declare that no portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute of learning.

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DEDICATION

I dedicate this work to, My Mother, My brother
Who give me before I ask?
My Wife, My sister
Who support me always?
And My Lovely Children; Hanadi, Mohamed and Ala

CHAPTER 1

INTRODUCTION

1.1 Facility Layout Problem concept

The Facility Layout Problem (FLP) is concerned with the physical arrangements or layout of departments in a given space. It is an important issue in the design of both manufacturing and service systems. The FLP is a broad subject in the field of industrial engineering where different types of problems can have significant impact on the viability and productivity of manufacturing and service systems. FLPs arise in: manufacturing (layout of departments in a given space); warehousing (layout of available space to minimise storage cost and material handling cost); hospitals (layout of departments to minimise the total moving distance per patient); and location of public facilities (layout of schools, police stations), etc.

In manufacturing systems, the FLP can be defined as the allocation of the departments or machines in a facility with an objective to minimise the total material handling cost of moving the required materials between the departments (Jithavech and Krishnaan, 2009). An effective arrangement of departments in a facility is a fundamental strategic issue facing most manufacturing systems. A properly designed facility reduces material handling cost, increases productivity, provides competitive advantage and accommodates changes in product design, production volume and product mix. The prime focus of many FLP researchers is on minimising the material handling cost (MHC), which is a function of the product of the flow quantity between departments travelled times the distance travelled. Estimates show that over $300 billion is spent annually in the United States (US) on facilities that require designing or redesigning.

Further, between 20%-50% of operating expenses in a manufacturing facility are related to MHC and a properly designed facility can reduce these costs by 10-30% (Tompkins et al., 2010). The estimates highlight that FLP requires long-term planning and any redesigning or modifications of the present layout are highly expensive, especially when production has to be stopped. In order to avoid future redesigning costs, the early stage of the layout design process should incorporate stochastic approaches that aim to design and evaluate potential layouts to ensure the optimum reduction in MHC and its efficiency over time before the layout design is implemented in real-life scenarios. The reduction in MHC is obtained by changing the position of departments in the layout so that the distance moved by material handling carriers between the departments is minimised.

The FLP is a well-studied combinatorial optimisation problem that is commonly formulated as a Quadratic Assignment Problem (QAP). The QAP is a mathematical model for assigning n equal area departments to n equal area locations such that the distance of material travel is minimised (Madhusudanan Pillia et al., 2011). The QAP has shown to be non-polynomial NP-hard (i.e., the problem cannot be solved in a reasonable amount of time). The term NP-hard depends on the Time Complexity Function (TCF). The TCF is defined as the greatest amount of time required by an algorithm to solve the QAP problem. In order to illustrate TCF, the following example is adopted from Heragu (2006): "If the TCF of an optimal layout is n, then it requires 10 times as much computer time to solve a problem with 100 departments as it does to solve a problem with 10 departments. On the other hand, if TCF of another algorithm is 2^n and it takes 1 second to solve the 20 department problem, it will take 366 centuries to find the solution to the 60 department problem". For an FLP with unequal area departments, Komarudin and Wong (2009) reported that the ant colony approach requires 23.33 hours to solve 35 departments. Table 1.1 is adopted from Heragu (2006) to show the computation time requirement comparison of polynomial and non-polynomial algorithms to solve FLP.

Table 1.1 Computation time requirement comparisons of P complete and NP-Hard (Heragu, 2006)

Time complexity function	Problem Size				P or NP-Hard
	N=10	N=20	N=40	N=60	
n	.001 seconds	.002 seconds	.004 seconds	.006 seconds	P- complete
n^3	.001 seconds	.008 seconds	.064 seconds	.216 seconds	P- complete
2^n	.001 seconds	1.0 second	12.7 days	366 centuries	NP-Hard

Much research has been done to develop several techniques to solve the FLP. QAP and mixed integer programming have been commonly utilised as an optimisation approach to model equal area and unequal area FLPs respectively. These optimisation approaches have shown to be NP-hard. Although a number of exact (optimal) algorithms such as Branch and Bound (B&B) have been proposed, finding an optimal solution for large-sized practical problems is still extremely hard and challenging because it requires high memory, whilst computational complexities increase exponentially as the number of departments increase (Xie and Shinidis, 2008). Alternatively, in order to obtain good solutions in a reasonable amount of time, various heuristic algorithms have been used to counteract the limitation of exact algorithms. The heuristic algorithms for solving FLP can be classified as construction type algorithms, where a solution is constructed from scratch to generate the layout, and improvement type algorithms, where an initial solution is used as input data to find improvements. Further heuristic algorithms can be classified according to their objective functions. The two objective functions are:

- Distance-based objective is used when the input data is quantitative and is given in the form of a from-to chart;
- Adjacency-based objective is used when the input data is qualitative and is given in the form of a Relationship (REL) Chart (Singh and Sharama, 2006; Tompkins et al., 2003).Surveys of some exact algorithms and heuristics based on their objectives for solving FLP are provided in Table 1.2.

Table 1.2 Some exact algorithms and heuristic approaches based on their objectives for solving FLP (Welgama and Gibson, 1995; Tompkins et al., 2003; Heragu, 2006)

Name of algorithm	Exact/Heuristic	Type	Distance/Adjacency
Branch and Bound	Exact	Construction	Distance
Cutting plane	Exact	Construction	Distance
ALDEP	Heuristic	Construction	Distance
CORELAP	Heuristic	Construction	Adjacency
NLT	Heuristic	Construction	Distance
FACOPT	Heuristic	Construction	Distance
CRAFT	Heuristic	Improvement	Distance
COFAD-F	Heuristic	Construction	Distance
PLANET	Heuristic	Hybrid	Both
BLOCPLAN	Heuristic	Hybrid	Both
LayOPT	Heuristic	Improvement	Distance
LOGIC	Heuristic	Construction	Distance
VIP-PLANTOPT	Heuristic	Hybrid	Distance

1.2 Types of layouts

There are four basic types of layouts and these can be classified as product layout, process layout, fixed position layout and group technology layout (Tompkins et al., 2003, 2010; Heragu, 2006; Drira et al., 2007).

1.2.1 Product layout

Product layout is known by names such as flow-line layout, assembly line layout and production layout. In a product layout, the machines and workstations are arranged according to the sequence of operations. Figure1.1 shows a typical product layout. The product layout is used by different factories, such as assembly plants, that manufacture either a single item or a few items in large quantities. Advantages of product layout include: high equipment utilisation leading to low unit costs; few operators are needed with increased automation; and a high rate of production can be achieved with simple planning and control. On the other hand, disadvantages include: the requirement of high initial investment; machine failure stops the whole line; and changes in product design render the layout obsolete (Tompkins et al., 2003; Heragu, 2006).

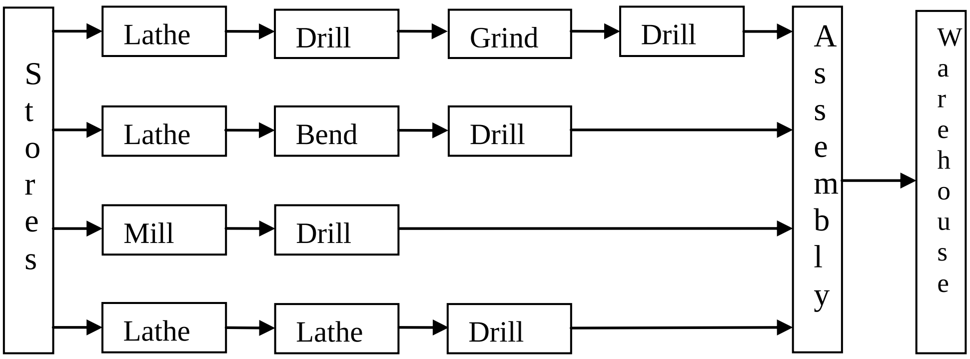


Figure 1.1 Product layout (Tompkins et al., 2003)

1.2.2 Process layout

Process layout is known by names such as job shop layout and functional layout. In a process layout, all operations of the same type are grouped together. For example, all milling machines are placed together in one department; all drilling machines are placed together in another and so on. Figure 1.2 shows a process layout. This layout is used by factories that manufacture different types of products or jobs in small quantities, where each job has a different sequence of operations from any other. Benefits of this layout include: the equipment is general purpose and less expensive; it allows a variety of products to be manufactured on the same equipment; and it allows an operator to become an expert in a particular function. Its disadvantages are: increased MHCs; decreased productivity; and the requirement of a high level of operator skills and supervision (Tompkins et al., 2003; Heragu, 2006; Drira et al., 2007).

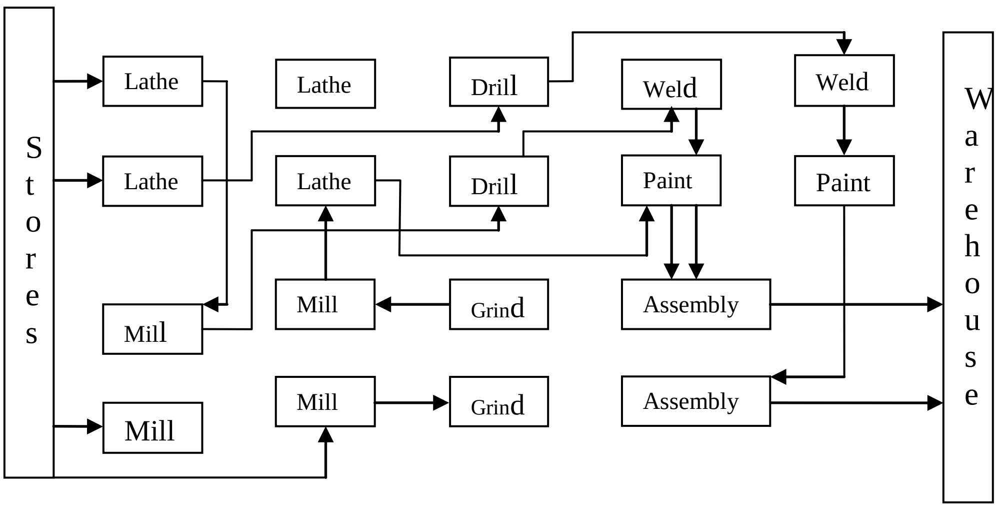


Figure 1.2 Process layout (Tompkins et al., 2003)

1.2.3 Fixed position layout

In a fixed layout the product is not moving, whilst resources (men, equipment, machines) are brought to where the product is located. This layout is useful for large and complex products that are not suitable for movement, such as shipyards, aircraft, and heavy constructions (buildings, bridges, roads, etc.). Advantages of a fixed layout include: minimal flow of materials; low fixed costs; and flexibility in product design changes. Disadvantages of a fixed layout include the requirement of high-level operator skills and close control and external factors, such as the weather, may affect the completion of projects.

1.2.4 Group technology layout

Group technology layout is sometimes called cellular layout. In a group layout, dissimilar machines are grouped and placed in work centres called cells that are used to process families of products that have some common characteristics with similar requirements. Figure 1.3 shows a group technology layout. Whilst this layout offers a reduction in setup time, decreased production costs and improved process capability, it has some disadvantages, including inadequate part families, increased machine downtime and the high cost of changing cells as the cell becomes out of date (Tompkins et al., 2003; Heragu, 2006).

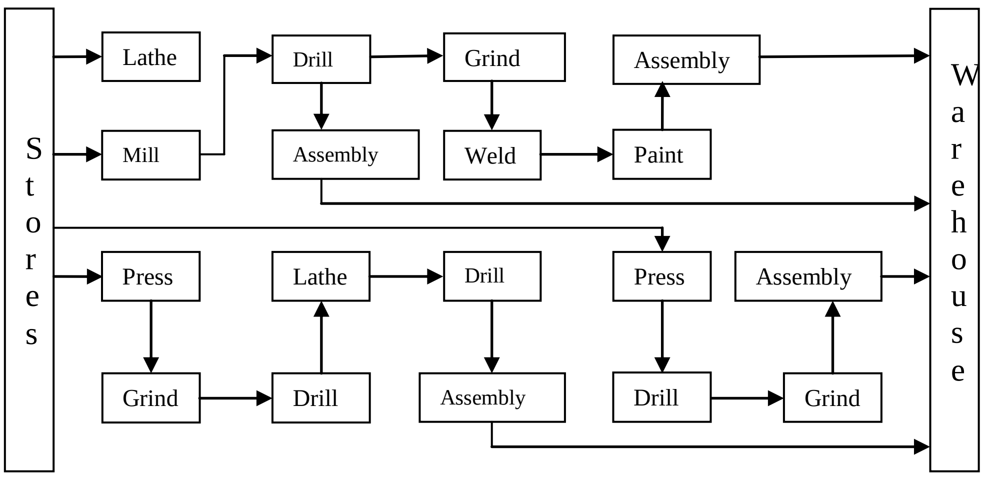


Figure 1.3 Group technology layout (Tompkins et al., 2003)

1.3 Facility Layout Problem research classification

Facility layout problem research can be classified as static or dynamic, depending on the nature of input requirements and the time period under consideration. The static facility layout problem (SFLP) approach assumes that the flow between pairs of departments, product demand and product mix are deterministic and this approach is usually performed for a single time period (Kamaldeep and Singh, 2010). In other words, the layout is designed without consideration of changes in product demands and product mix. Product demand is the quantity of each part type to be produced and product mix refers to a set of part types to be produced. On the contrary, a dynamic facility layout problem (DFLP) approach generally assumes that flow between departments, product demand and product mix are known with certainty and this approach is usually performed for multiple periods. In addition, in recent years, only a few researchers have attempted to address the SFLP and DFLP in a stochastic environment where product demand and product mix are represented by random variables with known parameters such as the mean, expected value and variance. The stochastic FLP approach aims to incorporate the true nature of many manufacturing environments and consider the uncertainty in product demands during the design of the facility layout (Jithavech and Krishnaan, 2009). The following sections provide a brief overview of the SFLP, DFLP and stochastic FLP approaches.

1.3.1 Static Facility Layout Problem

The SFLP approach assumes the flow of materials between departments, in the form of a from-to chart; it is also deterministic and constant over the entire time-planning horizon. The SFLP approach is a suitable method for analysing a single period layout problem by considering the product demand is stable for a long time period. The SFLP approach aims to determine the optimal location of departments by minimising the total MHC of moving the required material between the departments. In the literature, there has been a large amount of research that focuses on static facility layout problems. A comprehensive literature review on static layout research can be found in Kuisak and Heragu (1987), Welgama and Gibson (1995), Meller and Gau (1996) and, more recently, in Singh and Sharama (2006) and Drira et al. (2007).

Several optimisation formulation and heuristic algorithms based on different types of assumptions and constraints have been developed to solve the SFLP, such as: Branch and Bound (B&B) (Lawler, 1963); the quadratic assignment problem (Elshafie, 1977); graph theory (Hassan and Hogg, 1987); linear programming (Montereuli et al., 2002); non-linear programming (Van Camp et al., 1991); and mixed integer programming (Montereuil, 1990; Lacksonen, 1997). These optimisation approaches have shown to be NP-hard. Alternatively, heuristic algorithms such as simulated annealing (Dong et al., 2006), genetic algorithms (Krishnan et al., 2008), tabu search (Scholz et al., 2009; Machendall and Hakobyan, 2010), the ant colony (Komarudin and Wong, 2009), ALDEP (Seehof and Evans, 1967), CORELAP (Lee and Moore, 1967), non-linear programming (Van Camp et al., 1991), CRAFT (Armour and Buffa, 1963), MULTIPLE (Bozer and Meller, 1994) and FACOPT (Balakrishnan et al., 2003) have also been developed to overcome this computational difficulty.

1.3.2 Dynamic Facility Layout Problem

The general SFLP approach assumes that the flow of materials between departments in the form of a from-to chart is deterministic and constant over the entire time-planning horizon. Changes in product demand and product mix in a dynamic environment invalidate these assumptions, where markets are competitive and volatile in nature.

Therefore, the SFLP approach is not a suitable method for obtaining a good layout when flow data changes over time. Changes in the flow are the result of many factors, such as: fluctuations in product demand; changes in product mix; introduction of new products; and elimination of existing products. All these factors affect the flow of materials between departments and render the current facility layout inefficient and can increase the MHC, which may necessitate a change in the layout. (Krishnan et al., 2008) In order to maintain a good facility layout that operates effectively in a dynamic environment and which can handle changes in product demand and product mix, it is necessary to continuously assess the variations in product demand, the flow between departments/machines and the existing layout in order to determine the need for redesigning the layout (Madhusudanan Pillai et al., 2011). All this leads to the need for DFLP approaches for the development of layouts that overcome the disadvantages of the present layout and address future changes effectively.

The approaches that have been applied to solve the DFLP fall into two major categories (Madhusudanan Pillia et al., 2011):

- Flexible (adaptive or agile) approach;
- Robust approach.

The flexible approach assumes that product demands and product mix are known with certainty and layouts can be changed from one period to the next. This approach is preferred when there are considerable changes in product demands and product mix and when the MHCs are higher compared to rearrangement costs to construct the layout (Krishnan et al., 2008). Rearrangement costs can be defined as the cost of switching from one layout in one planning period to another in the next (Meng et al., 2004). Generally, the rearrangement costs may be viewed as a fixed cost due to the shutdown of operations or a variable cost due to moving the departments from their present location to a new location. However, in real-life scenarios, rearrangement costs are only guessed (Heragu, 2006). The use of a flexible approach requires the generation of the optimal layout in each period, adding the rearrangement costs and selecting the flexible layouts that minimise both MHCs and rearrangement costs. The objective of the flexible DFLP approach is generally to design the optimal layout for each period in the planning horizon with an objective of minimising the total MHCs and rearrangement (shifting) costs (Moslempour and Lee, 2011).

On the other hand, the robust approach assumes that product demands and product mix are known with certainty for multiple periods and the rearrangement costs are higher when compared to MHCs to construct the layout. The objective of a robust approach is to design a single layout that minimises the total MHCs in all periods and performs well for the entire planning horizon, even though product demand values or flow data are different in different periods of the planning horizon. The use of a robust approach to generate a single layout requires the generation of the optimal layout in each period, generating the optimal layout for the average flow (robust), applying the robust layout to various periods of the planning horizon, calculating its performance in terms of MHC in each period and identifying the percentage of the MHC for the robust layout with respect to the total optimal MHC in all periods. It is clear that the design of a single robust layout requires additional steps as compared with the design of a flexible layout. The robust approach is one of the methods used to design the most robust layout for a single period where multiple scenarios are considered, as well as for multiple periods. A comprehensive review of the DFLP can be found in Balakrishnan (1998), Konak (2007), Drira et al. (2007) and, more recently, in Moslemipour et al. (2011).

Rosenblatt (1986) was the first to present a systematic methodology to define and address the DFLP. He developed an optimal approach procedure based on dynamic programming (DP) for solving a DFLP with six departments and five periods. The DFLP is formulated as a QAP. The main idea is to generate the optimal layout in each period and to develop lower and upper bounds of the optimal solution. A lower bound value of the optimal solution to multiple periods is obtained by aggregating an optimal layout in each period and, in this case, no shifting costs are incurred. An upper bound is obtained by using either a flexible or robust approach. The flexible approach is to add the shifting costs to the lower bound; in this case, both flow of materials and rearrangement costs are incurred. The robust approach is to identify the minimal total MHC when the same layout is used for all periods. Rosenblatt suggested the use of heuristics, such as the Computerized Relative Allocation Facility Technique (CRAFT) or the Computerized Facility Design (COFAD), for large problems, to reduce the number of states in the DP model.

Since Rosenblatt's paper there has been continued research on developing heuristic algorithms to design robust or flexible layouts that can handle fluctuations in product demands and operate efficiently in dynamic environments. Therefore, some researchers have used the robust approach for the solution of equal area DFLP. Kouvelis et al. (1992) discussed the importance of designing robust layouts for manufacturing managers and suggested the use of a Branch and Bound (B&B) algorithm in which a single robust layout is generated for the DFLP. Suo and Lio (2008) discussed the concept of SFLP and DFLP and concluded that the robust approach is one of the most appropriate approaches for changeable and dynamic manufacturing systems. Hunagund and Madhusudanan (2007; 2008) mentioned the importance of designing a robust layout in real-life scenarios and developed a two-phase approach in which heuristic algorithms and LINGO mathematical modelling language are used to develop a single robust layout. This approach can handle up to nine equal departments. In their later work, Madhusudanan Pillia et al. (2011) developed a robust approach based on simulated annealing for solving the DFLP. Computational results indicate that the suggested method provides better performance and can solve up to 30 departments. Yang and Peters (1998) proposed a robust approach based on a construction-type algorithm for solving unequal DFLP. This approach can handle up to 12 departments.

On the other hand, some researchers have preferred the use of the flexible approach for the solution of DFLP. Baykasoglu and Gindy (2001), for example, proposed a simulated annealing approach to solve the DFLP whilst MacKendall et al. (2006) developed a hybrid approach based on simulated annealing to solve the DFLP. The results indicate significant improvements compared to existing procedures. Krishnan et al. (2006) developed a new tool called the dynamic from-between charts for solving the DFLP. Dunker et al. (2005) proposed a hybrid approach that combines DP and a genetic algorithm for solving unequal area DFLP.

1.3.3 Stochastic Facility Layout Problem

Forecasting techniques are the most commonly used techniques to project future product demands and product mix, which are the main input data for solving DFLP. However, forecasts are usually not accurate and thus the design of facility layout based on such forecasts turns out to be inefficient. This leads to the need for stochastic FLP approaches that are flexible enough to minimise the effects of the uncertainty and accommodate any possible changes in future product demands. The stochastic FLP approaches aim to incorporate the true nature of many manufacturing environments and to consider the uncertainty in product demands during the design of the facility layout. A recent review of stochastic FLP can be found in Moslemipour et al. (2011).

The stochastic FLP is modelled by using one of the following assumptions:

- A discrete set of product demand scenarios with known probability of occurrence; or
- A continuous set of product demand scenarios with known parameters of the probability density functions.

In recent years, some researchers have used the flexible approach to solve the stochastic single period FLP where multiple product demand scenarios with known probability of occurrence are considered. Shore and Tompkins (1980) developed a Computerized Facility Design Flexible (COFAD-F) routine to identify the most flexible layout for the stochastic single period unequal area FLP. Rosenblatt and Kropp (1992) presented an optimal solution procedure to generate the flexible layout for the stochastic single period equal area FLP. Their procedure involves compressing the flow matrices for the various states to a flow matrix for a single weighted average state and solving the resulting problem.

Some researchers have also used the robust approach to solve the stochastic single period FLP where the product demands are independent random variables and are normally distributed with known probability density function. Gupta (1986) presented a hybrid approach based on simulation and CRAFT to design flexible layouts with an objective to minimise the sum of weighted distance for the single period stochastic FLP. Longo et al. (2005) presented a hybrid approach to design a robust layout for the single period stochastic unequal area FLP. A genetic algorithm is first used to generate different layouts and, later, a discrete event simulation is used to evaluate the robust layouts under different scenarios. Bragila et al. (2003) used a simulation approach to design the most robust layout for the stochastic single raw machine layout problem. Liu et al. (2006) presented an approach based on simulated annealing and tabu search to design the robust layout for the stochastic single period unequal area FLP. Elsayed (2007) assumed stochastic material flow of 20%, 60% and 100% of the total flow and used simulation and tabu search to analyse the uncertainty of product demand under these scenarios.

In addition, only a few researchers have attempted to use the flexible approach to solve the stochastic equal area DFLP where multiple demand scenarios exist for each period and rearrangement costs are incurred. Savsar (1991) developed a simulation model to design the flexible layout for the stochastic multi-period FLP. Palekar et al. (1992) proposed the use of a DP approach in which the flexible layout is determined for the stochastic multi-period FLP. Krishnan et al. (2008) assumed a discrete set of product demand scenarios with known probability of occurrence and proposed the use of a genetic algorithm approach in which the flexible layout is generated for the stochastic multi-period FLP. Jithavech and Krishnaan (2009) presented a hybrid approach based on the @Risk simulation package and a genetic algorithm to design a flexible layout for the stochastic FLP in a single and a multi-period case. Moslempour and Lee (2011) used a simulated annealing approach to design a flexible layout for the stochastic multi-period FLP.

1.4 Drawbacks of FLP literature

Although extensive research on methodologies for solving FLP and the consideration of different types of assumptions and constraints has been conducted, research on stochastic FLP is limited and the use of a robust approach for DFLP and stochastic multi-period FLP is rarely considered. For instance, in the most recent research papers, Madhusudanan Pillai et al. (2011) recommended the use of a robust approach for unequal area DFLP as the direction for future studies and Moslempour and Lee (2011) also suggested the use of a robust approach for stochastic multi-period FLP as future work. In addition, no systematic methodology to construct robust layouts for DFLP and multi-period-stochastic FLP has so far been presented. The major drawback of many previous research efforts is that the findings are limited in applicability to practice because of the underlying assumptions, such as: the single objective function; deterministic flow; the assignment of a probability value to the from-to-chart; equal area departments; and only addressing small-size problems. Therefore, there is a need for systematic methodology to address the multi-period stochastic FLP and also to design, evaluate and select the most robust layout. There is also a need for new approaches that consider realistic assumptions, such as: the addition of departments; the deletion of departments; the expansion of departments; complex product demand distributions; and the simultaneous solving of larger FLPs with equal and unequal areas that have not been well addressed in the literature previously. More importantly, there is a need for systematic methodologies and solution approaches in a stochastic environment that account for applicability in practice and enhance the current research.

1.5 Research purpose

In a manufacturing environment that is characterised by a high degree of volatility and variability, assessing the forecasted product demands is one of the critical issues in designing an efficient layout, especially during the early stages of the design process. The first critical step in designing a manufacturing facility is to determine the volume of products to be produced within the facility. The volume of products is typically obtained by using forecasting techniques. However, such forecasts may or may not be accurate. Indeed, in many situations the uncertainty of the forecasted product demands and expected product demand distributions, which are obtained by forecasting and fitting technique, respectively, should be considered and evaluated during the early stages of the design of the manufacturing facility. In such situations, each manufacturing facility design has an expected MHC value and a variance value; these values should be quantified and used as criteria to select the optimal layout design. In order to quantify the uncertainty whilst considering manufacturing facility design with realistic assumptions, the layout design process requires the incorporation of stochastic approaches that evaluate the robustness and stability of facility layout designs in a stochastic environment, thus significantly reducing the impact of errors.

1.6 Research aim and objectives

The aim of this research is to present a systematic methodology in the form of a framework that allows the layout designer to: incorporate uncertainty in product demands into the design of a facility layout; show how to assess product demand forecasts; design robust layouts; evaluate robust layouts over time; and how to perform uncertainty analysis to select the optimal layout design under consideration. In order to achieve this aim, and as a result of developing such a methodology, the following objectives may be identified:

- **Objective 1**

Develop a simulation model to generate random variables with known mean and Standard Deviation (SD) and integrate this model with VIPPLANTOPT 2006 to evaluate the generated layouts and to quantify the impact of product demand uncertainty to facility layout designs in terms of robustness (MHC) and variability (SD). This development and integration process is described in Chapter Three.

- **Objective 2**

Develop two analytic robust and stable indices to evaluate any set of layouts and to quantify the impact of product demand uncertainty to facility layout designs in terms of robustness (MHC) and variability (SD) when the flow changes stochastically with known mean and variance. This development is presented in Chapter Four.

- **Objective 3**

Apply the developed analytic indices and simulation approach to address the single period stochastic FLP with unequal area and validate the effectiveness and efficiency of the proposed approaches via small, medium and large case studies (12, 20 and 30 departments). This application and validation is also described in Chapter Four.

- **Objective 4**

Develop a framework to enhance the application of the developed analytic indices and simulation approach to address the multi-period stochastic FLP with unequal area and validate the effectiveness and efficiency of the proposed framework via small, medium and large case studies (12, 20 and 30 departments). This development and validation is discussed in Chapter Five.

- **Objective 5**

Evaluate the performance of VIPPLANOPT 2006 software to address the QAP for the first time via a set of data that are taken from the literature and develop a new robust index to reduce the computation time for discrete stochastic FLP with equal area. This evaluation and the development of a robust index are presented in Chapter Six.

- **Objective 6**

Apply the developed framework to address single and multi-period stochastic FLPs with equal area and validate the framework via two case studies (30 departments). This application and validation is also discussed in Chapter Six.

1.7 Research motivation

The motivation of this research is to develop stochastic approaches that can realistically capture four important characteristics of the stochastic FLP that have not been well addressed:

- The product demands follow different types of distributions, such as normal, uniform and triangular, and change stochastically with a known mean and variance;
- A lack of existing approaches that consider the addition, deletion and expansion of departments;
- A lack of existing approaches for solving large-sized FLPs with equal and unequal areas simultaneously;
- A lack of existing approaches for evaluating a given set of layouts with hard constraints or complex geometry that may be preferred by the layout designer in terms of robustness and stability under a stochastic environment.

1.8 Research methodology

This section outlines the research methodology and describes the sequence of logical strategies followed in order to achieve the research aim. To illustrate the proposed methodology, it is essential to state a clear research question. The basic research question of this research is: How can the robustness and stability of facility layout designs under stochastic product demands be evaluated?

To achieve the research aim and address the research question, the sequence of the following strategies are identified:

1- Review previous work on FLP

A comprehensive literature review on static FLP, DFLP and stochastic FLP is conducted by searching such sources of information, such as the university library system, textbooks, academic journals and conference proceedings—using both manual and electronic means and utilising appropriate keywords. The comprehensive literature review on static FLP, DFP and stochastic FLP includes: layout types; robust approaches; flexible approaches; simulation approaches; exact approaches; the QAP; heuristic algorithms; single period stochastic FLP; multi-period stochastic FLP; and methodologies for discrete and continuous stochastic FLP. Section 2.2 presents solution approaches based on different assumptions and considerations in addressing the SFLP. Section 2.3 provides solution approaches based on different assumptions and constraints to address the DFLP. Section 2.4 gives in-depth detail about the stochastic single period and the stochastic multi-period FLP. Section 2.5 provides a conclusion on FLP literature.

2- Select the most appropriate optimisation approach

VIPPLANOPT 2006 software (Visually Interfaced Package of PLAN Layout OPTimization) is a research product developed by Engineering Optimization Software to solve static unequal FLP in an open field (www.planopt.com). In this thesis, this software is selected and utilised for the first time as an optimisation approach to construct the proposed methodology because it has the ability to:

- Provide a good graphical friendly interface that is preferred by layout designers in practical applications.
- Generate high quality solutions in a reasonable amount of time.
- Handle large-sized problems.
- Handle intricacies of unequal area departments.
- Evaluate the performance of layout designed for state i and used in state j (different from-to chart)
- Optimize inside a given boundary shape.

In addition, the author has engaged in several e-mail communications with Engineering Optimization Software to seek information and discuss software issues.

3- Develop a hybrid (simulation) approach (objective 1)

To achieve the first objective, chapter three presents the two phases of the hybrid approach that considers the development of a simulation model and the integration of this model with VIPPLANOPT 2006 software. Section 3.3.2 describes the steps required to develop a simulation model whereas section 3.3.3 presents the integration of VIPPLANOPT 2006 software with the simulation model. A 10-department case study is developed to validate the effectiveness of the simulation approach to address the single period stochastic FLP.

4- Development of new analytic robust and stable indices (objective 2)

Bragilia et al. (2003) presented a methodology and developed the Layout Configuration Robust Index (LCRI) to estimate the robustness of layout configuration in a stochastic environment. However, manual calculations are required to apply the LCRI that may not be practical for large-size problems. In this thesis, the author investigates the previous methodology in order to improve and explore new solution approaches that eliminate the need for manual calculations and address different aspects of stochastic FLPs as well. To achieve the second objective, two analytic indices are developed and validated via numerical examples from Bragilia et al. (2003). The first index is referred to as the robust index whereas the second is referred to as the stable index. The aim of these indices is to evaluate the robustness and stability of facility layout designs under stochastic product demands. The development and mathematical formulation of analytic robust and stable indices is given in section 4.3.

5- Apply the analytic and simulation approaches to address the single period stochastic FLP (objective 3)

Once the simulation and analytic approaches are developed, they are applied to assess the product demand forecast and address the single period stochastic FLP. Section 4.5 presents the development of three case studies to gauge the efficiency of the proposed approaches to evaluate facility layout designs in a stochastic environment and quantify the impact of uncertainty. Computation results indicate that the analytic and hybrid approaches are effective in assessing the uncertainty of product demands to ensure the efficiency of the selected layouts over time and in applying the analysis results to make better decisions.

6- Development of a framework for multi-period stochastic FLP (objective 4)

To enhance the application of the proposed analytic and simulation approaches and achieve the aim of this research, section 5.2 presents the steps required to develop a framework for the design of optimal robust layout design for multi-period stochastic FLP. The framework consists of three phases and aims to address different aspects of stochastic FLPs. The first phase is the generation of optimal layouts. The second phase is the evaluation of the robustness and stability of the facility layout designs by using the analytic and simulation approaches. The final phase is the selection of the optimal layout design in terms of robustness and/or stability. The framework is also validated via case studies and computation results confirmed that it is efficient in reducing the impact of uncertainty. Using the three phases, the layout designer can design and evaluate any set of robust layouts that are preferred by changing the parameters of the input data; for instance, project layout against robust layout, stable layout against initial layout, robust layout against adaptive layout and so on. The layout designer can also design robust layouts, evaluate any set of layouts and select a single layout for DFLP and single period stochastic FLP by eliminating time periods and multi-period stochastic FLP.

7- Evaluate the performance of VIPPLANOPT software to address the QAP and develop a new robust index to reduce the computation time for discrete stochastic FLP with equal area. (objective 5)

To strengthen and generalise the proposed framework to address different aspects of stochastic FLP, the performance of VIPPLANOPT 2006 software to address the QAP is tested for the first time via a set of six problems ranging in size from six departments to 30 departments that are taken from the literature. This set of problems became an acceptable benchmark and is widely used by researchers for evaluating different solution techniques (Rosenblatt and Golany, 1992; Hu and Wang, 2005). Based on comparison data provided in Table 6.1, the performance of VIPPLANOPT 2006 outperforms seven of 10 heuristics for solving the QAP. Therefore, VIPPLANOPT 2006 is a new and effective tool to address this type of hard optimisation problem. Once the VIPPLANOPT 2006 software had proved to be effective in addressing the QAP, the author investigated Rosenblatt and Kropp's (1992) methodology for discrete stochastic FLP in order to improve and explore new solutions that eliminate the need for manual calculations and the use of Shore and Tompkin's (1980) TFP (Total Facility Penalty) as criteria to evaluate the robustness of facility layouts in terms of MHC (single objective). Section 6.3.2 presents the development of a new robust index for discrete stochastic FLP and the validation of the proposed robust index via a numerical example from Rosenblatt and Kropp (1992).

8- Apply the proposed framework to address the single and multi-period stochastic FLP with equal area (objective 6)

In order to generalise the application of the proposed framework to address the single period stochastic and the multi-period stochastic FLP with equal area, two case studies (30 departments) are developed in sections 6.4.1 and 6.4.2, respectively. The results of the case studies confirm that the proposed framework is effective in evaluating the robustness and stability of facility layout designs under different scenarios.

9- Justify the proposed methodology via small, medium and large case studies

As mentioned earlier, the literature review indicates that very little attention is actually given to the design and evaluation of robust layouts with practical assumptions, such as the addition, deletion and expansion of departments in a stochastic environment. Therefore, small, medium and large case studies are constructed to validate and justify the proposed methodology. In those case studies, a process layout is assumed. However, the proposed methodology can be used in the same manner depending on the capability of the VIPPLANTOP 2006 software to address different layout types—for instance, product layout in section 4.3.2.

1.9 Chapter outline

This thesis is organised into seven chapters. Chapter One presents the concept of the facility layout problem and types of layouts and also provides a brief overview of facility layout problem research classification, along with the drawbacks of the literature review. The aim and objectives are outlined and the purpose and motivation of the research are established. The research methodology is also discussed.

Chapter Two presents a detailed survey of the current and existing literature relevant to the publications concerning the static facility layout problem, the dynamic facility layout problem and the stochastic facility layout problem.

Chapter Three presents a hybrid (simulation) approach in which a simulation model is developed and integrated with VIPPLANOPT 2006. It also includes the development of a case study to illustrate the effectiveness of the developed approach.

Chapter Four details the development of new robust and stable indices along with the use of the hybrid approach to address the single period stochastic FLP while considering hard constraints. The ability of the proposed approaches to address such a scenario is tested and confirmed via small-, medium- and larger-sized problems.

Chapter Five presents a framework for the solution of multi-period stochastic FLP with unequal area using the proposed analytic and hybrid approaches. Several case studies are constructed to gauge the effectiveness of the proposed framework for solving different aspects of multi-period stochastic FLP.

Chapter Six provides the application of the developed framework to address the QAP. A new robust index is also developed and formulated to reduce the computation time by 1/n factor where n is the number of solution times for discrete stochastic FLP with equal area. In addition, the validity of the proposed framework is verified using single period and multi-period case studies.

Finally, Chapter Seven demonstrates that the aim and objectives outlined earlier in this thesis have been met and that the findings provide contributions to research in the FLP area. The chapter also suggests possible future extensions of this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

FLP has attracted the attention of many researchers in the last five decades. It is practical, complex and a broad subject and even simple small sized problems of robust layout may result in much complexity. As a result, researchers from different universities and institutes and other disciplines including operation researchers, industrial, mechanical, chemical and electrical engineers, economists and urban planners, etc., have contributed to the development of the FLP area. Their combined effort has resulted in the development of SFLP, DFLP and stochastic FLP approaches that assist the layout designer in generating layouts in different environments. As stated in the previous chapter, the prime focus of this research is on designing robust layouts for DFLP as well as stochastic FLP when the product demands change dynamically and stochastically over time.

This chapter details the current and existing literature relevant to the publications concerning SFLP, DFLP and stochastic FLP. Section 2.2 presents solution approaches based on different assumptions and considerations to address the SFLP. Section 2.3 provides solution approaches based on different assumptions and constraints to address the DFLP. Section 2.4 gives in-depth detail about the stochastic single period and the stochastic multi-period FLP. Section 2.5 provides a conclusion on FLP literature.

2.2 Static Facility Layout Problem (SFLP)

The SFLP approach assumes that the flow of materials between departments in the form of a from-to chart is deterministic, constant and known a priori for a single time period. The from-to chart is a matrix where each element represents the total cost of the materials flow per unit distance between a pair of departments. In addition, the output of the SFLP approach is a block layout that specifies the size and shape of departments, as well as their relative locations. A detailed layout of departments is obtained by handling additional constraints such as input/output points and aisle structure. Researchers have studied and investigated the application of SFLP approaches since the mid 1950s. As a result, there were different solution approaches based on different assumptions and considerations that have been used to address this problem. These assumptions and considerations include the facility shape, geometry and multi-objective, multi-storey layout of the flexible manufacturing system and material handling system. The importance of these assumptions is discussed below.

A facility is usually represented as a block with a certain shape. According to Tam and Li (1991), there are three shapes that are used to represent a facility; these include rectangles, squares and circles. A rectangle block is the most widely used to represent a facility. A square block is a special case of a rectangle with equal height and width. A circle block is seldom used when solving an SFLP. Chiang (2001) defined the important geometric characteristics of a facility, such as aspect ratio, shape, size and orientation.

The rectilinear distance metric is the most widely used criteria to measure a distance from centre to centre of the departments or between the locations of input and output points. Rosenblatt and Golany (1992) proposed an approach based on assigning distances between pairs of equal area departments to pairs of equal area locations. A network formulation is used to solve distance assignment problems. Bozer and Meller (1997) studied different distances to determine the expected (rectilinear) distance between two departments when input and output points of the department are not known in a detailed layout. Montreuil et al. (2002) proposed a continuous model that can solve the SFLP while taking into consideration the location of input and output points. The proposed model is a linear programming model and can be solved by using CPLEX software.

In addition, most SFLP approaches use the distance-based objective when the input data is quantitative and is given in the form of a from-to-chart as a criterion to generate and evaluate the layouts with an objective to minimise the MHC. This objective is usually formulated as a QAP. However, some researchers have considered that using only a quantitative objective is not realistic for solving the FLP as it provides only partial solutions. Therefore, the complete solution requires the need for both quantitative and qualitative objectives to be considered during the layout design process. Earlier research by Rosenblatt (1979) involved the development of a heuristic algorithm to combine quantitative and qualitative objectives to solve the Multi-Objective Facility Layout (MOFLP). The objectives are to minimise the material handling cost and maximise the closeness rating measure. Rosenblatt utilised an optimisation approach to generate different layouts and, by specifying the different weights for these objectives, the best layout is obtained. Wanghodekar and Sahu (1986) proposed a construction heuristic called Multiple objectives Facility Layout Planning (MFLAP) to deal with conflicting and congruent objectives. Harmonosky and Tothero (1992) proposed an approach that can handle more than two factors or parameters while solving MOFLP. The proposed approach is efficient for larger-sized problems with equal area and can handle up to nine factors. Chen and Sha (2005) presented a heuristic approach based on generating efficient layouts to solve the MOFLP. They concluded that the generation and evaluation of various efficient solutions to MOFLP is a hard task, due the lack of a suitable measure that considers multiple objectives.

There were also different solutions approaches developed to solve SFLP, such as: Branch and Bound (B&B) (Lawler, 1963); QAP (Elshafie, 1977); graph theory (Hassan and Hogg, 1987); simulated annealing (Meller and Bozer, 1996); genetic algorithms (Isiler, 1998; Tate and Smith, 1995; Wang, 2004); tabu search (Chaing and Kouvelis, 1996, Chiang 2001); linear programming (Montereuli et al., 2002); non-linear programming (Van Camp et al., 1991); mixed integer programming (Montereuil, 1990; Lacksonen, 1997); general guidelines (Kuisak and Heragu, 1987; Hassan, 2002); comparison between different techniques (Wilsten and Shayan, 2007); particle swarm optimization (Lien and Cheng, 2012); hybrid systems (Tseng et al. 2012) and the Machine Layout Problem (Afentakis et al., 1990; Das, 1993).

Due to the high cost of land, the lack of available horizontal space and the need to expand in a vertical dimension, the concept of transforming a two-dimensional (2D) FLP into a three-dimensional (3D) FLP is presented by Bozer et al. (1994), who developed an algorithm similar to CRAFT called MULTI-floor Plant Layout Evaluation (MULTIPLE) to deal with the multi-storey FLP. Meller and Bozer (1996) proposed another improvement-type algorithm called Simulated Annealing Based Layout Evaluation (SABLE) based on simulated annealing for improving the solution quality. The performance of the algorithm is compared with MULTIPLE and results show that SABLE is efficient in generating alternative layouts in terms of quality. Kochhar and Heragu (1998) also proposed an algorithm called MULTI Floor Heuristically Operated

Placement Evolution (MULTI-HOPE) based on a genetic algorithm to solve the multi-floor FLP. Computational results indicate that the proposed algorithm is effective in finding a number of good layouts and its solution quality is better than MULTIPLE and SABLE. Barbosa-Povova et al. (2002) proposed the use of a mixed integer linear programming formulation in which equipment units within a 3D multi-floor FLP are assigned.

In general, most facility layout problems are formulated as a QAP formulation. The use of the QAP formulation assumes that the departments have equal area, whilst the geometry and shape of departments are not considered. These assumptions are not valid for modelling all types of facility layout problems. For example, in the Machine Layout Problem (MLP), where the machines do not have the same shape and area, the distance between two machines cannot be computed a priori because the location of these machines are not known. Therefore, the layout of MLP cannot be formulated as a QAP formulation in such cases. This limitation of the QAP formulation motivates some researchers to use a continuous representation. The continuous representation models help to generate rectangular departments with boundaries in order to be located anywhere on a continuous plane. The MLP can be defined as the arrangement of machines on the factory floor in order to minimise the total time required to transfer material between machines (Das, 1993). According to Das (1993), the solution to MLP requires the selection of the type of process and Material Handling System (MHS) in order to perform the economic analysis and to develop a detailed machine layout. The layout of machines in a Flexible Manufacturing System (FMS), which is an extension of MLP, is defined by specifying the spatial coordinates of each machine, the vertical or horizontal orientation of each machine and the location of input/output points.

Heragu and Kuisak (1987) and Das (1993) also classified four layout types of MLP: the Single Row Machine Layout Problem (SRMLP); the Multi-Row Machine Layout Problem (MRMLP); the Loop Machine Layout Problem (LMLP); and the Open Field Machine Layout Problem (OFMLP). The use of continuous representation is presented by Montreuil (1990) who presented a mixed integer programming model (MIP) for MLP. The objective function minimises the material handling cost per unit of distance travelled. Similarly, Heragu and Kusiak (1991) developed two models to address the SRMLP and MRMLP. Tam and Li (1991) developed a hierarchical approach in which cluster analysis, initial layout and layout refinement are considered to generate good layouts using continuous representation. Computational results show that the proposed approach provides good layouts and these layouts are sensitive to the quality of initial layouts. Van Camp et al. (1991) developed a heuristic based on the Non-Linear programming Technique (NLT) that minimises the material handling cost. The heuristic is effective and yields good solutions compared with the existing technique. Houshyar and White (1992, 1997) proposed a heuristic approach based on integer programming to solve the SRMLP. This approach is valid for small-sized problems.

Similarly, Amaral (2006) proposed a MIP model to solve the SRMLP. First, a mathematical formulation is developed and, later, the CPLEX 8 software package is used to solve the model. The proposed model is tested using data taken from the literature and provides satisfactory results. Xie and Shinidis (2008) also presented a new approach based on modifying the Branch and Bound (B&B) algorithm to solve the MLP with continuous representation. The proposed approach provides good solutions compared to the existing approaches. Solimanpur and Jafari (2008) developed a mixed integer non-linear mathematical programming model to address the MLP. A B&B

approach is used to solve the model. Computational results show that the proposed approach provides good solutions for small- and medium-sized problems. Das (1993) also proposed a heuristic to solve the OFMLP. First, an MIP model is introduced and, later, a heuristic is developed. In order to find the best approach to solve the Closed Loop Machine Layout Problem (CLMLP), Panahi et al. (2008) compared three meta-heuristics, namely the Genetic Algorithm (GA), Simulated Annealing (SA) and Ant Colony approaches (AC), to solve the CLMLP with unequal area. The results of these heuristics are also compared with the LINGO 8 software package. Among these, the SA is found to be the most efficient heuristic to solve the CLMLP.

To obtain a good layout whilst considering MHS, it is essential to simultaneously integrate the block layout with devices such as conveyors and robots for solving MLP. For example, Aiello et al. (2002) suggested the use of the GA approach in which the location of departments and input and output points and the material handling device are considered for MLP. Wu and Appelton (2002) used the GA approach that considers both the layout and aisle structure for MLP. El-baz (2004) presented an approach based on the GA to solve the MLP. The proposed approach takes into account different types of manufacturing systems, including single row, multi-row and open field layout problems. The author assumed the flow data are certain and known a priori. Computational results show that the proposed approach provides good solutions. Fico et al. (2004) used the GA approach in which the best arrangement of automated guide vehicles in single and multi-rows are considered, along with the shape of rectangular machines. Test problems that include 14 devices are used to evaluate the approach. Computational results show that the proposed approach yields good solutions. Gapalakri et al. (2004) described and proposed an approach that integrates the raw material,

material handling system and warehouse inventory levels. The proposed approach aims to generate layouts that minimise overall material handling costs as well as floor space requirements.

The limitation of the QAP formulation also motivates some researchers to focus on developing models for solving unequal area FLP. Tam (1992) presented a heuristic based on SA to solve the FLP with unequal area in a continuous representation. Heragu (1992) and Lacksonen (1994) proposed MIP models that can handle unequal area constraints. Tam and Smith (1995) proposed the use of GA to solve an unequal area FLP. Similarly, Hu and Wang (2004) proposed an approach based on GA to solve an equal area facility layout problem. The proposed approach considers material flow factor, shape ratio and area utilisation. The proposed approach is tested using data taken from the literature and results indicate significant improvements compared with existing approaches. Liu et al. (2007) proposed the GA approach to tackle the intricacies of unequal area for FLP with a continuous representation. According to Balamurugan et al. (2006), the existing approaches for addressing the FLP with unequal areas may fall short of providing good solutions because they have some limitations, such as single design criteria, manual adjustment and approximated shape. The authors formulated and presented an approach based on GA to solve the MLP with fixed shape and size. Results indicate that the proposed approach generates layouts with minimal manual revision.

The use of fuzzy set theory to handle SFLP is presented by Evans et al. (1987) who proposed a fuzzy approach in which closeness and importance ratings are used to enable the layout designer to specify the importance associated with each pair of departments to be located in the layout. Dweiri and Meier (1996) also presented a fuzzy approach based on a fuzzy decision making system (FDMS) for FLP. First, a heuristic based on

FDMS is used to generate the REL chart and develop the layouts. Later, FDMS is used to evaluate the layouts. The evaluation process helps to score both the distance and REL chart in the layout. Deb and Bhattacharyya (2005) proposed a distinct decision support system based on a multi-factor fuzzy inference system for solving MLP. The proposed approach considers the location of pick-up and drop-off points in the desired layouts.

By taking different approaches to handle intricacies of unequal area departments, Chiang (2001) presented an integrated visual facility layout design model to solve the FLP with geometric constraints on a continual site. The proposed model considers that all departments have fixed sizes, shapes and orientation. The model uses the tabu search heuristic as the optimisation approach to find good solutions. Computational results show that the proposed model is effective and provides good layouts. Balakrishnan et al. (2003) developed a hybrid approach called Facility Optimization (FACOPT) based on GA and SA to solve the FLP. The heuristic can handle up to 30 departments and generates good layouts. Shayan and Chilttilappilly (2004) presented an approach based on GA to solve the FLP. A slicing tree structure is used to code a candidate layout into a tree structure. Computational results show the effectiveness of the approach, which can be used to solve large-sized problems.

The concept of incorporating workflow interference in FLP is presented by Chianget et al. (2006) who proposed a multi-objective approach for design automated systems and various layout problems. First, a mathematical model is introduced and, later, the CPLEX Package optimiser is used to solve the model. Wilsten and Shayan (2007) employed five SFLP approaches: Graph Theory (GT) (Foulds and Robinson, 1976); CRAFT (Armour and Buffa, 1963); the optimum sequence algorithm (Heragu, 1997); BLOCPLAN (Donaghey and Pire, 1991); and GA (Shyan and Chittippilli, 2004). Their objective was to find the best SFLP approach to solve a case study in practise. A case study of a furniture company that produces five products and consists of 12 departments is utilised to find the best approach. Computational results show that BLOCPLAN provides the best solution, followed by GT, then GA. The other approaches fail to provide good solutions.

In all of the SFLP approaches mentioned above, researchers have assumed a steady environment where the flow data in the form of a from-to chart is deterministic and known with certainty. However, changes in product demand and product mix in a dynamic environment invalidate these assumptions, where markets are competitive and volatile in nature. Therefore, there is a need for DFLP approaches that handle changes in product demand and product mix.

2.3 Dynamic Facility Layout Problem (DFLP)

The DFLP is used when the product demand or product flow between departments is forecasted and is different in different periods of the planning horizon. As SFLP, QAP is the most commonly used formulation with an extension to consider rearrangement costs in the objective function. The objective of DFLP analysis is to design a flexible or robust layout (Moslemipour et al., 2011). The flexible layout is a layout that minimises MHC as well as rearrangement costs when relocation costs are low and the need for re-layout is justified. On the other hand, the robust layout is a single layout that minimises the MHC in all periods even though product demand values are different in different periods of the planning horizon. In real-life scenarios, it is likely that robust layout is more popular than re-layout and robust layout is preferred by many manufacturing firms that are reluctant to incur the disruption to production and redesigning costs that are associated with re-layout (Benajaafar and Sheikhzadeh, 2000; Lahmar and Benjaafar, 2005; Krishnan et al., 2008).

The work by Rosenblatt (1986) was the first to present a systematic methodology for defining and addressing the DFLP. He utilised an optimal approach procedure based on DP in which flexible or robust layout is generated for DFLP. Flexible layout is obtained by generating the optimal layout in each period, adding rearrangement costs and selecting the flexible layout that minimises both MHCs and rearrangement costs. Robust layout is obtained by applying the optimal layout in each period to various periods of the planning horizon and selecting a single layout that minimises the total MHC while considering all periods. In this study, it is clear that the flexible layout, as well as the robust layout, represents the upper bound on the optimal solution.

Identifying bound procedure is very important in the analysis of DFLP. Since Rosenblatt's paper there has been continued research on the bounding procedure. Batt (1987) identified an upper bound by solving the DFLP as static in which the flow of all periods are aggregated in a single period to generate a single layout. As a result, Batt's upper bound dominates Rosenblatt's second approach in generating a robust layout because it reduces computational time by solving the static FLP only once. Urban (1992) made an attempt to develop a set of lower bounds for DFLP that require less computational time but that cannot guarantee tighter bounds.

In addition, Balakrishnan et al.(1992) extended the work of Rosenblatt (1986) by developing a different formulation to DFLP. This formulation is called the Constraint Dynamic Facility Layout Problem (CDFLP). They considered the case where a budget constraint exists for layout redesigning. For example, this may occur when the funds are limited to redesign the layout. So, under this constraint the DFLP is solved. They suggested the use of the Constrained Shortest Path (CSP) algorithm of Mote (1988), which is a combination of simplex method and enumerations strategy for the CDFLP. Tested problems including 12 departments and four periods, 15 departments and four periods, and 20 departments and four periods were tested and results show that CSP performs better than DP in most of the situations.

Further, Urban (1998) developed an optimal procedure to solve a special case of DFLP based on the concept of incomplete dynamic programming. The author considers the case in which rearrangement costs are assumed to be fixed. The idea of incomplete dynamic programming helps to reduce the computational time by eliminating the need to evaluate branches at each of the stages when rearrangement costs are not considered. Test problems ranging in size from six departments and four periods to 15 departments and eight periods are solved and the author concluded that the concept of incomplete dynamic programming is efficient for developing lower and upper bounds for the general DPLP with fixed costs.

The limitation of the QAP formulation also motivates some researchers to focus on developing heuristic approaches to reduce the computation time that increases as the number of departments and periods increase. Urban (1993) developed a steepest descent pair wise exchange heuristic that is similar to the CRAFT heuristic to solve the DFLP. The main difference is that rearrangement costs are considered when generating a flexible layout. Computational results show that the proposed heuristic provides good solutions, especially for large problems. Balkrishnan and Cheng (2000) also proposed an improved dynamic pair wise exchange heuristic to solve the DFLP. The proposed heuristic combined Urban’s (1993) heuristic with DP to solve larger-sized problems. Computational results show that the proposed modifications yield good results for 15 and 30 department problems. Kochhar and Heragu (1999) developed the Dynamic Heuristically Operated Placement Evolution (DHOPE) algorithm that is designed for the dynamic multi-floor FLP. The drawback of this algorithm is that it is restricted to solving only two periods with data known a priori. Yang and Peters (1998) proposed a construction-type algorithm that considers both rearrangement costs and unequal area DFLP.

In order to find an effective approach to design the flexible layout for DFLP, Lacksonen and Enscore (1993) modified five algorithms to find the best solution for DFLP. These algorithms are: CRAFT; cutting planes (CP); B&B; DP; and cut trees (CT). The idea is to make a comparison to find the best algorithm to solve the DFLP. Test problems ranging in size from six departments and three periods to 30 departments and five periods are solved. According to the results, the CP algorithm is found to be the best of the five algorithms for all test problems. Balakrishnan and Meng (2009) compared Urban’s (1993) heuristic and Balakrishnan and Cheng’s (2000) heuristic to find the best heuristic that performs well in fixed and rolling horizons. They conclude that heuristics that perform well under fixed horizons may not provide good solutions under rolling horizons and that identifying a heuristic that performs well in all situations is a hard task.

In addition, researchers have also applied four well-known meta-heuristics, such as the GA, SA, ACO, tabu search and hybrid approaches, as solution procedure to solve the DFLP. Conway and Venkataramanan (1994) used a GA to solve the CDFLP formulation of Balkrishnan (1992). This approach can handle multiple and non-linear objective functions, as well as side constraints. Computational results show that GA performs well in comparison to DP for the six and nine department problems. Similarly, Balakrishnan and Cheng (2000) developed an improved GA, which is different from the GA used by Conway and Venkataramanan (1994). The computational results show Balakrishnan and Cheng’s (2000) GA performs better than Conway and Venkataramanan’s (1994) GA, especially for larger-sized problems. Kaku and Mozzola (1997) employed a tabu search approach in which diversification strategy and intensification strategy are used to generate better solutions. Baykasoglu and Gindy (2001) proposed an SA approach to solve the DFLP. The computational results show that, especially for larger-sized problems, the proposed SA approach outperforms the previous GA presented in Conway and Venkataramanan (1994) and Balakrishnan and Cheng (2000). Krishnan et al. (2006) developed a tool called the Dynamic From-Between Chart (DFBC) for the analysis of redesign layouts. The proposed tool considers changes in product demand using a continuous function. The proposed tool consists of two stages. In the first stage, a modified Wanger-Within procedure is used to make a decision on the periods at which redesign will take place whereas in the second stage, a GA is used to determine the flexible layout. They tested the proposed tool via case study and the results indicate that the use of DFBC is efficient in redesign layouts. MacKendall et al. (2006) also developed an SA approach for DFLP with equal departments. Computation results indicate it is efficient for equal area DFLP. Konak et al. (2007) proposed the use of tabu search in which the authors consider unequal area departments, fixed department area, expanded department area and two time periods for the facility re-layout problem (FRLP). Tabu search is used as an optimisation approach and computational results show that the use of tabu search is flexible in handling various aspects of FRLP.

The application of hybrid ant systems (HAS) to solve the DFLP was presented by Mackendal and Chang (2006). They combined three algorithms—HAS_QAP, HAS II and HAS III—for DFLP. Equal area departments were assumed in this study. The hybrid approach was tested using two sets of data taken from the literature and results show significant improvements compared to the existing procedure used to solve the DFLP. In their later study, Mackendall and Hakobyan (2010) developed a construction and improvement heuristic to solve the DFLP with unequal area and fixed department shape. Computation results indicate that the proposed heuristic is efficient for unequal area DFLP. Addressing the DFLP with a hybrid approach was also suggested by Lacksonen (1994), who presented a two-phase algorithm for solving DFLP whilst assuming departments can have unequal area. In the first phase, a CP heuristic is utilised to solve the QAP formulation that is presented in Lacksonen (1993) and in the second phase, an MIP approach is used to find the desired block layout. Test problems ranging in size from four departments and two periods to 12 departments and three periods were solved. Similarly, Azadivar and Wang (2000) presented a hybrid approach for DFLP. The proposed approach takes into account system performance measures such as the cycle time and productivity, dynamic characteristics and operational constraints. They applied GA to optimise the layout for manufacturing effectiveness and simulation to evaluate system performance. Computation results show that the hybrid approach provides improvements in the value of the objective function but an optimal solution cannot be guaranteed.

Erel et al. (2003) proposed a three-phase approach for DFLP. In the first phase, good layouts that are near the optimal solution are selected. In the second phase, a shorter path problem over good layouts is solved via DP. In the final phase, the best solutions from the second phase are improved with a local improvement procedure. This procedure can be continued until a fixed number of iterations are met. Comparisons with Conway and Venkataramanan's (1994) GA, Balakrishnan and Cheng's (2000) GA and Baykasoglu and Gindy's (2001) SA show that the proposed approach is competitive. Balakrishnan et al. (2003) also developed a hybrid approach to solve the DFLP. The approach consists of three phases. In the first phase, Urban's (1993) heuristic is used to obtain initial population. In the second phase, the crossover operator applies DP to find the best combination of all different layouts. In the final phase, the mutation process uses CRAFT to improve the solution. Computational experiments show that the combination of GA and DP provide better solutions than GA alone. Likewise, Dunker et al. (2005) proposed the use of a hybrid approach in which DP and GA are combined to address the DFLP with unequal area departments. For each period a GA is used to generate good layouts whilst DP is used to evaluate the fitness of the layouts. The proposed approach is tested using two examples of Yang and Peters (1998) and results indicate that the layouts found by the hybrid approach are an improvement on previous ones.

In all of the DFLP approaches mentioned above, researchers have used the flexible approach to design the flexible layout for DFLP. The application of the robust approach to design a single robust layout that minimises the MHC in all periods is presented by Kouvelis et al. (1992) who suggested the use of B&B, in which a single robust layout is obtained within p% of the optimal solution. Computational results indicate that the proposed approach fails to provide good solutions for problems with more than 15 departments due to the complexity of the QAP formulation. Yang and Peters (1998) proposed a robust MLP approach that formulates and generates a single layout for MLP.

Hunagund and Madhusudanan Pillai (2007, 2008) proposed a method for design of a robust machine layout for cellular manufacturing systems under a dynamic environment. The proposed method involves the development of a layout for the average demand scenario of various periods. The proposed method consists of two phases. In the first phase, a heuristic is used to generate solutions, which is used as input to the next phase whereas in the second phase, LINGO mathematical modelling language is used to solve the QAP formulation. Computational results indicate that the proposed method provides better performance and can solve a problem that includes up to nine machines. In their later work, Madhusudanan Pillia et al. (2011) extended their previous work and developed a robust approach based on simulated annealing for solving DFLP. Computational results indicate that the suggested method provides better performance and can solve up to 30 departments.

2.4 Stochastic Facility Layout Problem

In all of the previous DFLP approaches, researchers have assumed dynamic environments, where the flow data or product demand is forecasted, certain and known a priori in the early stage of the layout design. However, in a stochastic environment where product demand and product mix are highly uncertain and unpredictable, the need for stochastic FLP approaches that design flexible or robust layouts and handle uncertainty in product demand and product mix has emerged.

2.4.1 Designing Flexible or Robust Layouts for Single Period Stochastic FLP

The modelling of uncertainty in FLP is first discussed by Shore and Tompkins (1980), who developed the concept of layout flexibility. They considered a stochastic environment, where product demand is assumed to be independent and equal probability value is assigned for each demand state. The idea of the study is to use TFP as a criterion for selecting the most flexible layout. TFP is defined as the determination of joint probabilities for various demand states. As a result, the layout that has the lowest TFP value is selected to be the most flexible layout. They developed the Computerized Facility Design Flexible heuristic (COFAD-F), which is based on the COFAD of Shore and Tompkins (1976), to identify the flexible layout. The proposed heuristic can handle up to six demand states and 10 department problems.

The work by Gupta (1986) presented a hybrid approach based on simulation and CRAFT to design the flexible layouts with an objective to minimise the sum of weighted distance for the single period stochastic FLP. The idea of the paper is to use a Monte Carlo Simulation (MCS) to randomly generate 50 matrices. For each matrix, the CRAFT is utilised to generate the layout. Then, for each layout, the distance between all department pairs is calculated and the average distance over the 50 generated layouts is computed. Then, a penalty function is used as a measure for evaluating the flexibility of a layout and the layout with the smallest penalty value is selected as the most flexible layout.

Rosenblatt and Lee (1987) presented a robust approach for the single period stochastic FLP with an objective to minimise the MHC. The uncertainty in demand is represented by a three-point estimate: high, most likely and low. Each point has the same probability of occurrences. Their definition of robustness is the ability (flexibility) of a layout to handle demand changes in a dynamic environment. Robustness of a layout is measured by the number of times that the material handling cost falls within a pre-specified percentage of the optimal solution under different sets of scenarios. They illustrate the idea of robustness with small examples; with three products, a three-point estimate and four departments. As a result, a total of 324 (4! $\times 3^{\wedge 3}$) MHCs for different layouts and scenarios are developed for evaluation. This approach uses a total enumeration strategy and computation times become prohibitive as the number of products and departments increase. Therefore, to reduce the computation time, they suggested considering only products that highly affect the material handling costs of the system.

Rosenblatt and Kropp (1992) also formulated and proposed an optimal solution procedure for the single period stochastic FLP, where multiple scenarios (states) are considered. They assumed some prior knowledge about the different level of product mix and their associated probabilities of occurrence. The single period stochastic FLP is formulated as a QAP and is based on the following assumptions:

- A set of finite possible scenarios (states) which may occur;
- Each from-to chart represents a scenario;
- Each scenario has a finite probability of occurrences.

The main idea of the study is to combine the flow matrices for the various states to a single weighted-average state and to find the solution to the resulting combination matrix. The optimal solution to the resulting combination matrix has an expected cost that is at least as low as the expected cost of any other solution. Thus, a TFP of Shore and Tompkins (1980) is used to evaluate the robustness of facility layouts and compare the results with the optimal layout of the combination matrix. Similarly, Benjaafar and Sheikhzadeh (2000) assumed a stochastic environment in a job shop layout where product demand and product mix are subject to variability. They also considered that duplication of the same department may exist in the same facility. This approach is utilised to design a flexible layout that performs well over a set of possible scenarios.

The concept of defining the most robust layout for the SRMLP under a stochastic environment is presented by Bragila et al. (2003). The uncertainty in demand is represented by normal random variables with known mean and variance. They suggested the use of a simulation approach in which a Layout Configuration Robust Index (LCRI) is developed and is used to estimate the robustness of layout configuration for a given problem. Similarly, Konak et al. (2004) used a hybrid approach in which simulation is used to model uncertainty and a tabu search based-heuristic is used to generate the flexible layout. Unequal area departments, as well as routing flexibility, are considered in this study. Further, Bragila et al. (2003) presented two theorems to solve the single period stochastic FLP when the uncertainty in demand is assumed to be normal random variables with known parameters. In this paper, the first theorem shows that the robust layout that minimises the total MHC may be obtained by studying the average flow matrix between the machines whereas the second theorem shows that when the flow is normally distributed, the cost functions of any solutions are also normally distributed, with a mean and a variance. Bragila et al. (2005) used a simulation approach that considers the design of stable layout. Stable layout is defined as the ability of the layout to minimise the variance of the total MHC. Stable layout is obtained by generating the optimal layout when variance of product demands is used in the form of a from-to chart. Longo et al. (2005) presented a hybrid approach to solve the FLP under a stochastic environment. The basic concept of their study is to create an initial layout based on an intensity traffic methodology. Firstly, a GA is used to generate different layouts and, later, a discrete event simulation is used to evaluate the best layouts under different scenarios. Norman and Smith (2006) modelled uncertainty in material handling costs on a continuous scale by use of expected values and standard deviations of product forecasts. They solved the problem using a flexible bay construct and a GA meta-heuristic. Likewise, Liu et al. (2006) proposed an approach based on SA and tabu search to solve the FLP under a stochastic product demand and logistic flow. The proposed approach considers MHC and unequal area, as well as shape factor. Based on Bragila et al.'s (2003) theorem, the MHC is formulated by the mean and the standard deviation values. The shape of the department is assumed to be fixed and rotation is allowed. Computational results indicate it is very difficult to find a good solution under these considerations. Elsayed (2007) assumed the material flow exhibit of 20%, 60% and 100% of the total flow to be stochastic. A modified MS Excel, a set of QAP add-ins of Jensen and Bard (2003) and simulation are used to evaluate different layouts. Tearwattanarattikal et al. (2008) used PROMODEL as a simulation tool to compare a set of alternative layouts under different scenarios. Smutkupt and Wimonkasame (2009) presented a hybrid approach based on CRAFT and the ARENA simulation package to analyse a set of alternative layouts under different scenarios.

2.4.2 Designing Flexible Layouts for Multi-Period Stochastic FLP

Savsar (1991) used a simulation approach in which adaptive and reactive flexibility are incorporated for the stochastic FLP. His definition of reactive flexibility is the measure of the insensitivity of a layout to handle changes in material flow volumes; in this case, random material flow costs are considered. On the other hand, his definition of adaptive flexibility is the ability of a layout to be easily changed. In this case, random re-layout costs are considered. Equal area departments and two periods are assumed in this paper.

By using this approach, the flexible and adaptive layout is determined. Palker et al. (1992) formulated the multi-period stochastic FLP as a quadratic integer program with the objective function of minimising the sum of the MHCs and rearrangement costs. Rearrangement costs are assumed to be proportional to distance between the old and new locations. The aim of this study is to design a master facility plan under a stochastic environment. They used a DP as an optimisation procedure for smaller-sized problems and a modified program of Burkard and Derigs (1980) for larger ones. Yang and Peters (1998) proposed a flexible machine layout design procedure based on a construction-type algorithm for multi-period stochastic FLP. A discrete set of product demand scenarios with known probability of occurrence and unequal size machines in an open field floor space are assumed in this paper. This approach is restricted to solving smaller-sized problems.

Similarly, Krishnan et al. (2008) assumed a discrete set of product demand scenarios with a known probability of occurrence for single period and multi-period stochastic FLPs. The stochastic FLP is modelled as QAP and GA is used to design the flexible layout that minimises the maximum loss by considering all scenarios. Krishnan et al. (2008) also presented a hybrid approach based on the @Risk simulation software and GA for single period and multi-period stochastic FLPs. The proposed approach is utilised to analyse the layout based on the product demand forecast and the product demand distribution. Equal area departments and normal, uniform and triangular distributions are considered to design the flexible layout. The proposed approach is tested via case studies and the results indicate that the proposed approach is beneficial in estimating the risk of the facility layout. They concluded that assigning a known probability to a from-to chart is not efficient and eliminates the true nature of uncertainty. Jithavech and Krishnan (2009) extended their previous work to larger-sized problems, including 20 and 25 equal area departments. Moslempour and Lee (2011) recently proposed the use of an SA approach in which the flexible layout is designed for FMS. The product demand is assumed to be normal distribution with known parameters. The QAP formulation is used to model the problem and computational results indicate that the suggested method provides better performance and can solve up to 12 machines with two different periods.

2.5 Conclusion on FLP Literature

Despite the importance and practicability of the stochastic FLP, the majority of research focuses on developing static and dynamic FLP approaches in which the layout is designed without consideration of uncertainty and the true nature of stochastic product demands. Most of the previous solution approaches have assumed equal area departments and single objective function (i.e., minimise MHC) and that product demand is a known, fixed quantity. However, these approaches may fall short of providing an effective solution in a stochastic environment, where product demand is subject to variability. From the literature survey, the following major drawbacks in current solution approaches to dynamic and stochastic FLPs have been obtained:

- Lack of approaches to design robust layouts for the DFLP and multi-period stochastic FLP. This lack is due to the incapability of most approaches that are designed to solve a single problem and not to apply the same layout with the same configuration to various periods of the planning horizon;
- Most research on the stochastic FLP area assumes discrete product demand distributions by assigning a known probability to a from-to chart. However, this

type of solution may not be practical and eliminates the true nature of product demands;

- Lack of approaches that handle practical constraints, such as unequal area departments, addition of departments, deletion of departments and expansion of departments;
- Lack of approaches that assume the product demands change stochastically with known mean and variance for multi-period stochastic FLP and follow different types of distribution, such as normal, uniform and triangular;
- Lack of existing approaches for solving equal area and unequal area FLPs simultaneously;
- Lack of existing approaches for evaluating any set of layouts with complex geometry that is preferred by layout designers, in terms of robustness and stability under a stochastic environment.

To quantify the uncertainty whilst considering manufacturing facility design with realistic assumptions, the layout design process should incorporate stochastic approaches that evaluate and analyse the impact of uncertainty under different scenarios. The next chapter presents the development of a hybrid approach.

CHAPTER 3

A HYBRID (SIMULATION) APPROACH FOR STOCHASTIC FLP

3.1 Introduction

FLP is a hard optimisation problem and becomes harder when stochastic variables, such as unequal department sizes inside a given boundary shape, are included. This chapter presents two phases of the hybrid approach that considers the development of a simulation model and the integration of this model with the VIPPLANOPT 2006 algorithm. The proposed approach aims to quantify the impact of product demand uncertainty to facility layout designs in terms of robustness and variability. To better understand the structure of the simulation model and the generation of random variables, a simulation overview is presented in Section 3.2. Section 3.3 presents the two phases of the hybrid approach. Section 3.3.1 presents the first phase of the hybrid approach. Section 3.3.2 describes the second phase and the steps required to develop a simulation model. Section 3.3.3 presents the integration of the VIPPLANOPT 2006 software with the simulation model. Section 3.4 provides a mathematical formulation of the stochastic FLP with unequal area. Section 3.5 presents the development of a 10-department case study to demonstrate the effectiveness and efficiency of the hybrid approach for designing and evaluating facility layout designs that can handle uncertain production environments and address the single period stochastic FLP. Section 3.6 presents a conclusion on the subjects of this chapter.

3.2 Simulation Overview

Simulation has become an increasingly important technique for solving different types of complex problems and testing the solution under different scenarios before implementing it in a real system (Tearwattanarattikal et al., 2008). Studies have shown that simulation is one of the most popular techniques applied to different sectors such as manufacturing, healthcare, services, etc. Evidence of this popularity is found in the number of simulation packages that have been developed to deal with complex and practical real world applications (Mohsen et al., 2010). Simulation can be defined as "the use of a computer to construct a model designed to imitate and capture the dynamic behaviour of a system in order to evaluate the different ways of improving its efficiency" (Cowan et al., 2003). MCS is a useful technique for analysing the impact of uncertainty by selecting random numbers from a probability distribution to use in a simulation study. In the context of FLP, Aleisa and Lin (2005) state that simulation and layout optimisation are the most important tasks that should be considered when designing an efficient layout in any layout study.

3.2.1 Normal Distribution

Normal distribution is the most widely used distribution in simulation studies. This distribution is symmetrical, with a strong central tendency, but the shape varies according to the parameter σ (Montgomery, 2007).

A continuous random variable K with probability density function

$$f(k) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{(k-\mu)^2}{2\sigma^2}\right\}, \qquad -\infty \langle k \langle \infty \tag{3.1}$$

Has a normal random variable with parameters μ and σ where

$-\infty \langle \mu \langle \infty$ and σ > 0. Also E (K) = μ and V (K) = σ^2

The notation N (μ , σ^2) is used in this thesis to denote a normal distribution with mean μ and variance σ^2 .

3.2.1.1. Useful properties of Normal Distribution

Property 1 If K is N (μ, σ^2), then cK (for any constant c) is N ($c\mu, c^2\sigma^2$).

Property 2 If K is N (μ, σ^2), then c+K (for any constant c) is N ($\mu + c, \sigma^2$).

Property 3 If K_1 is $N(\mu_1, \sigma_1{}^2)$, K_2 is $N(\mu_2, \sigma_2{}^2)$, and K_1 , K_2 are independent, then $K_1 + K_2$ is $N(\mu_1 + \mu_2, \sigma_1{}^2 + \sigma_2{}^2)$ (Waynel, 1994).

3.2.2 Generation of normal random variables

The use of MCS in the analysis of uncertainty for stochastic FLP requires the generation of random numbers that represent the flow between pairs of departments. Most programming languages as well as simulation software contain a pseudo random number generator to generate random numbers by using commands and functions. For instance, the RAND () function is capable of generating a uniformly distributed random number between zero and one when it is entered into a cell in a Microsoft Excel spreadsheet and its value is updated each time by pressing key F9 (Popescu and Popescu, 2005). In the case of normal distribution, it is possible to use an Excel spreadsheet to generate approximate normal random variables by using the following functions (Waynel, 1994):

=NORMINV (RAND (), μ, σ) or

=RAND()+RAND()+RAND()+RAND()+RAND()+RAND()+RAND()+RAND()+

RAND()+RAND()+RAND()+RAND()-6

In general, the standard excel functions such as BETAINV and NORMINV, etc. are all based on the approximation formula that usually results in generating low quality random numbers. In this thesis, EasyFit 5.3 software is used to overcome the limitation of Excel's approximation functions. EasyFit 5.3 is an Excel add-in that allows the generation of high-quality random variables from 52 different supported distributions (Waynel, 1994; Pooch and James, 2000).

3.2.3 Testing for goodness of fit

The selection of random variables is one of the biggest difficulties that a researcher faces when designing a simulation model. In many cases, the random variable is assumed to follow a particular distribution. Of course, the output of the simulation model is usually sensitive to this assumption. Therefore, there must be methods that help to check and test the assumption of a particular distribution. The chi-square goodness of fit test, the Kolmogorov-Smirnov test and the Anderson darling test have shown to be efficient in testing the assumption of a particular distribution (Pooch and James 2000; Montgomery, 2007). A brief description of these tests is given below.

3.2.3.1 Kolmogorov-Smirnov test

The Kolmogorov-Smirnov test is designed to test the hypothesis that a sample of data comes from a continuous distribution. The objective of this test is to find the largest vertical difference between the theoretical and empirical cumulative distribution functions. The hypothesis regarding the distributional form is rejected at the chosen significance (α) if the computed value of the test statistic is greater than the critical value obtained from a table (EasyFit 5.3 user manual, 2009).

3.2.3.2 The chi-square goodness of fit test

The chi-square is commonly used to investigate whether the actual and the expected number of observations for various values of the random variable differ from one another. The hypothesis regarding the distributional form is rejected at the chosen (α) if the calculated value of the test statistic is greater than the tabulated critical value (EasyFit 5.3 user manual, 2009).

3.2.3.3 The Anderson darling test

The Anderson darling test is a useful test for measuring how well data follow a particular distribution. The hypothesis regarding the distribution form is rejected at chosen (α) if the calculated value of the test statistics' value is greater than the tabulated critical value (EasyFit 5.3 user manual, 2009).

3.3 The development of a hybrid approach

This section presents the two phases of the hybrid approach that include the design and evaluation of any set of layouts in a stochastic environment and the selection of a single layout that minimises the maximum loss due to uncertainty in product demand.

3.3.1 Phase I Generation of optimal layouts

As mentioned above, in the first phase, VIPPLANOPT 2006 software is a research product developed by Engineering Optimization Software to solve static unequal FLP in an open field (www.planopt.com). It is a powerful software package for generating high-quality solutions for small-, medium- and large-sized problems. According to the website (www.planopt.com), the professional version of the software can solve up to 1000 department problems. The optimisation process of the software is based on a hybrid smart growth that enables the generation of high-quality solutions in a reasonable amount of time. The website states that "This is due to the algorithm's embedded optimization philosophy of natural constructive growth while identifying, for each department, the feasible design space with the highest probability of local optima. The design space is mapped onto a straight line. A pseudo exhaustive search is then carried out for the optimal solution at each stage of a multi stage optimization process" (www.planopt.com) In addition, in order to generate high quality layouts, the VIPPLANOPT 2006 requires a seed that helps to start the optimisation process. Unlike other algorithms, the dependence of the optimal layout on the seed has been reduced. For this reason, there are only 2N seeds where N is the number of departments (VIPPLANOPT user manual, 2006). For example, if N=6, then the optimal solution will be in 12 different seeds. One seed is optimal and the rest of seeds are near optimal (the best) solutions (VIPPLANOPT user manual, 2006).

The main inputs for VIPPLANOPT 2006 are:

- Number of departments and area of each department;
- From-to chart either symmetrical or non-symmetrical;
- Department type either hard, soft with variable aspect ratio but of constant area or anchored;
- Department position either movable with variable position or fixed;
- Department orientation either fixed or flips by rotating 90 degrees;
- Location and size of each restricted area for each layout (if necessary).

The most important feature of VIPPLANOPT is the ability to optimise inside a given boundary shape which is considered to be one of the most difficult issues in FLP—

making the difficult problem even harder. The only limitation is that the software cannot print out the final layout.

3.3.2 Phase II Development of a Simulation Model

This section presents the development of a simulation model to generate random variables when the flow between pairs of departments changes stochastically with known mean and variance. The stochastic flow between departments represents the variability in the current fluctuation of market demand. The use of MCS is based on the EasyFit 5.3 software's ability to generate exact normal random variables or other continuous random variables; for instance, the generation of random variables—when product demand is independent and normally distributed with known mean and variance—can be described in the following steps:

1. Read the distribution of product demand along with the sequence of workstations (departments) for each product;
2. Identify if more than two products are combined in flow intensity;
3. Construct mean and standard deviation matrices;
4. Generate normal random variables for each flow between pairs of departments based on step three;
5. Conduct the chi-square goodness of fit test, the Kolmogorov-Smirnov test and Anderson darling test at the chosen significance α for each flow generated. If data follow a normal distribution, accept. Otherwise, go to step four;
6. Identify the number of from-to charts to be generated (F);
7. Develop the first from-to chart (F_g) and set to 0;
8. Set $F_g = F_g + 1$;

9. If F_g >F then stop. Otherwise, go to step 8.

Due to the fact that the flow between pairs of departments f_{ij} is a random variable, a large number of from-to charts are generated. Each from-to chart represents a different simulation run, different product mixes and layout designs. In this thesis, 100 simulation runs (e.g., weeks) are generated to evaluate the efficiency of any set of layouts over time.

3.3.3 Integration of VIPPLANOPT 2006 with the simulation model

This section presents the integration of a simulation model with VIPPLANOPT 2006 software. The integration process consists of two phases. In the first phase, VIPPLANOPT is utilised to generate the optimal layouts or identify the layout configurations to be evaluated over time. In the second phase, MCS based on mean and standard deviation matrices are used to generate random variables that represent the variations in product demands. Once MCS is performed, the optimisation process uses the outputs from the simulation model and evaluates the outcomes of the inputs to compute the MHC and SD values for each layout. After obtaining the MHC and SD values for various layouts to be evaluated over time, the final step of the integration process is to perform uncertainty analysis by using MHC and SD indices of the simulation results as criteria to select the best layout under consideration. The flow chart representing the logic of designing, evaluating and selecting a single layout that is robust and/or stable to changing market demands is shown in Figure 3.1.

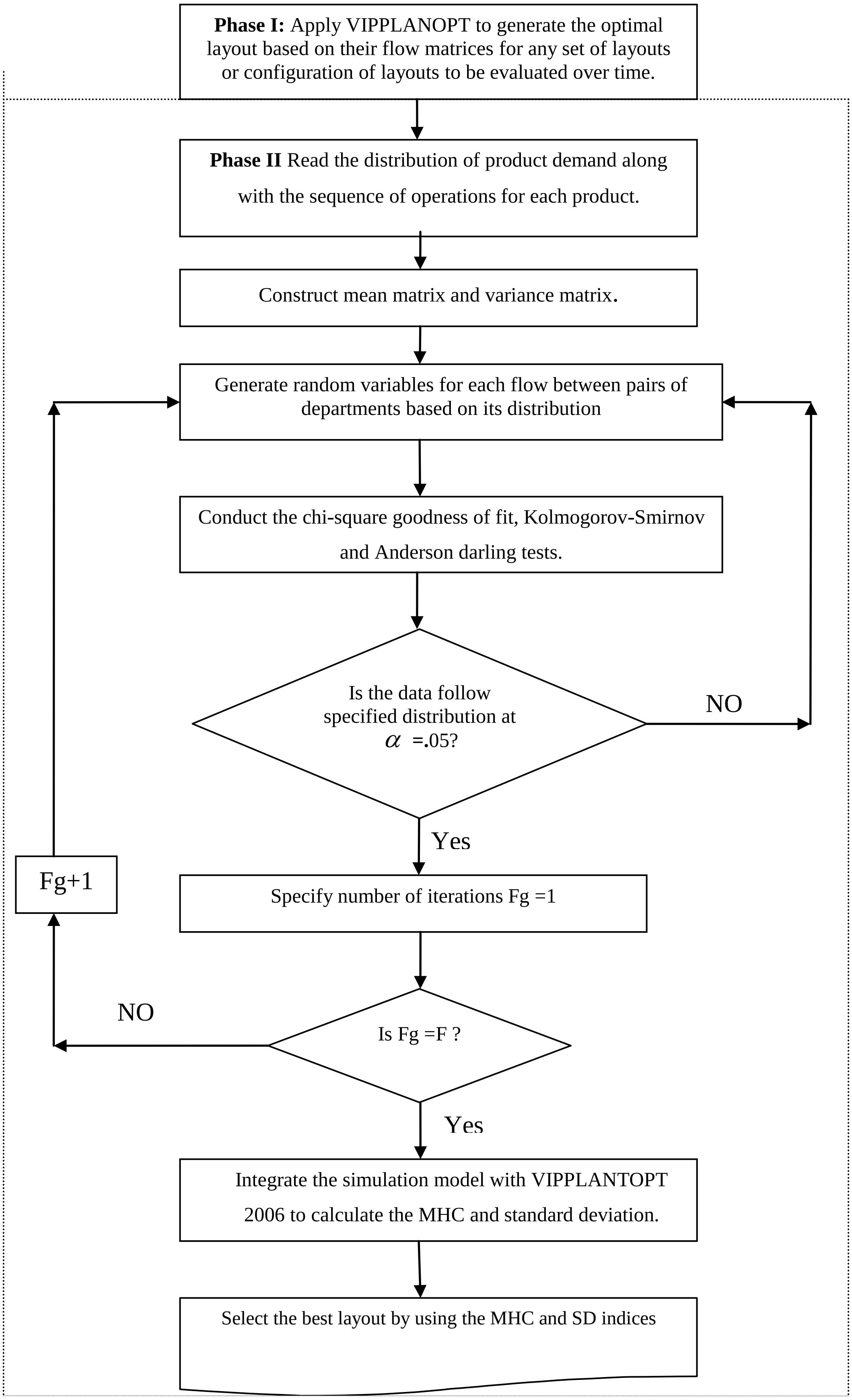


Figure 3.1 Flow chart of integration VIPPLANOPT 2006 with simulation model

3.4 Mathematical formulation of unequal area stochastic FLP

The unequal area model of FLP was originally presented and formulated by Armour and Buffa (1963) who assumed a rectangular area with fixed dimensions H*W, where H and W are the height and width of the rectangular area, respectively. The rectangular area is divided into N sub departments where N is the number of departments. In addition, the area of each department and the flow between each pair of departments are assumed to be known a priori. The objective function is to minimise the material handling cost that is expressed as the following:

$$MinZ = C\sum_{i=1}^{n}\sum_{\substack{j=1 \\ i\neq j}}^{N} F(i,j) * d(i,j,\Pi) \tag{3.2}$$

Where

$F(i,j)$ is the total flow between a pair of departments.

$d(i,j,\Pi)$ is the rectilinear distance between department i and department j in the layout Π.

C is the cost to transport one unit of flow for one unit of distance.

In the stochastic situation, $F(i,j)$ is replaced by $F_{stochastic}$, matrix (from-to chart), which represent stochastic variables that are normally distributed with mean μ and variance σ^2 respectively. Then, matrix $F_{stochastic}\lfloor x_{ij} \rfloor$ can be used to represent x_{ij} for all departments. Braglia et al. (2003) provide a useful theorem that is valid for stochastic FLP with unequal area as well. According to the theorem, the most robust layout, i.e., the layout that minimises the total MHC is identified by the solution of a QAP in which the flow matrix is replaced by the averages of the single probability distribution.

3.5 Performance analysis

In this section, a 10-department case study is developed to demonstrate the effectiveness of the hybrid approach for solving the single period stochastic FLP.

3.5.1 10-department case study

The constructed case study involves 10 departments of unequal areas and five products. The material handling cost is fixed at $1/unit distance. The size of the plant is 90m long and 60m wide and the area of each department is given in Table 3.1. Probability density functions of the product's demands follow a normal distribution and are of continuous type and are independent. Distances between departments are rectilinear. Product demand distribution and sequence of process are shown in Table 3.2.

Table 3.1 Area requirements for 10-department case study

Department	Area (m^2)	Length (m)	Width (m)	Department	Area (m^2)	Length (m)	Width (m)
1	300	10	30	6	900	30	30
2	100	10	10	7	800	20	40
3	600	20	30	8	600	30	20
4	200	10	20	9	900	30	30
5	400	10	40	10	600	20	30

Table 3.2 Product demand distribution and process sequence for 10-department case study

Product	Product demand distribution	Process sequence
1	Normal (200,400)	3-5-10
2	Normal (150,900)	1-5-8-7
3	Normal (300,100)	2-9-6-4
4	Normal (300,2500)	2-9-5-8-7
5	Normal (250,2500)	2-7

Based on data provided in Table 3.2, a total of ten flows (f_{35}, f_{510}, f_{15}, , f_{58}, f_{87}, f_{29}, f_{96}, f_{64}, $f_{95}$and, f_{27}) are considered in developing the mean and standard deviation from-to charts. Note that products 2, 4 and 3, 4 are combined in flows 5, 8, 8, 7 and 2, 9, respectively. Using property 3 in section 3.1.1, then the flow between pairs of departments f_{58} is N (150+300,900+2500), the flow f_{87} is N (150+300,900+2500) and the flow f_{29} is (300+300,100+2500). The main idea is to use the process sequence to construct the mean and standard deviation values in the form of a from-to chart. The associated from-to charts are presented in Table 3.3 and Table 3.4.

Table 3.3 From-to chart showing mean values for 10-department case study

	1	2	3	4	5	6	7	8	9	10
1					150					
2							250		600	
3					200					
4						300				
5								450	300	200
6									300	
7								450		
8										
9										
10										

Table 3.4 From-to chart showing standard deviation values for 10-department case study

	1	2	3	4	5	6	7	8	9	10
1					30					
2							50		51	
3					20					
4						10				
5								58	50	20
6									10	
7								58		
8										
9										
10										

The first phase of the hybrid approach is utilised to identify the most robust layout for this case study by generating the optimal layout for the mean matrix that is shown in Table. 3.3. The most robust layout that minimises the total MHC is shown in Figure 3.2.

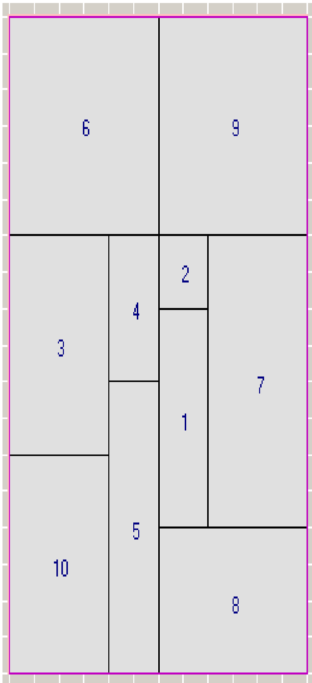


Figure 3.2 Layout 1 is the most robust layout for 10-department case study

Once the most robust layout is obtained, the second phase is utilised to ensure its efficiency over time. MCS is used to generate normal random variables based on mean and standard deviation values over 100 simulation periods (e.g., weeks). Then the EasyFit software is utilised to conduct goodness of fit at α =.05 for each flow generated (contained in Appendix A). The results of the hypothesis tests to reject sample data at α = .05 for flow 3-5 are shown in Figure 3.3 and Table 3.5. The output graph is obtained by using this equation $\int_b^a f(x)dx = P(a \leq X \geq b$ for continuous distributions. X-Axis represents a histogram of equal width intervals divided by total number of data points whereas Y-Axis represents the probability density function values

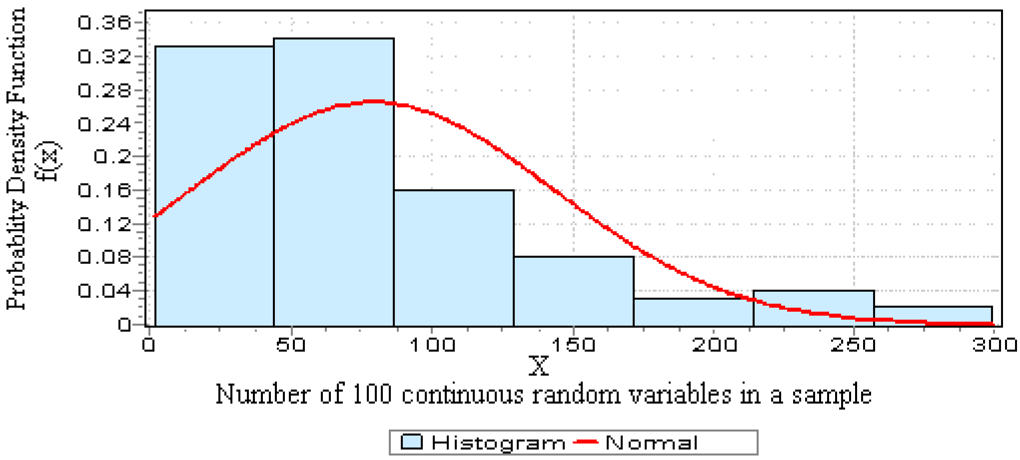


Figure 3.3 Sample data does not follow a normal distribution for flow 3-5 Normal (200 20)

Table 3.5 The results of hypothesis tests for flow 3-5

Normal [#43]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.14195 0.03202 33				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	Yes	Yes	Yes	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 3.2166 32				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	Yes	Yes	Yes	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 10.117 0.1198 29				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	Yes	No	No	No	No

To illustrate the proposed methodology to evaluate any set of layouts under stochastic product demands, the most robust layout is evaluated against three layouts. These layouts could be the initial layouts, layouts based on the product demand forecast or any set of layouts that are preferred by the layout designer. The configurations of these layouts are shown in Figures 3.4, 3.5 and 3.6, respectively. Each layout with the same configuration is simulated over 100 simulation periods to quantify its efficiency over time.

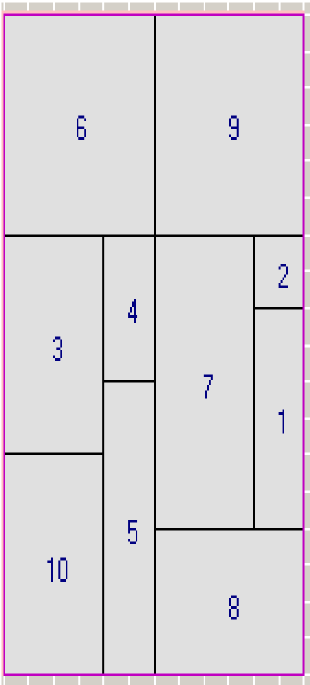


Figure 3.4 Layout no. 2

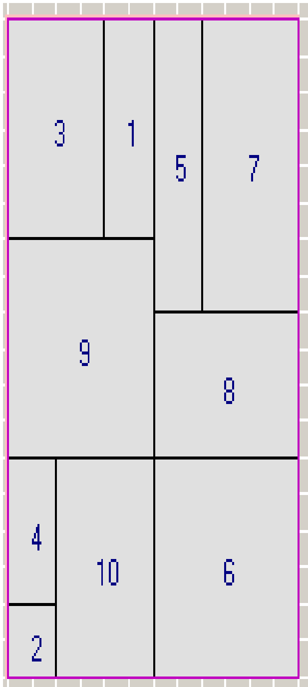


Figure 3.5 Layout no. 3

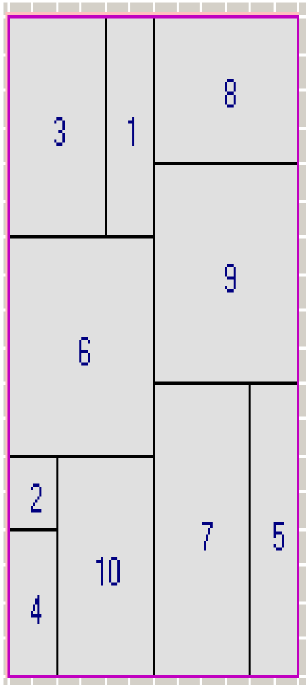


Figure 3.6 Layout no. 4

The final step in the integration process is to develop the MHC index and SD index to minimise the maximum loss of the selected layout due to uncertainty in product demand and select the best layout in terms of robustness and/or stability. The summary of the computation results is illustrated in Figure 3.7 and Table 3.6.

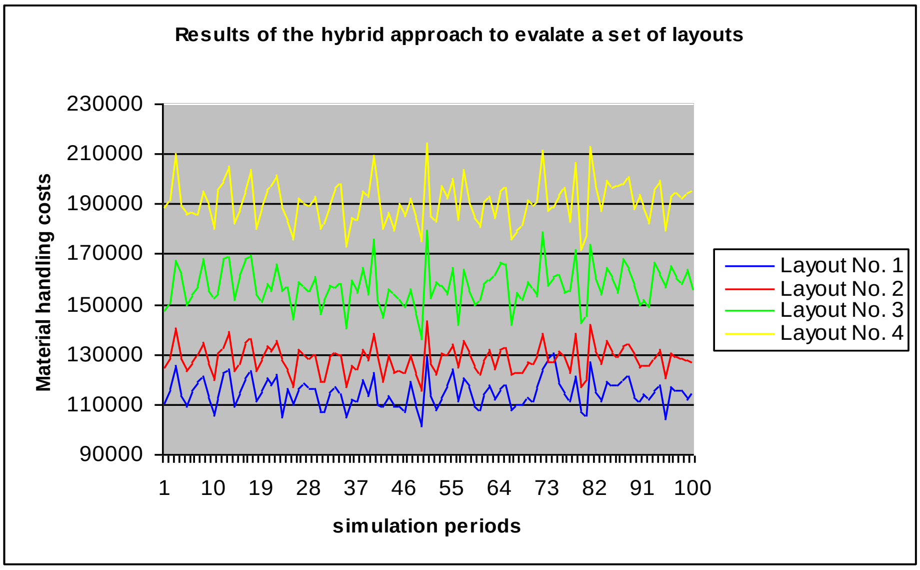


Figure 3.7 Evaluation of four layouts over 100 simulation runs

Table 3.6 Average total MHC and SD values over 100 simulation periods

Layout No.	Average total material handling cost ($MHC)	Standard Deviation ($SD)
Layout 1	114828	5844.4
Layout 2	128163	5629.8
Layout 3	157300	8128.8
Layout 4	190989	8773.4

Based on Figure 3.7, the analysis of the case study is performed with respect to the average material handling costs for layouts based on 100 simulation periods. Table 3.6 shows a comparison of the average total MHC and SD values for each layout evaluated. Based on the results, layouts 2, 3 and 4 do not provide high quality solutions in terms of average total MHC as compared with layout 1. Layout 1 is selected as the most robust layout that minimises the average total MHC even though the flow is different in different periods of the planning horizon. On the other hand, layout 2 is the best layout that offers improvement in terms of variability (SD). To evaluate the robustness and stability of layouts 1 and 2, the following MHC and SD indices of the simulation results are used.

$$\text{MHC Index} = \frac{MHC \ \ of \ \ Layout \ \ 1 - MHC \ \ of \ \ Layout \ \ 2}{MHC \ \ of \ \ Layout \ \ 2} \times 100 \tag{3.3}$$

Where

MHC is the average total material handling costs of the layout configurations.

$$\text{SD Index} = \frac{SD \ \ of \ \ Layout \ \ 1 - SD \ \ of \ \ Layout \ \ 2}{SD \ \ of \ \ Layout \ \ 2} \times 100 \tag{3.4}$$

Where

SD is the standard deviation of the total material handling costs of the layout configurations.

Using equations (3.3) and (3.4), the most robust layout resulted in a reduction of MHC by $13335 (10.4% reduction) as compared with layout 2, and also incurred an additional $214.6 in terms of variability (3.6% increase). However, in this case, the variability of layout 2 is not high enough to cause layout 1 to lose its optimality. Therefore, for this case study, layout 1 is chosen as the best layout that reduces the impact of uncertainty. The results indicate that the developed hybrid approach is efficient in analysing the uncertainty of product demands to ensure the efficiency of the selected layout over time.

3.6 Conclusion

This chapter presents a new hybrid approach in which a simulation model and VIPPLANOPT 2006 are integrated to select a single layout for stochastic FLP. This approach aims to design a robust layout, evaluate any set of layouts in a stochastic environment and select a single layout that minimises the maximum loss due to uncertainty in product demands. The two phases of the hybrid approach and integration procedures are presented, along with a case study for the procedure validation. Computation results indicate that using only MHC as a single (deterministic) objective may not be realistic for solving the FLP and may provide only partial solutions. Therefore, the complete solution requires the need for both robustness and variability measures to be considered during the layout design process. Computation results also indicate that the proposed hybrid approach is efficient in analysing the uncertainty of product demands to ensure the efficiency of the selected layout over time and in applying the analysis results to make better decisions. In the next chapter, the application of the hybrid (simulation) approach to generate a single robust layout for single period stochastic FLP whilst considering product demand forecast as random variables and hard constraints such as deletion and expansion of departments is presented.

CHAPTER 4

ANALYTIC AND HYBRID APPROACHES FOR SINGLE PERIOD STOCHASTIC FLP

4.1 INTRODUCTION

In chapter 3, the integration of VIPPLANOPT with the simulation model has proven to be effective in analysing the impact of demand uncertainty on facility layout designs and in applying the analysis results of the MHC and SD indices to make better decisions. Traditionally, the first important and critical step to design a manufacturing facility is to determine the product demands (quantities to be produced) within the facility. Product demand values are typically obtained by using forecasting techniques or historical data. However, these values may or may not be the same as product demand distribution values which are typically obtained by using fitting techniques. Therefore, the layout based on product demand forecast values is different from the layout based on the expected demand distribution values and this should be incorporated into the design of manufacturing facility and a comparative analysis made.

In such cases, two fundamental issues should be considered when dealing with uncertainty in product demands. The first is generating the best layout for product demand forecast and product demand distribution. The second is ensuring the robustness and stability of each layout in terms of MHC and SD values. Once these measures are obtained, they can be used as criteria to select the best layout. This chapter details the development of robust and stable indices along with the use of the hybrid approach to address the single period stochastic FLP whilst considering hard constraints.

4.2 Notations

In chapter 4 and the following chapters, the layout based on Product Demand Forecast (PDF) values is referred to as the project layout and the layout based on product demand distribution (mean) values is referred to as the robust layout.

4.3 Development of analytic Robust and Stable indices (Analytic approach)

In this section, two analytic indices are developed to evaluate any set of layouts and to quantify the uncertainty of product demands in terms of MHC and SD when the flow is represented by normal distribution with known mean and variance. In order to illustrate the formulations of the proposed analytic indices, the following example is utilised.

4.3.1 Stochastic example

This example is adapted from Braglia et al. (2003) and modified to suit the application in this thesis. The second theorem states that the cost function of the layout, when the flow is assumed as a normal distribution with mean μ_{ij} and variance $\sigma_{ij}^{\;2}$, can be expressed as follows:

$$Z(l) = \sum_{i=1}^{N} \sum_{J=i+1}^{N} x_{ij} d_{ij} . \qquad (4.1)$$

This cost also fits normal distribution with mean

$$M(l) = \sum_{i=1}^{N} \sum_{J=i+1}^{N} \mu_{ij} d_{ij} (l). \qquad (4.2)$$

And variance $Z(l) = \sum_{i=1}^{N} \sum_{J=i+1}^{N} \sigma^2{}_{ij} d^2{}_{ij}(l).$ $\qquad (4.3)$

The following example involves four departments of unequal areas. The layout is a product layout-type. From-to charts showing mean values, SD values and the area of each department are shown in Tables 4.1, 4.2 and 4.3, respectively.

Table 4.1 From-to chart showing mean values

	1	2	3	4
1		1136	981	1097
2	1136		987	947
3	981	987		980
4	1097	947	980	

Table 4.2 From-to chart showing standard deviation values

	1	2	3	4
1		296	269	291
2	296		220	233
3	269	220		248
4	291	233	248	

Table 4.3 Area requirements for stochastic example

Department	1	2	3	4
Area (m^2)	2	8	10	2

Now let us compare analytically the robust layout 3-4-1-2 and the project layout 1-4-3-2, respectively. In the second theorem of Bragila et al. (2003), in the case of normal distribution, the following calculations are suggested for the robust layout 3-4-1-2:

$M(l) = \sum_{i=1}^{N} \sum_{J=i+1}^{N} \mu_{ij} d_{ij}(l).$ =(6*980)+(8*981)+(13*987)+(2*1097)+(7*947)+

(5*1136)= 41062,

Variance $Z(l) = \sum_{i=1}^{N} \sum_{J=i+1}^{N} \sigma^2{}_{ij} d^2{}_{ij}(l)$ =(6^2 *248^2)+(8^2 *269^2)+(13^2 *220^2)+

(2^2 *291^2)+(7^2 *233^2)+(5^2 *296^2) = 20214133.

For the project layout 1-4-3-2:

$M(l) =$ (2*1097)+(8*981)+(17*1136)+(6*981)+(15*947)+(9*987) = 58322

Variance $Z(l) = (2^2 * 291^2) + (8^2 * 269^2) + (17^2 * 296^2) + (6^2 * 248^2)$

$+(15^2 * 233^2) + (9^2 * 220^2)$ = 48640421.

Using VIPPLANOPT software, the same results are obtained as shown in Figure 4.1.

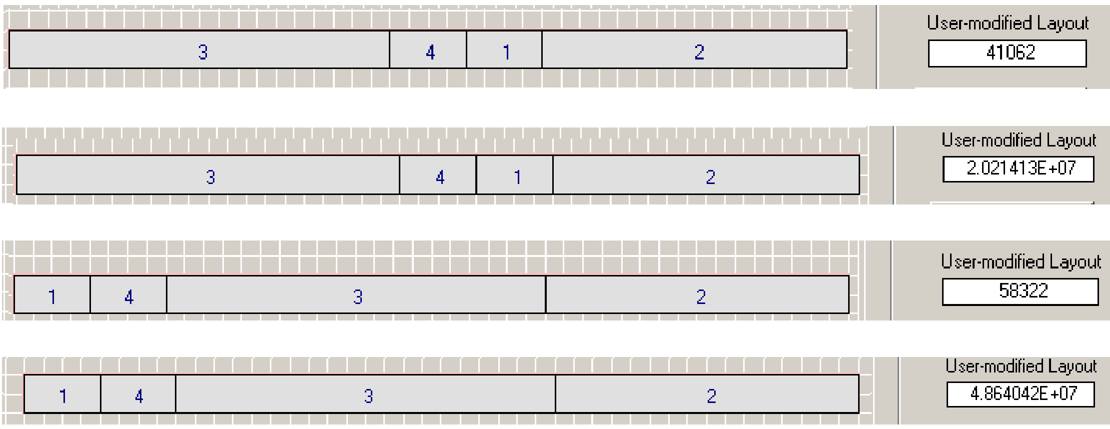


Figure 4.1 The computation results of VIPPLANOPT for a stochastic example

Figure 4.1 highlights that VIPPLANOPT is effective in comparing any set of layouts a priori. According to the results, the robust layout 3-4-1-2 resulted in a reduction of MHC by 17260 (29.6% reduction) and a reduction of variability by 2478.2 (35.5% reduction) when compared with project layout 1-4-3-2. Based on equations (4.2), (4.3) and the results, it is possible to develop two analytic indices that help to evaluate the robustness and stability of facility layout designs under stochastic product demands.

The first index is referred to as the robust index whereas the second index is referred to as the stable index. The developments of robust and stable indices are given below:

Robust index =

$$\frac{MHC \;\; of \;\; using \;\; the \;\; project \;\; Layout_{\;1-4-3-2} \;\; in \;\; state \;\; F - Optimal \;\; MHC \;\; of \;\; the \;\; robust \;\; Layout_{\;3-4-1-2} \;\; in \;\; state \;\; F}{MHC \;\; of \;\; using \;\; the \;\; project \;\; Layout_{\;1-4-3-2} \;\; in \;\; state \;\; F} \times 100$$

$$\frac{MHC \;\; of \;\; using \;\; Layout_{\;1-4-3-2} \;\; in \;\; F[\mu_{ij}] - MHC^{*} \;\; of \;\; the \;\; robust \;\; Layout_{\;3-4-1-2} \;\; in\, F[\mu_{ij}]}{MHC \;\; of \;\; using \;\; Layout_{\;1-4-3-2} \;\; in \;\; F[\mu_{ij}]} \times 100$$

$$\text{Robust Index} = \frac{C\left(\sum_{i=1}^{N}\sum_{j=i+1}^{N} u_{ij} d_{ij}\right)_{layout\;1-4-3-2} - C\left(\sum_{i=1}^{N}\sum_{j=i+1}^{N} u_{ij} d_{ij}\right)_{layout\;3-4-1-2}}{C\left(\sum_{i=1}^{N}\sum_{j=i+1}^{N} u_{ij} d_{ij}\right)_{layout\;1-4-3-2}} \times 100 \; \ldots \quad (4.4)$$

Where

MHC is the average total material handling costs of the layout configuration.

State F is the expected value matrix of product demand distribution or (from-to chart showing mean values)

μ_{ij} is the mean of the product demand distribution of the total flow between department i and department j.

C is the cost to transport one unit of flow for one unit of distance.

d_{ij} is the rectilinear distance between department i and department j in the layout configuration to be evaluated. The rectilinear distance between two points (X_i, Y_i) and (X_j, Y_j) is calculated as: follows:

$$d_{ij} = |X_j - X_i| + |Y_j - Y_i|$$

Similarly, Stable index =

$$\frac{VAR \;\; of \;\; using \;\; Layout_{\;3-4-1-2} \;\; in \;\; state \;\; F - VAR \;\; of \;\; using \;\; Layout_{\;1-4-3-2} \;\; in \;\; state \;\; F}{VAR \;\; of \;\; using \;\; Layout_{\;1-4-3-2} \;\; in \;\; state \;\; F} \times 100$$

$$\frac{VAR \;\; of \;\; using \;\; Layout_{\;3-4-1-2} \;\; in \;\; F\left[\sigma_{ij}^{\;2}\right] - VAR \;\; of \;\; using \;\; Layout_{\;1-4-3-2} \;\; in \;\; F\left[\sigma_{ij}^{\;2}\right]}{VAR \;\; of \;\; using \;\; Layout_{\;1-4-3-2} \;\; in \;\; F\left[\sigma_{ij}^{\;2}\right]} \times 100$$

$$\frac{\left[C \quad \left(\sum_{i=1}^{N}\sum_{j=i+1}^{N}\sigma^2{}_{ij}d^2{}_{ij}\right)\right]_{layout \quad 3-4-1-2} - \left[C \quad \left(\sum_{i=1}^{N}\sum_{j=i+1}^{N}\sigma^2{}_{ij}d^2{}_{ij}\right)\right]_{layout \quad 1-4-3-2}}{\left[C \quad \left(\sum_{i=1}^{N}\sum_{j=i+1}^{N}\sigma^2{}_{ij}d^2{}_{ij}\right)\right]_{layout \quad 1-4-3-2}} \times 1000 \qquad (4.5)$$

Taking the square root, the Stable index can be expressed as follows:

$$\text{Stable Index} = \frac{\sqrt{C \quad \left(\sum_{i=1}^{N}\sum_{j=i+1}^{N}\sigma^2{}_{ij}d^2{}_{ij}\right)_{layout \quad 3-4-1-2}} - \sqrt{C \quad \left(\sum_{i=1}^{N}\sum_{j=i+1}^{N}\sigma^2{}_{ij}d^2{}_{ij}\right)_{layout \quad 1-4-3-2}}}{\sqrt{C \quad \left(\sum_{i=1}^{N}\sum_{j=i+1}^{N}\sigma^2{}_{ij}d^2{}_{ij}\right)_{layout \quad 1-4-3-2}}} \times 1000 \qquad (4.6)$$

Where

VAR is the variance of the total material handling costs of the layout configuration

State F is the variance matrix of product demand distribution

$\sigma^2{}_{ij}$ is the variance of the product demand distribution of the total flow between department i and department j.

$d^2{}_{ij}$ is the Squared Euclidean Distance (SED) between department i and department j in the layout configuration to be evaluated and is computed as follows:

C is the cost to transport one unit of flow for one unit of distance.

$$d^2{}_{ij} = \left(X_j - X_i\right)^2 - \left(Y_j - Y_i\right)^2$$

Using equations, (4.4), (4.6) and VIPPLANOPT, the same results are obtained:

Robust index= $\dfrac{41062-58322}{58322}\times 100=-29.6\%$

Stable index= $\dfrac{4496-6974.27}{6974.27}\times 100=-35.5\%$

It is interesting to mention that the mathematical formulations of the robust and stable indices are originally based on Rosenblatt and Kropp's (1992) methodology for discrete stochastic FLP and can be used effectively to compare any set of layouts in terms of MHC and SD for continuous stochastic FLP with or without respect to the most robust layout (optimal state F). More details about the derivations of these indices can be found in chapter 6. The two analytic indices have proven to be efficient in quantifying the impact of uncertainty on facility layout designs. However, these indices are NP-hard and the computations' complexity increases as the number of departments or additional constraints increase. In this thesis, the two analytic indices are validated via the simulation indices in order to provide two practical methods that allow addressing different aspects of FLP depending on the nature and complexity of the problem.

4.4 Performance analysis

In this section, three case studies are developed to gauge the effectiveness of the proposed robust, stable indices and hybrid approach for the solving of the single period stochastic FLP.

4.4.1 12-department case study (single period)

This case study involves 12 departments of unequal areas and seven products. The material handling cost is fixed at $1/unit distance. The size of the plant is 30m long and

70m wide. Area requirements and from-to charts showing mean and variance values are given in Appendix B. Probability density functions of product demand follow a normal distribution and are independent. Distances between departments are rectilinear for the robust, MHC and SD indices and SED for the stable index. Product demand distribution and sequence of process are shown in Table 4.4.

Table 4.4 Product demand distribution and process sequence for 12-department case study

Product	Product Demand Forecast (PDF)	Product demand distribution	Process sequence
1	50	Normal (50 1600)	1-3-4
2	48	Normal (50 100)	3-5-6
3	26	Normal (100 1600)	2-5-7
4	50	Normal (50 900)	4-9-11
5	240	Normal (200 1600)	2-4-6-8-10
6	120	Normal (100 900)	2-4-6-10
7	41	Normal (100 900)	10-12

The first phase of the hybrid approach is utilised to generate the optimal layouts for PDF and expected value matrices. These layouts are shown in Figures 4.1 and 4.2, respectively. Once the optimal layouts are determined, the second phase is to quantify the impact of uncertainty under various scenarios by using the simulation method. Four scenarios are considered for uncertainty analysis. The first scenario includes the evaluation of optimal layouts. The second scenario includes the expansion of departments. The third scenario includes the deletion of one department. The final scenario includes the deletion of two departments. The configuration of the project and robust layouts for different scenarios are shown in Figures 4.2, 4.3, 4.5, 4.6, 4.8, 4.9, 4.11 and 4.12, respectively. The computation results from using the simulation method for different scenarios are shown in Figures 4.4, 4.7, 4.10 and 4.13.

4.4.1.1 Scenario 1: Evaluation of project layout against robust layout

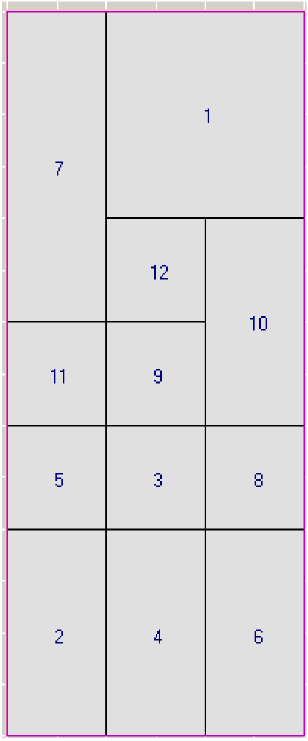


Figure 4. 2 Scenario 1 for project layout

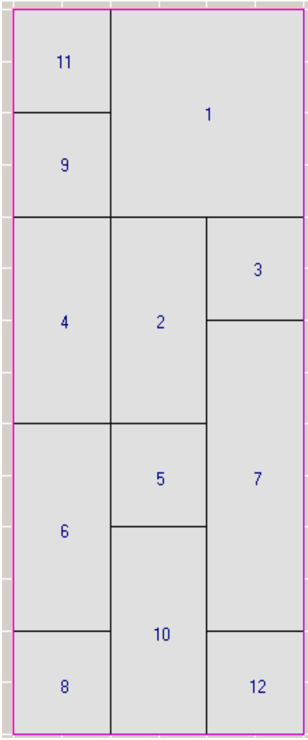


Figure 4. 3 Scenario 1 for robust layout

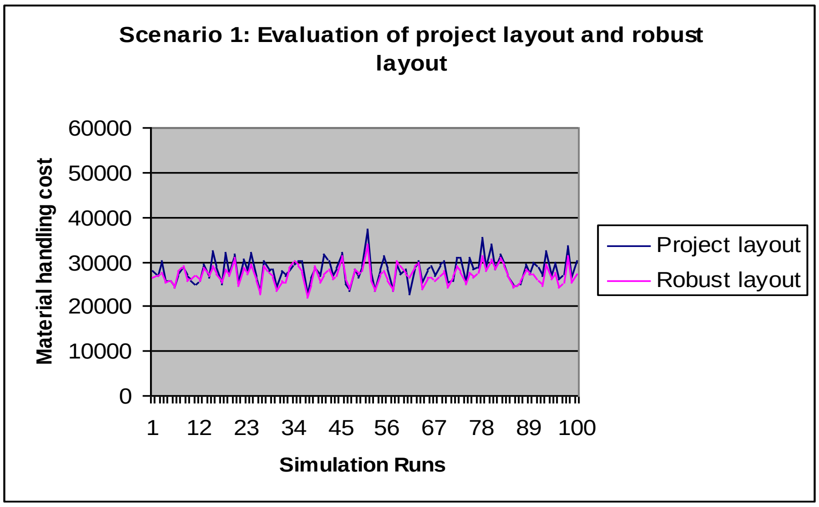


Figure 4. 4 Results of the simulation method for scenario 1

Figure 4.4 shows how the robust layout provides high quality solution in terms of a low average total MHC ($27080) over time. This solution essentially gives savings of 3.7% when compared with the project layout ($28130).

4.4.2.2 Scenario 2: Expansion and contraction of departments

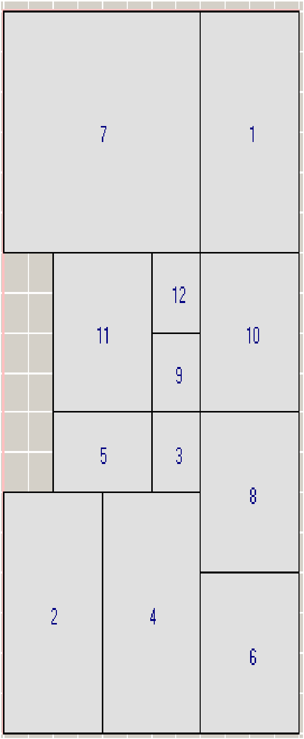


Figure 4. 5 Scenario 2 for project layout

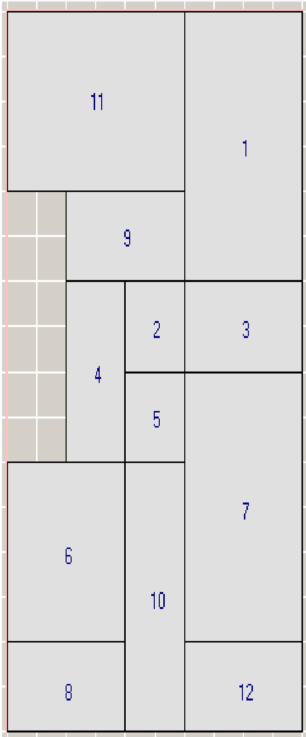


Figure 4. 6 Scenario 2 for robust layout

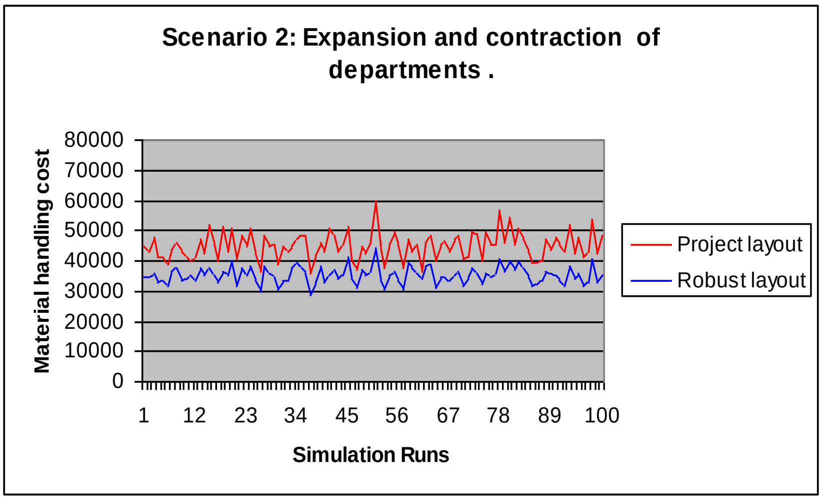
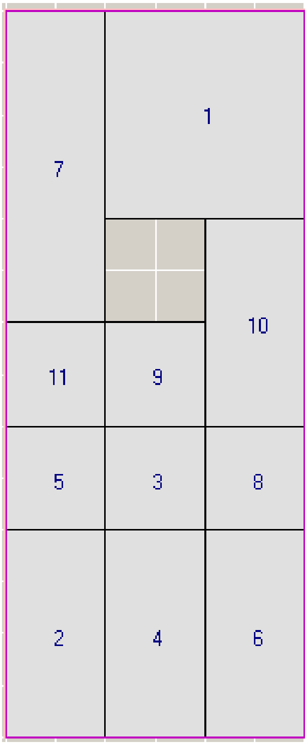


Figure 4. 7 Results of the simulation method for scenario 2

Figure 4.7 shows how the robust layout provides high quality solution in terms of a low average total MHC ($35255.7) over time. This solution essentially gives savings of 21.5% when compared with the project layout ($44919).

4.4.3.3 Scenario 3: Deletion of department number 12



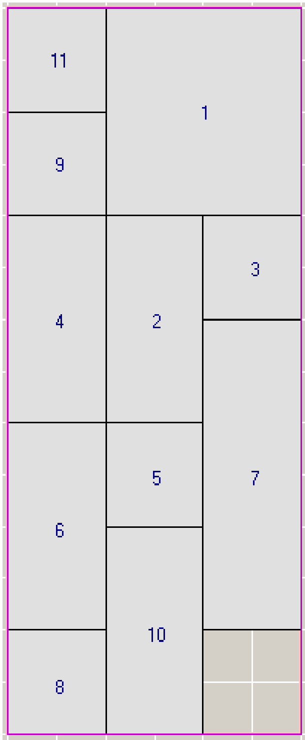


Figure 4. 8 Scenario 3 for project layout **Figure 4. 9 Scenario 3 for robust layout**

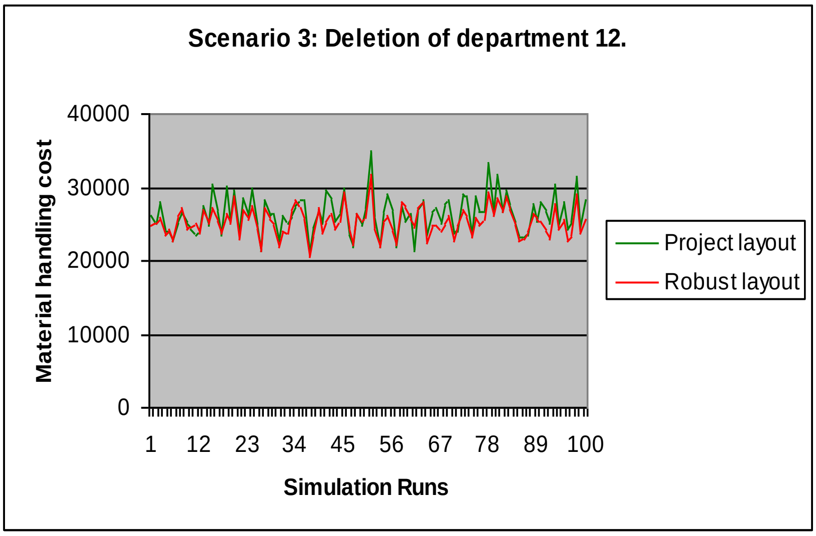


Figure 4. 10 Results of the simulation method for scenario 3

Figure 4.10 shows how the robust layout provides high quality solution in terms of a low average total MHC ($25288) over time. This solution essentially gives savings of 3.84% when compared with the project layout ($26295).

4.4.4.4 Scenario 4: Deletion of departments numbers 11 and 12

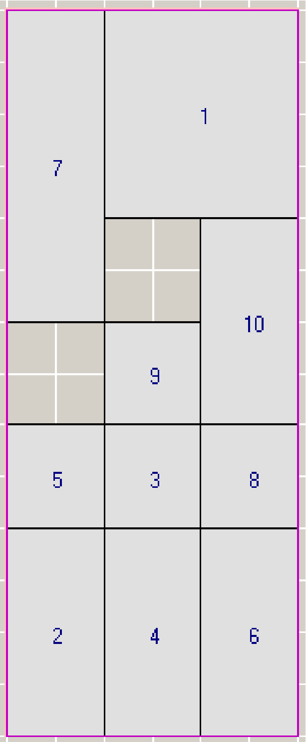


Figure 4. 11 Scenario 4 for project layout

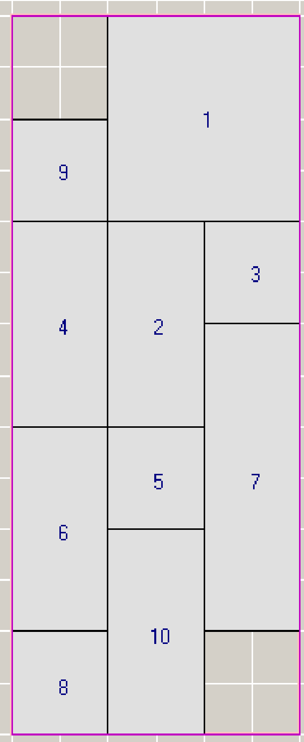


Figure 4.12 Scenario 4 for robust layout

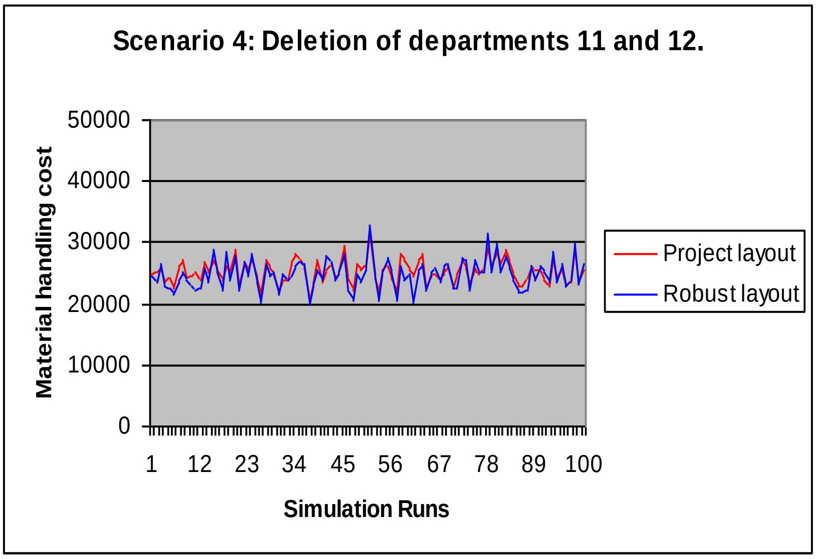


Figure 4. 13 Results of the simulation method for scenario 4

Figure 4.13 shows how the robust layout provides high quality solution in terms of a low average total MHC ($24770.8) over time. This solution essentially gives savings of 3.9% when compared with the project layout ($25780).

Once the four scenarios are performed, the comparison summary of the analytic robust and stable indices is illustrated in Table 4.5. Furthermore, the comparison summary of the robust, stable, MHC and SD indices both analytically and via simulation method for the 12-department single period case study is shown in Table 4.6.

Table 4.5 Comparisons of analytic indices for 12-department case study

Scenarios		Project layout		Robust layout		MHC*	Analytic indices Reduction (-)	
		$MHC	$SD	$MHC	$SD	$MHC	Robust index (column 5,7)	Stable index (column 4,6)
1	Project layout against robust layout	26445	2650.9	26750	2011.4	27750	-3.6	-24.15
2	Expansion and contraction of departments	60530	3633	35250	2379	44750	-21.2	-34.51
3	Deletion of department 12	25830	2629.6	25250	1986.2	26250	-3.8	-23.93
4	Deletion of departments 11 and 12	25330	2612.4	24750	1963.4	25750	-3.8	-25

*MHC for using project layout in state of robust layout

Table 4.6 Comparison of results both analytically and via simulation method

Scenarios		Project layout		Robust layout		Comparison of robust, stable, MHC and SD indices Reduction (-)	
		$MHC	SD	$MHC	SD		
1	Analytic method	27750	2650.9	26750	2010	-3.6	-24.15
	Simulation method	28130	2760	27080	2110	-3.7	-23.5
	95% confidence interval	[27589.04,28670.96]		[26666.44, 27493.56]			
2	Analytic method	44750	3633	35250	2379	-21.2	-34.51
	Simulation method	44918.87	4421	35255.65	2747	-21.5	-37.86
	95% confidence interval	[44052.3,45785.4]		[34712.2,35789.07]			
3	Analytic method	26250	2629.6	25250	1986.2	-3.8	-23.93
	Simulation method	26295.18	2588.0	25287.77	1970.2	-3.84	-24.04
	95% confidence interval	[25787.9,26802.43]		[24901.5 ,25674.0]			
4	Analytic method	25750	2612.4	24750	1963.4	-3.8	-25
	Simulation method	25780.27	2537.4	24770.8	1930.3	-3.9	-23.9
	95% confidence interval	[25282.9,25780.27]		[24392.5,25149.14]			

The analysis of the case study is performed with respect to robust and stable indices for layouts based on PDF values and the robust layout. Based on the results (Table 4.5, columns 8 and 9), the robust layout performs best in scenario two, which reduces the MHC and SD by 21.1% and 34.51%, respectively, when compared with the project layout. On the other hand, for scenarios one, three and four, the project layout performs worst and did not provide any reduction in terms of MHC and SD when compared with the robust layout. As a result, the robust layout is selected as the best layout for the 12-department case study. In order to provide a more statistical insight in using the analytic and simulation methods, a $\alpha(100-\alpha)$% confidence interval is developed as

$$\overline{X} \pm t_{(\alpha/2,n-1)}\sqrt{\frac{s^2}{n}} \tag{4.7}$$

Using equation (4.7), the values of MHC are computed for all scenarios and illustrated in Table 4.6. For illustration purpose, in scenario 1, $\overline{X}$ =28130, s=2760, $\alpha/2$ =1.96 and n=100. The 95% confidence interval for expected MHC is [27589.04, 28670.66] or 27589.4 < expected MHC for scenario 1>28679.66. In Table 4.6, through observation, all of the MHC values obtained by using analytic indices fall within the range of the 95% confidence interval of MHC values acquired via the simulation method. Hence, it can be concluded that the results show a good agreement between the two methods and both methods can be used effectively to identify the same layouts.

4.5 20-department case study (single period)

This case study consists of 20 departments of unequal areas and 10 products. The layout is a process layout-type. The material handling cost is fixed at $1/unit distance. The size of the plant is 50m long and 90m wide. Area requirements and from-to charts are given in Appendix C. Probability density functions of product demand follow a normal distribution, a uniform distribution and are independent. Distances between departments are rectilinear for the robust, MHC and SD indices and SED for the stable index. Product demand distribution and sequence of process are shown in Table 4.7.

Table 4.7 Product demand distribution and process sequence for 20-department case study (single period)

Product	PDF	Product demand distribution	Process sequence
1	40	Uniform (30 100)	1-3-4-9-15
2	120	Uniform (100 300)	10-12-14-16
3	50	Normal (50 64)	7-13-15-16
4	50	Normal (50 36)	7-13-15
5	100	Uniform (50 400)	2-5-7
6	100	Uniform (50 150)	9-11-13-17-19
7	150	Normal (150 1600)	2-13-18
8	150	Normal (150 1600)	3-5-6-13-20
9	200	Normal (200 1600)	2-4-6-8-10
10	70	Normal (70 900)	2-4-6-10

The first phase of the hybrid approach is utilised to generate the optimal layouts for PDF and expected value matrices. These layouts are shown in Figures 4.13 and 4.14, respectively. Similar to the 12-department case study, once the optimal layouts are obtained, the second step is to quantify the impact of uncertainty under various scenarios by using the simulation method. The configuration of project and robust layouts for different scenarios are shown in Figures 4.14, 4.15, 4.17, 4.18, 4.20, 4.21, 4.23 and 4.24, respectively. The computation results from using the simulation method for different scenarios are shown in Figures 4.16, 4.19, 4.22 and 4.25. The computation results from using robust and stable indices and the results of the simulation method are compared and provided in Table 4.8.

4.5.1 Scenario 1: Evaluation of project layout against robust layout

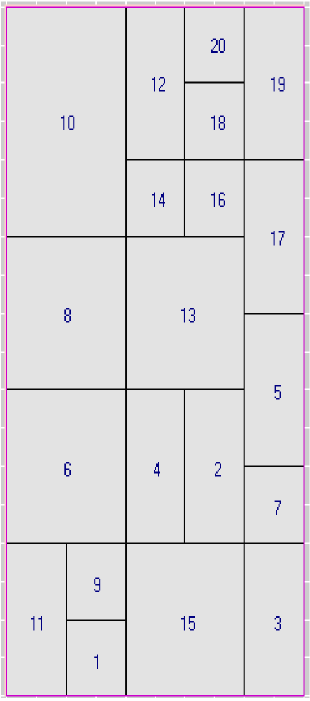


Figure 4. 14 Scenario 1 for project layout

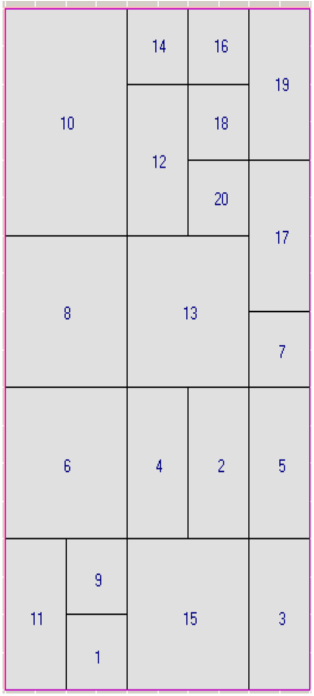


Figure 4.15 Scenario 1 for robust layout

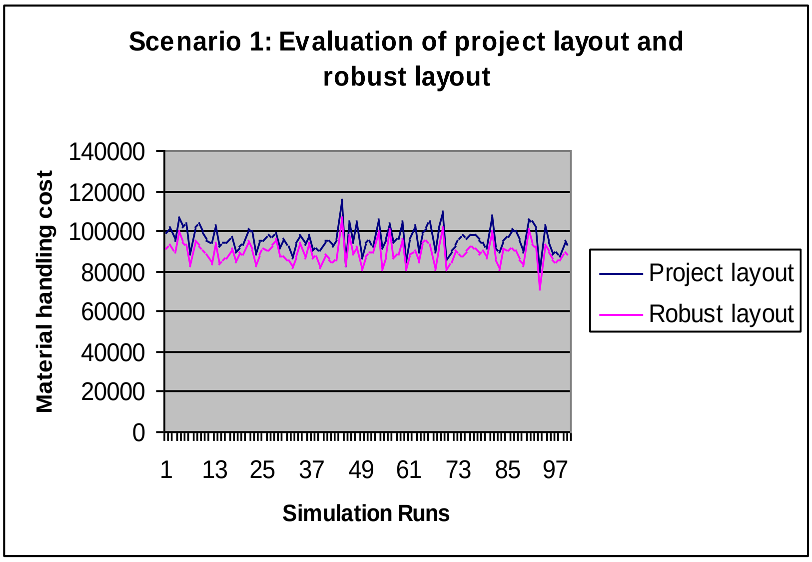


Figure 4.16 Results of the simulation method for scenario 1

Figure 4.16 shows how the robust layout provides high quality solution in terms of a low average total MHC ($89312.6) over time. This solution essentially gives savings of 9.5% when compared with the project layout ($98700).

4.5.2 Scenario 2: Expansion of departments

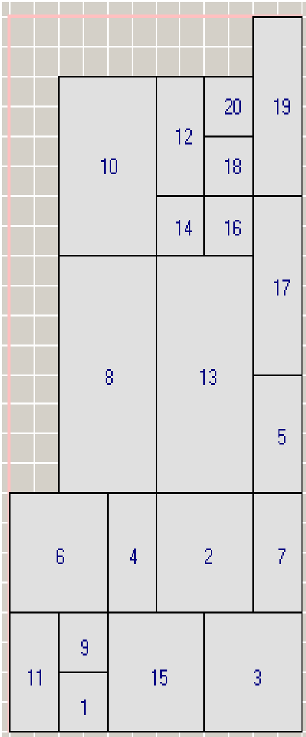


Figure 4.17 Scenario 2 for project layout

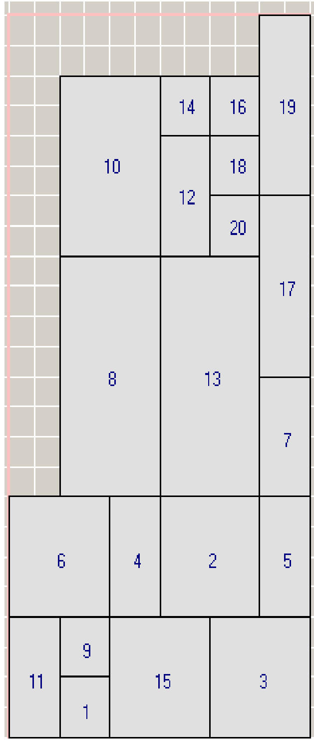


Figure 4.18 Scenario 2 for robust layout

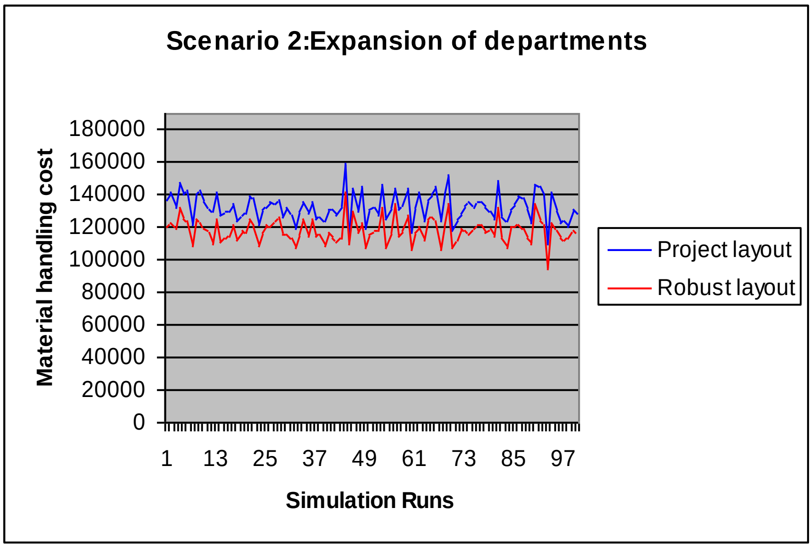


Figure 4. 19 Results of the simulation method for scenario 2

Figure 4.19 shows how the robust layout provides high quality solution in terms of a low average total MHC ($118460.5) over time. This solution essentially gives savings of 10.7% when compared with the project layout ($132665.9).

4.5.3 Scenario 3: Deletion of department 20

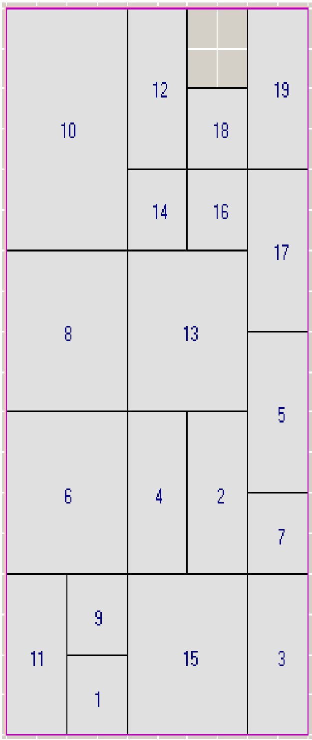


Figure 4. 20 Scenario 3 for project layout

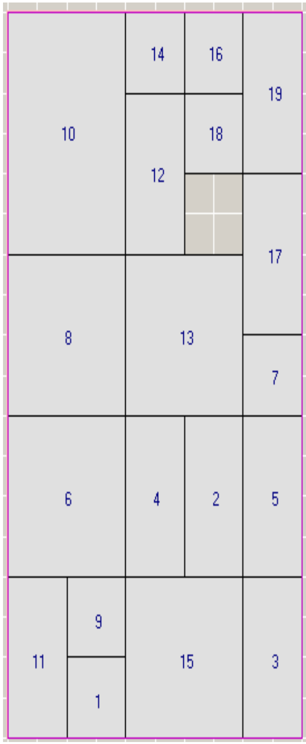


Figure 4. 21 Scenario 3 for robust layout

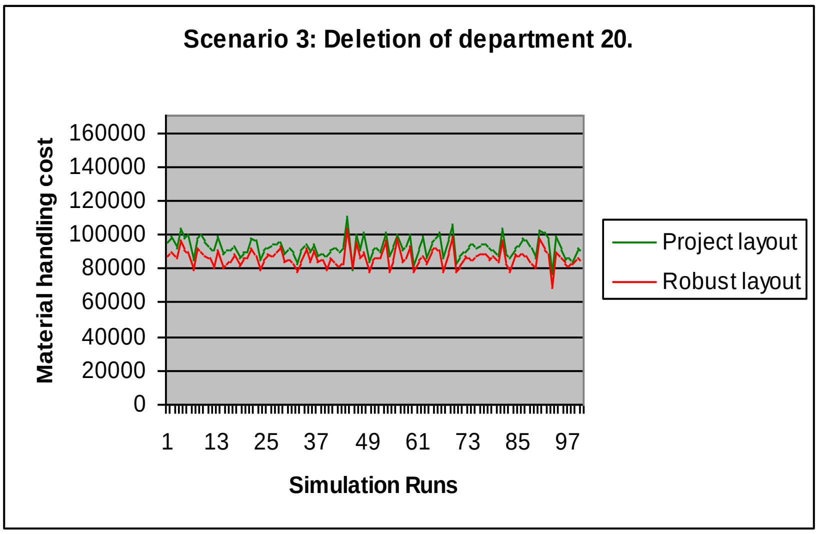


Figure 4. 22 Results of the simulation method for scenario 3

Figure 4.22 shows how the robust layout provides high quality solution in terms of a low average total MHC ($86380) over time. This solution essentially gives savings of 6.5% when compared with the project layout ($92400).

4.5.4 Scenario 4: Deletion of departments 19 and 20

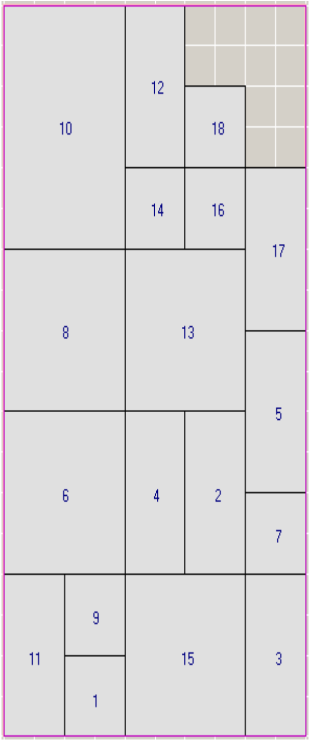


Figure 4. 23 Scenario 4 for project layout

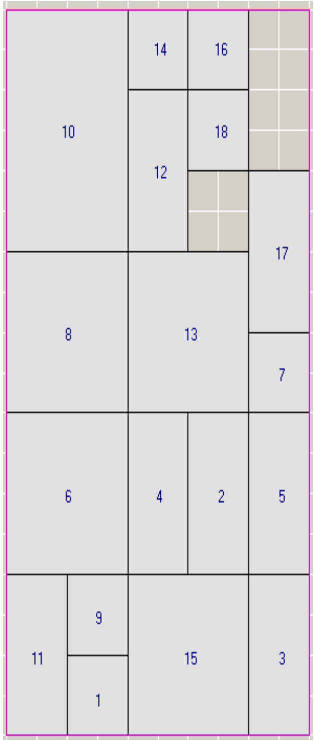


Figure 4. 24 Scenario 4 for robust layout

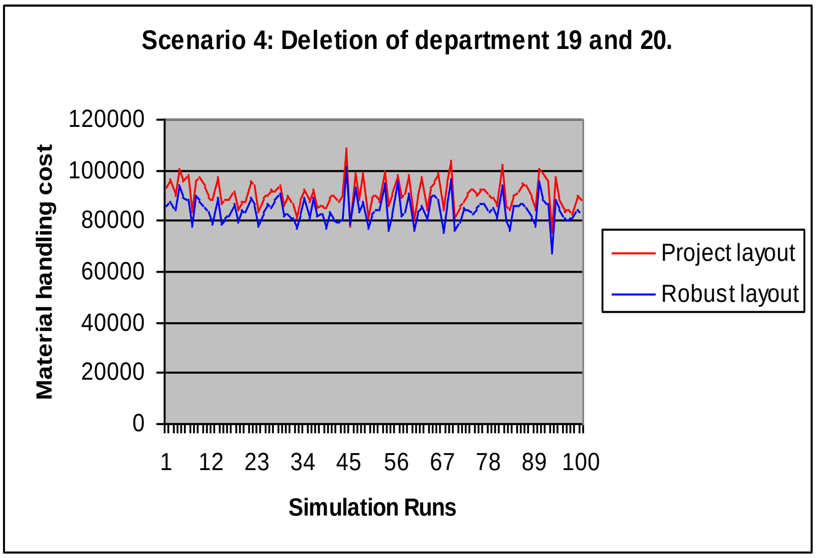


Figure 4. 25 Results of the simulation method for scenario 4

Figure 4.25 shows how the robust layout provides high quality solution in terms of a low average total MHC ($84350) over time. This solution essentially gives savings of 6.5% when compared with the project layout ($90586).

Table 4.8 Comparison of results both analytically and via simulation method

Scenarios		Project layout		Robust layout		Analytic results Reduction (-)		Simulation results Reduction (-)	
		$MHC	$SD	$MHC	$SD	Robust Index %	Stable Index %	MHC Index %	SD Index %
1	Project layout against robust layout	89600	5170.0	89325 (98575)*	4670.0	-9.38	-9.67	-9.51	-11.8
2	Expansion of departments	12095	4282.9	118175 (132675)	3846.7	-10.92	-10.18	-10.79	-13.3
3	Deletion of department 20	83600	4863.1	86325 (92575)	4608.2	-6.75	-5.35	-6.56	-9.3
4	Deletion of department 19 and 20	81600	4828.7	84325 (90575)	4571.9	-6.9	-5.3	-6.8	-9.2

*Number in parenthesis indicates MHC for using project layout in state of robust layout

The analysis of the case study is performed with respect to robust and stable indices for layouts based on project demand values and the robust layout. Based on the results (Table 4.8, columns 7 and 8), the robust layout performs best in scenario two, which reduces the MHC by $9250 (10.92% reduction) and SD by $436.2 (10.18% reduction) when compared with the project layout. On the other hand, for scenarios one, three and four, the project layout does not provide any reduction in terms of MHC or SD when compared with the robust layout. Therefore, the robust layout is selected as the best layout that is robust and stable to changing market demands for this case study.

4.6 30-department case study (single period)

This case study involves 30 departments of unequal areas and 17 products. The layout is a process layout-type. The material handling cost is fixed at $1/unit distance. The size of the plant is 50m long and 120m wide. Departmental areas and from-to charts showing mean and variance values are given in Appendix D. Probability density functions of product demand follow a normal distribution, a uniform distribution and triangular distribution. Distances between departments are rectilinear for the robust, MHC and SD indices and SED for the stable index. Product demand distribution and sequence of process are shown in Table 4.9.

Table 4.9 Product demand distribution and process sequence for 30-department case study (single period)

Product	PDF	Product demand distribution	Process sequence
1	50	Triangular (25,50, 80)	1-3-4-9-15
2	80	Uniform (10 90)	10-12-14-16
3	40	Normal (40,64)	7-13-15-16
4	40	Normal (40,36)	7-13-15
5	200	Normal (270,1600)	2-5-7
6	100	Normal (100,900)	2--5-7-30
7	190	Uniform (40 220)	9-11-13-17-19-21
8	50	Normal (50,64)	14-23-25
9	50	Normal (50,36)	14-23-25-28
10	190	Triangular (100,220, 350)	2-13-18
11	120	Triangular (100,150, 200)	3-5-6-13-20
12	490	Triangular (300,600, 930)	25-27-29
13	200	Normal (300,10000)	2-4-6-8-10
14	100	Normal (260,4900)	2-4-6-10
15	650	Triangular (230,500, 800)	16-18-20-22
16	230	Uniform (100 360)	24-26-28-30
17	320	Uniform (200 1800)	1-30

In the 30-department case study, some of the probability density functions of product demands are assumed to follow a triangular distribution. Triangular distribution requires the minimum (a), most likely (m) and maximum values (b) to define the distribution. EasyFit 5.3 software is firstly utilised to calculate the mean and the variance of the distribution using the following equations:

$$\text{Mean}=\frac{a+m+b}{3} \qquad (4.8)$$

$$\text{Variance} = \frac{a^2 + m^2 + b^2 - am - ab - mb}{18} \qquad (4.9)$$

Then the first phase of the hybrid approach is utilised to generate the optimal layouts for PDF and expected value matrices. These layouts are shown in Figures 4.25 and 4.26, respectively. Similar to the 20-department case study, once the optimal layouts are obtained, the second step is to quantify the impact of uncertainty under various scenarios by using the simulation method. Four scenarios are considered for uncertainty analysis. The configuration of project and robust layouts for different scenarios are shown in Figures 4.26, 4.27, 4.29, 4.30, 4.32, 4.33, 4.35 and 4.36, respectively. The computation results from using the simulation method for different scenarios are shown in Figures 4.28, 4.31, 4.34 and 4.37. The summary of the robust, stable, MHC and SD indices comparison for the 30-department case study is illustrated in Table 4.10.

4.6.1 Scenario 1: Evaluation of project layout against robust layout

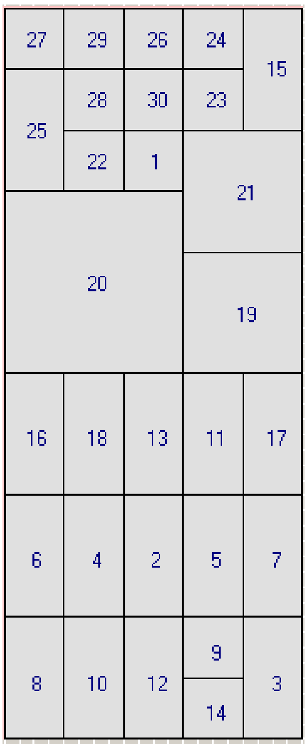


Figure 4. 26 Scenario 1 for project layout

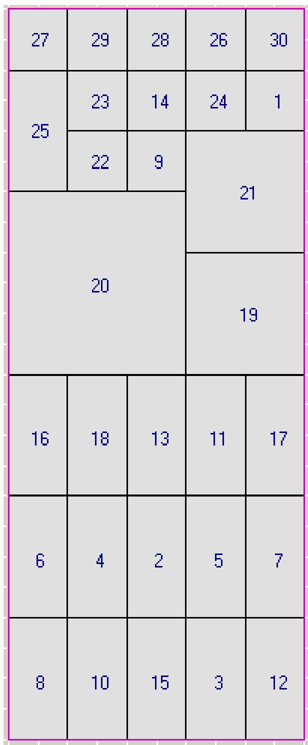


Figure 4. 27 Scenario 1 for robust layout

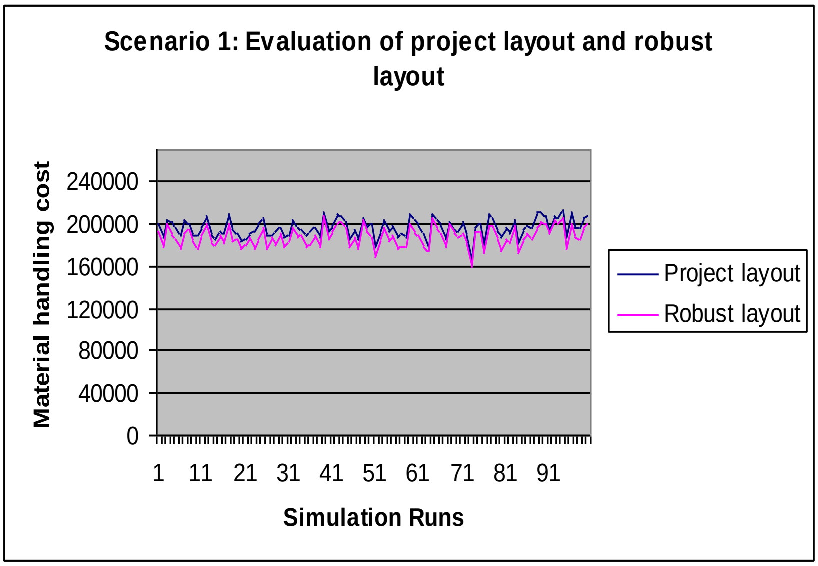


Figure 4. 28 Results of the simulation method for scenario 1

Figure 4.28 shows how the robust layout provides high quality solution in terms of a low average total MHC ($187909.9) over time. This solution essentially gives savings of 4.2% when compared with the project layout ($196289.6).

4.6.2 Scenario 2: Expansion of departments

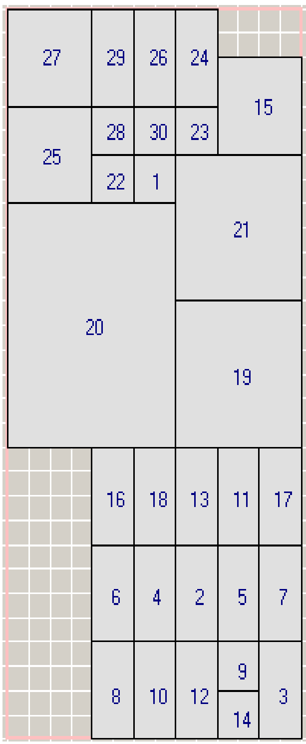


Figure 4. 29 Scenario 2 for project layout

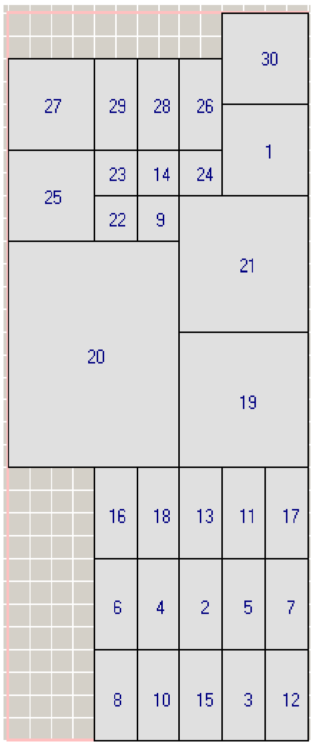


Figure 4. 30 Scenario 2 for robust layout

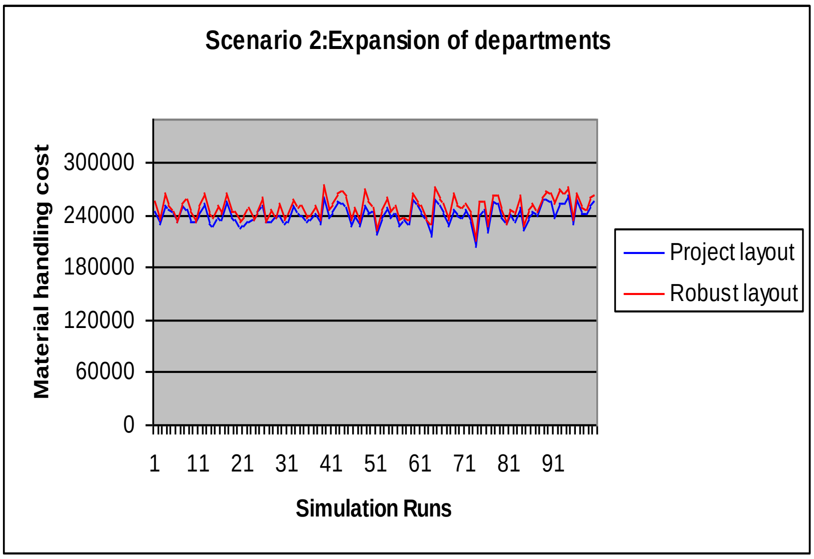


Figure 4. 31 Results of the simulation method for scenario 2

Figure 4.31 shows how the project layout provides high quality solution in terms of a low average total MHC ($240770) over time. This solution essentially gives savings of 3.5% when compared with the robust layout ($249900).

4.6.3 Scenario 3: Deletion of department 30

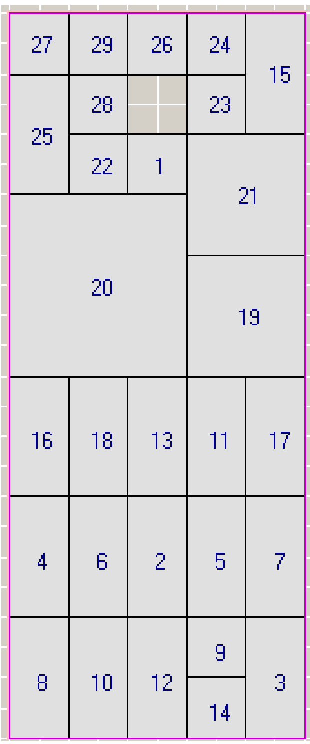


Figure 4. 32 Scenario 3 for project layout

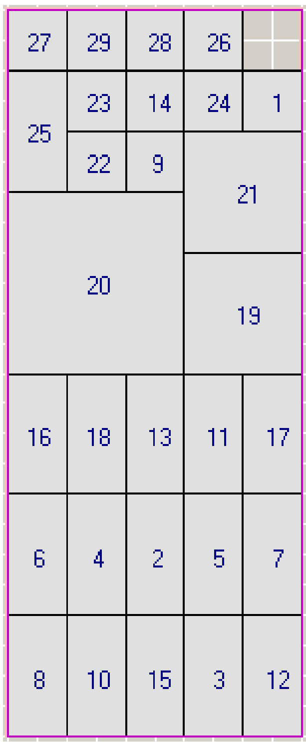


Figure 4. 33 Scenario 3 for robust layout

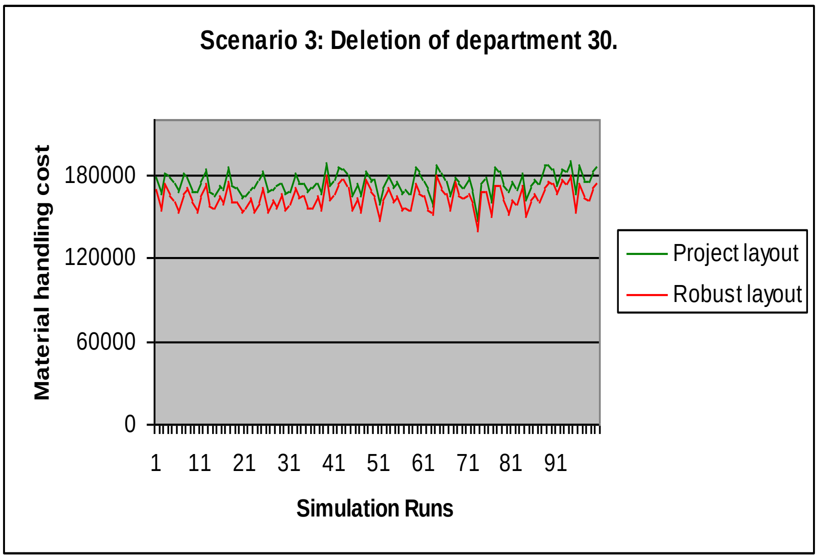


Figure 4. 34 Results of the simulation method for scenario 3

Figure 4.34 shows how the robust layout provides high quality solution in terms of a low average total MHC ($163655) over time. This solution essentially gives savings of 6.1% when compared with the project layout ($174377).

4.6.4 Scenario 4: Deletion of departments 29 and 30

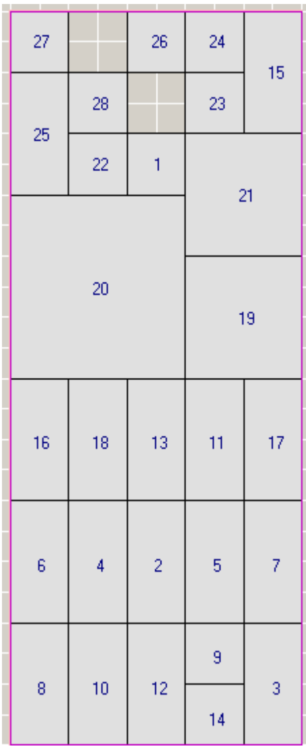


Figure 4. 35 Scenario 4 for project layout

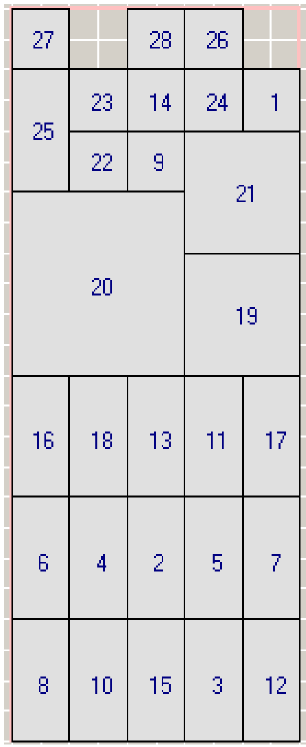


Figure 4. 36 Scenario 4 for robust layout

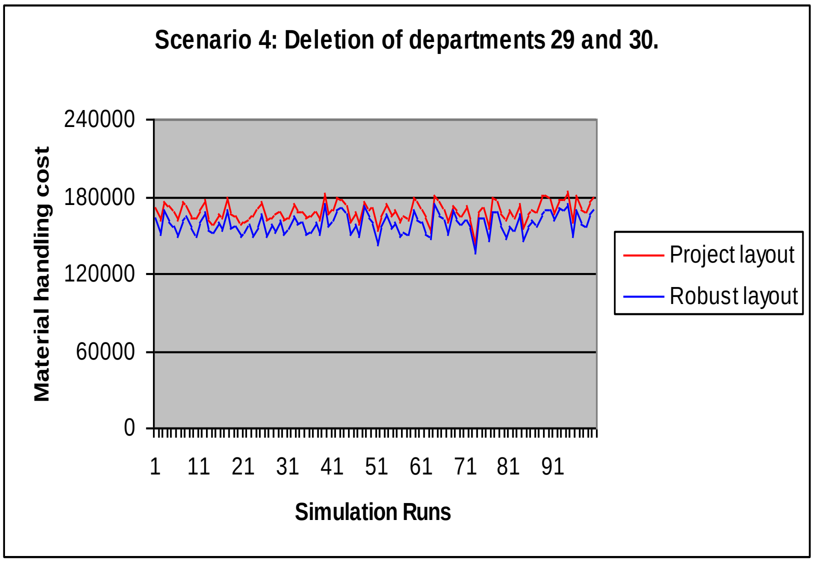


Figure 4. 37 Results of the simulation method for scenario 4

Figure 4.37 shows how the robust layout provides high quality solution in terms of a low average total MHC ($158765) over time. This solution essentially gives savings of 5.9% when compared with the project layout ($168875).

Table 4.10 Comparison of results both analytically and via simulation method

Scenarios		Project layout		Robust layout		Analytic results Reduction (-)		Simulation results Reduction (-)	
		$MHC	$SD	$MHC	$SD	Robust Index %	Stable Index %	MHC Index %	SD Index %
1	Project layout against robust layout	185300	8804.8	188100 (196280)*	9337.8	-4.7	+5.60	-4.20	+7.50
2	Expansion of departments	234950	10492.7	249170 (240770)	14149.9	+5.7	+25.80	+5.5	+15.93
3	Deletion of department 30	170300	7085.62	165000 (174480)	7556.8	-5.43	+6.24	-6.20	+5.20
4	Deletion of departments 29 and 30	165400	6967.86	158900 (168380)	7446.58	-5.60	+6.45	-5.91	+5.70

*Number in parenthesis indicates MHC for using project layout in state of robust layout

The analysis of the 30-department case study is done with respect to robust and stable indices for layouts based on project demand values and the robust layout. Based on the results (Table 4.10, columns 7 and 8), for scenario one, the robust layout resulted in a reduction of MHC by \$8180 (4.7% reduction) and also incurred an additional \$533 in terms of variability (5.6% increase). For scenario two, the project layout performs best and resulted in a reduction of MHC by \$8400 (3.4% reduction) and SD by \$3657.2 (25.8% reduction). On the other hand, for both scenarios three and four, the robust layout resulted in a reduction of MHC by 5.43% and 5.6%, respectively. However, it also incurred an additional 1.8% and 6.45% increase in terms of variability. Therefore, the project layout is chosen as the best layout that is stable for the 30-department case study because the reduction in variability is high when compared with the additional increase in MHC for scenarios one, three and four. The results validate the fact that incorporating an analysis PDF during the early stage of the layout design process is essential and may lead to the design of an efficient layout depending on the nature of input data.

4.7 Conclusion driven from case studies

Three case studies are developed to demonstrate the proposed methodology to evaluate project layout against robust layout in a stochastic environment where the product demand changes stochastically with known mean and variance. Through experimentation, the following results are obtained:

- Comparing project layout and robust layout based on their minimum MHC without ensuring their efficiency over time via analytic indices or simulation method may lead to selecting an inefficient layout—for instance, scenarios three and four in the 20-department case study;

- Increasing the number of departments increases the MHC and SD values while reducing the number of departments may reduces the MHC and SD values;
- The MHC index of simulation results provides close results to robust index over 100 simulation runs. In addition, the SD index of simulation results also provides good results when the variability of product demands is low and slightly different values in certain cases when the variability of product demand is high when compared with the stable index. Therefore, when the SD index of the simulation method is the major concern, the simulation method can be performed once again by replacing rectilinear distance with SED to obtain the exact stable values. However, computation time is required in such cases;
- Using the robust index as criterion to select the most robust layout without consideration of variability will result in selecting the robust layout in all case studies. However, adding the stable index as a second criterion will result in selecting the project layout that is based on PDF values, as illustrated in the 30-department case study. Therefore, the strategy of designing the most robust layout with or without consideration of variability should be identified a priori with respect to the practical considerations and the economic level of the manufacturing facility;
- Using project layout in state of robust layout is equivalent to the results of the simulation method for evaluating project layout and robust layout over time. Therefore, any optimisation approach that has the ability to solve the robust and stable indices or use one layout in a different state will result in reducing the computation time of the simulation method by factor 1/n where n is the number of simulation periods for both MHC and SD indices. On other hand, due to the lack of optimisation approaches that may overtake the complexity of analytic

indices that fall within the NP-class, the proposed simulation method can provide good solutions in terms of MHC and good approximation to stable index when the variance is high.

4.8 Conclusion

This chapter presents the mathematical formulation of robust and stable indices and the application of analytic and hybrid approaches to assess the impact of product demand uncertainty to project and robust layouts in terms of MHC and SD values. The proposed approaches aim to incorporate the product demand forecast and quantify the impact of uncertainty in product demands to the efficiency of project and robust layouts under different scenarios. Computation results indicate that the proposed approaches are effective in reducing the impact of uncertainty for single period stochastic FLP and in applying the results to make better decisions. In the next chapter, an extension of the proposed approaches to consider the multi-period stochastic FLP is presented.

CHAPTER 5

A FRAMEWORK USING ANALYTIC AND HYBRID APPROACHES FOR MULTI-PERIOD STOCHASTIC FLP

5.1 INTRODUCTION

In Chapter Four, the results from the case studies confirmed that analytic and hybrid approaches are effective in assessing the uncertainty of product demand to ensure the efficiency of the selected layouts over time and in reducing the impact of errors during the design process. To further enhance the application of the proposed approaches, this chapter presents a framework for the optimal robust layout design for multi-period stochastic FLP. Section 5.2 presents the general framework to incorporate the uncertain nature of product demand into the FLP and to select a single robust layout that can cope with fluctuations and uncertainties in product demands for multi-period stochastic FLP. Section 5.3 presents the development of several case studies to demonstrate and validate the application of the proposed framework for multi-period stochastic FLP. Section 5.4 details the development of the 30-department case study to demonstrate the application of the robust and stable indices for solving different aspects of multi-period stochastic FLP and the effective evaluation of different types of layouts, such as the most robust layout against the most stable layout. Section 5.5 presents the conclusion driven from the case studies. Section 5.6 concludes the subjects of this chapter.

5.2 The general framework to design a single robust layout for multi-period stochastic FLP

In order to present a systematic methodology to design the optimal robust layout for multi-period stochastic FLP, whilst considering hard constraints such as the product demand forecast, a more complex distribution, and the addition, deletion and expansion of departments, the developed analytic and hybrid approaches to address the single period stochastic FLP are modified and enhanced, taking into consideration the time periods and the additional steps, using the following phases:

5.2.1 Phase 1: Design or generation of the optimal or best layouts

In the first phase, VIPPLANOPT is utilised to design and identify the upper and lower bounds on the optimal solution for multiple periods using the following additional steps for both project and robust layouts:

1. Generate the optimal layouts based on PDF and expected value matrices, respectively, for each period of the planning horizon. These layouts represent the lower bounds on the optimal solutions for multiple periods;
2. Generate the optimal layout using the sum of flows over the entire planning horizon for both matrices. These layouts are called the most robust layouts;
3. Apply the most robust layouts to their various periods of the planning horizon and calculate the total MHC to identify the upper bound on the optimal solutions;
4. Use Total Penalty Cost (TPC) as an indicator to test the suitability of the identified layout to be the robust layout for the given data set;

$$\text{TPC} = \frac{\sum_{p=1}^{p} C_p^{\,Robust} - \sum_{p=1}^{p} C_p^{\,Optimal}}{\sum_{p=1}^{p} C_p^{\,Robust}} \times 100 \tag{5.1}$$

Where

$\sum_{p=1}^{p} C_p^{\,Robust}$ = MHC when robust layout is applied to period p.

$\sum_{p=1}^{p} C_p^{\,Optimal}$ = MHC of optimal layout of period p.

5. Is TPC value less than 15%? Go for robust approach. Otherwise, go for adaptive approach.

In step four, the TPC is used in the most recent publication by Pillai et al. (2011) to test the suitability of the determined layout to be a robust layout for the given data set. They showed that the TPC values should be less than 15% to eliminate the use of the flexible approach.

5.2.2 Phase 2: Evaluation of project and robust layouts

In the second phase, the proposed analytic and hybrid approaches presented in the previous chapters are utilised to evaluate the robustness and stability of project and robust layouts under different scenarios.

5.2.3 Phase 3: Selection of the optimal robust layout

The final phase is to compare and analyse the results of the developed indices' values to select the optimal robust layout design under consideration. Using the three phases mentioned above, the framework representing the logic of incorporating PDF to design a single robust layout for the multi-period stochastic FLP is illustrated in Figure 5.1.

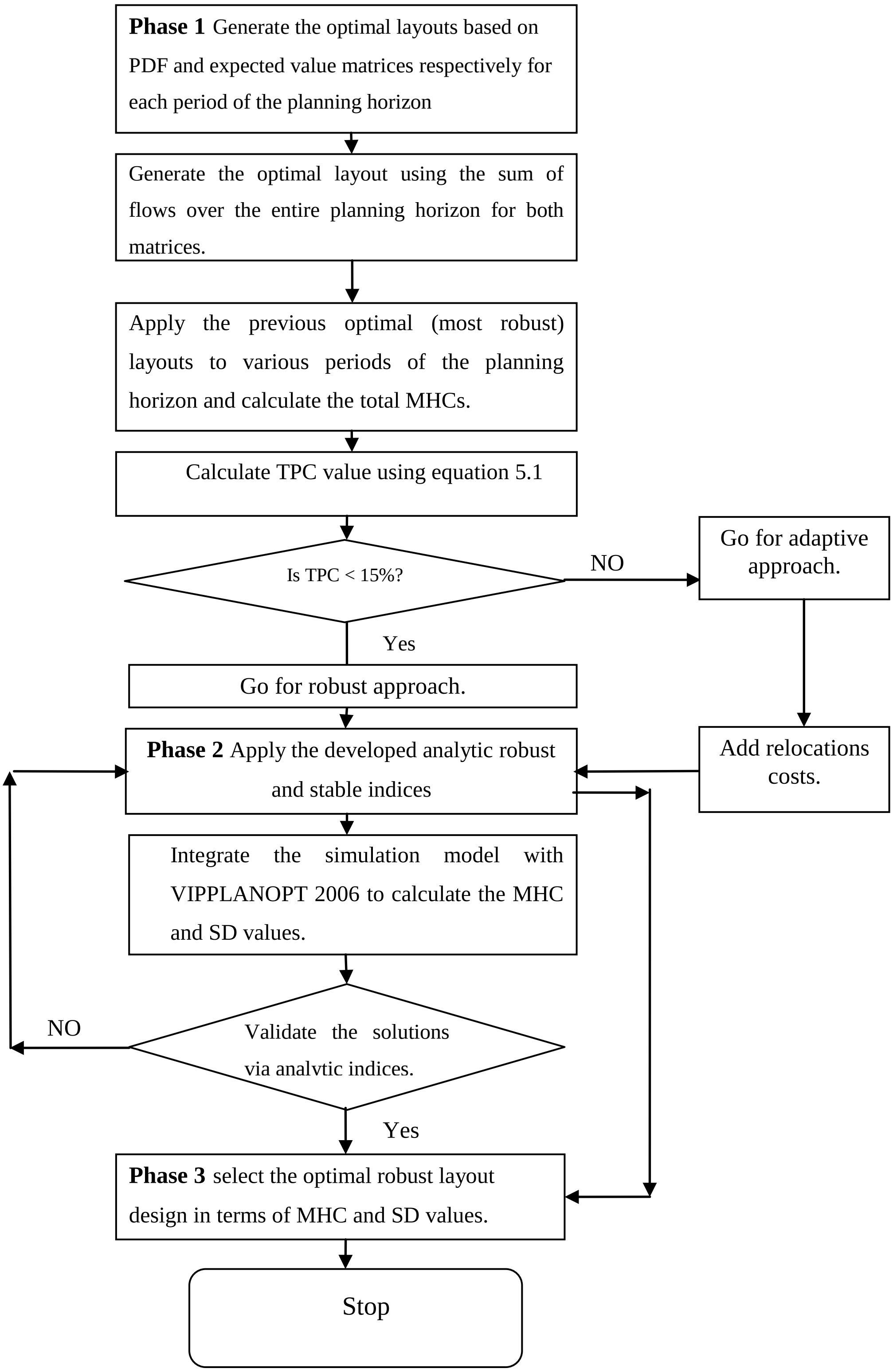


Figure 5.1 A framework for the optimal robust layout design for the multi-period stochastic FLP using analytic and hybrid approaches

5.3 Performance analysis

This section presents four case studies that are developed to demonstrate the application of the proposed framework for solving different aspects of multi-period stochastic FLP.

5.3.1 12-department case study (Multi period)

The constructed case study involves 12 departments of unequal areas and seven products. The layout is a process layout-type. The material handling cost is fixed at $1/unit distance. The size of the plant is 70m long and 30m wide. The area of each department and from-to charts showing mean and variance values are given in Appendix E. Probability density functions of product demand follow a normal distribution. Distances between departments are rectilinear for the robust, MHC, and SD indices and SED for the stable index. The horizon planning is three periods. Product demand distribution and sequence of process are shown in Table 5.1.

Table 5.1 Product demand distribution and process sequence for 12-department case study (Multi period)

Product	Period 1		Period 2		Period 3		Process sequence
	PDF	Distribution Normal	PDF	Distribution Normal	PDF	Distribution Normal	
1	140	(140 1600)	250	(180 2300)	180	(160 900)	1-3-4
2	300	(400 12900)	130	(100 900)	110	(100 900)	3-5-6
3	120	(100 1600)	100	(100 900)	410	(400 2300)	2-5--7
4	100	(50 900)	100	(100 900)	340	(300 900)	4-9-11
5	180	(200 1600)	200	(200 1600)	220	(200 1600)	2-4-6-8-10
6	130	(100 900)	130	(130 900)	130	(100 900)	2-4-6-10
7	130	(100 1600)	120	(120 1600)	50	(50 1600)	10-12

The proposed framework for the solution of multi-period stochastic FLP using analytic and hybrid approaches is applied. The first phase of the framework is used to generate the optimal project layouts based on the PDF matrix for each period of the planning horizon. These layouts are shown in Figures 5.2, 5.3 and 5.4, respectively. The MHC of optimal project layouts for each period of the planning horizon is provided in Table 5.2. Once the optimal layouts are determined, the second step is to generate the optimal layout by using the sum of the flow matrices over the entire planning horizon. Figure 5.5 shows the project (most robust) layout and its MHC value. This layout is called the most robust layout for PDF values and is then applied to various periods of the planning horizon and the MHC of each period is aggregated to obtain the total MHC of the entire planning horizon. Equation (5.1) is used to compute the TPC value and this value indicates that the performance of the proposed layout is high and falls within 1.63% of the optimal solution. The MHC for using the project (most robust) layout in various periods, the total MHC of the planning horizon and the TPC are illustrated in Table 5.3.

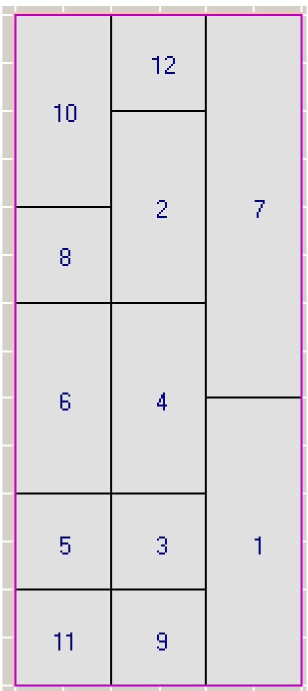


Figure 5.2 Project layout for Period 1

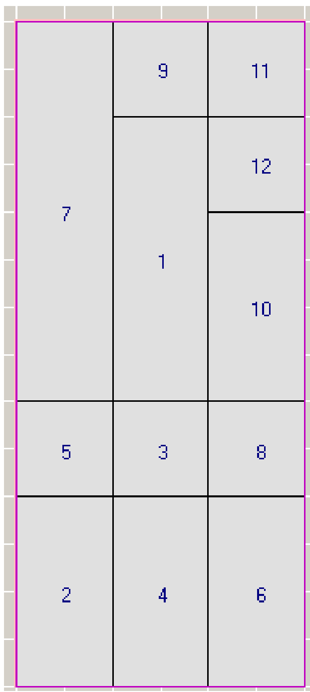


Figure 5.3 Project layout for Period 2

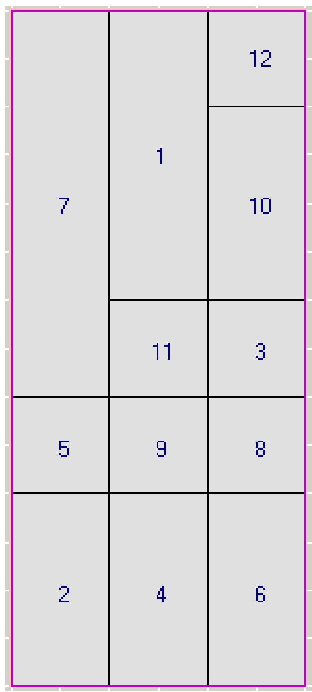
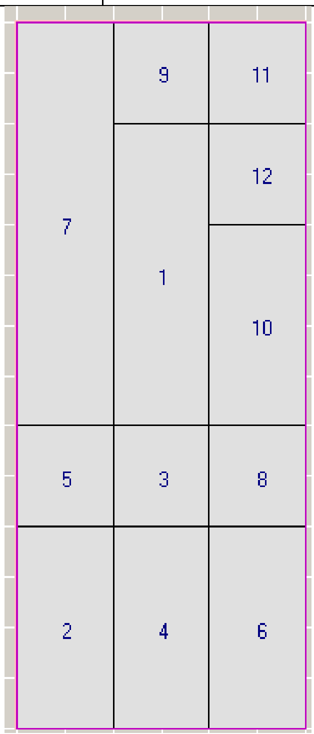


Figure 5.4 Project layout for Period 3

Table 5. 2 MHC of optimal project layouts in various periods and total MHC of planning horizon

Periods	1	2	3	Total MHC of the planning horizon
$ MHC	47050	43900	65500	156450



$52820

Figure 5.5 Project (most robust) layout and its MHC value

Table 5. 3 MHC for using project (most robust) layout in various periods, total MHC of planning horizon and TPC

Periods	1	2	3	Total MHC of the Planning Horizon
$ MHC	47150	43900	68000	159050
Total Penalty Cost TPC %				$\frac{159050-156450}{159050}\times 100 = 1.63\%$

Similarly, the first phase of the proposed framework is utilised once again to generate the optimal layouts based on the expected value matrix for each period of the planning horizon. These layouts are shown in Figures 5.6, 5.7 and 5.8, respectively. The MHC of robust layouts for each period of the planning horizon is illustrated in Table 5.4. Once the optimal layouts are determined, the second step is to generate the most robust layout by using the sum of the expected value matrices over the entire planning horizon. Figure

5.9 shows the most robust layout and its MHC value. This layout is applied to various periods of the planning horizon and the MHC of each period is aggregated to obtain the total MHC of the entire planning horizon. Equation (5.1) is also used to compute the TPC value and this value indicates that the performance of the proposed layout is high and falls within 0.22% of the optimal solution. The MHC for using the most robust layout in various periods, the total MHC of the planning horizon and the TPC are provided in Table 5.5.

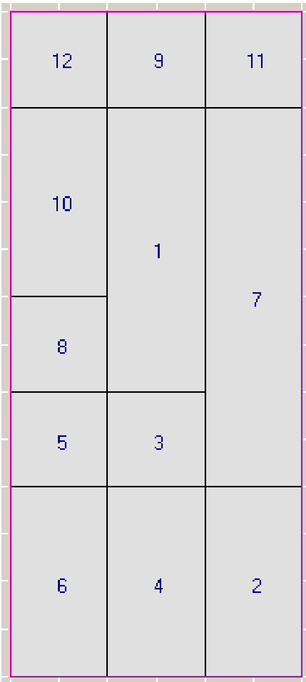


Figure 5.6 Robust layout for Period 1

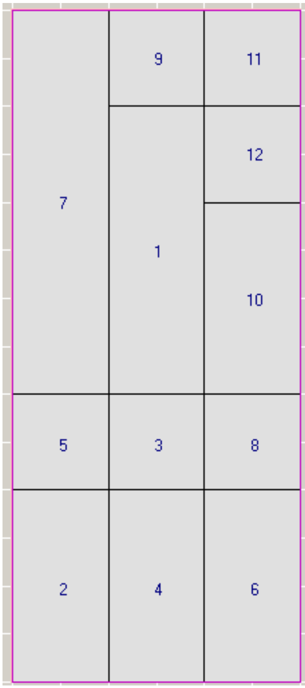


Figure 5.7 Robust layout for Period 2

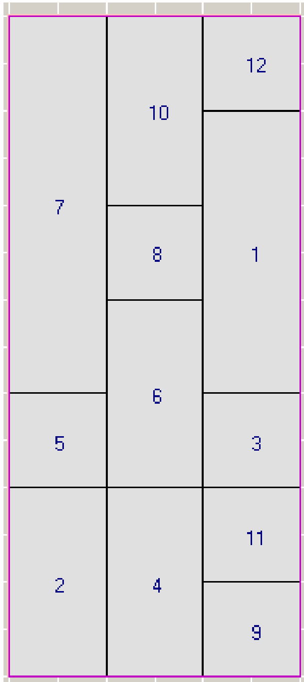
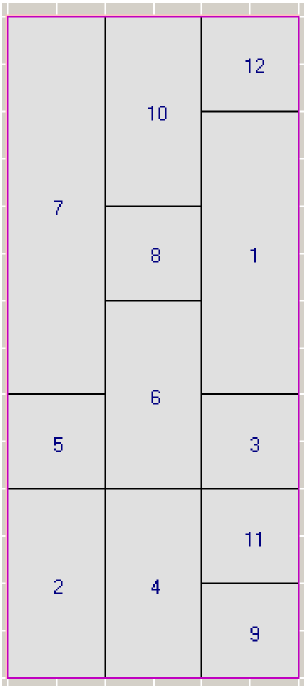


Figure 5.8 Robust layout for Period 3

Table 5.4 MHC of optimal robust layouts in various periods and total MHC of planning horizon

Periods	1	2	3	Total MHC of the planning horizon
$ MHC	43150	38700	52920	134790



$45900

Figure 5.9 The most robust layout and its MHC value

Table 5.5 MHC for using the most robust layout in various periods, total MHC of planning horizon and TPC

Periods	1	2	3	Total MHC of the planning horizon
$ MHC	43350	38800	52940	135090
TPC				0.22%

Once the most robust layouts are identified, the second phase of the proposed framework is utilised to quantify the impact of uncertainty under various scenarios by using the simulation method and analytic indices. In addition, the same scenarios for single period stochastic FLP are considered for uncertainty analysis in a multi-period case. The configuration of project and robust layouts for different scenarios are shown in Figures 5.5, 5.9, 5.11, 5.12, 5.14, 5.15, 5.17 and 5.18. The computation results from using the simulation method for different scenarios are given in Figures 5.10, 5.13, 5.16 and 5.19. The comparison summary of the analytic robust and stable indices is given in Table 5.6. Furthermore, the comparison summary of the stable, robust, MHC and SD indices for the 12-department case study is illustrated in Table 5.7.

5.3.1.1 Scenario 1: Evaluation of project layout against robust layout

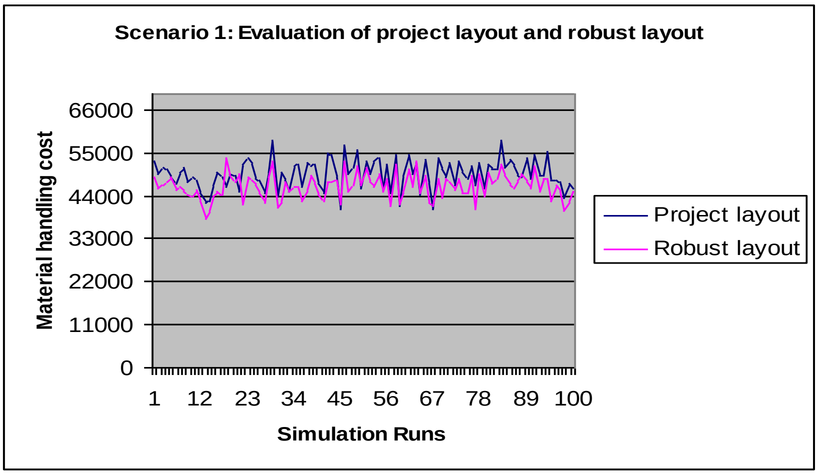


Figure 5.10 Results of the simulation method for scenario 1

Figure 5.10 shows how the robust layout provides high quality solution in terms of a low average total MHC ($46346.4) over time. This solution essentially gives savings of 6.4% when compared with the project layout ($49507.8).

5.3.1.2 Scenario 2: Expansion of departments

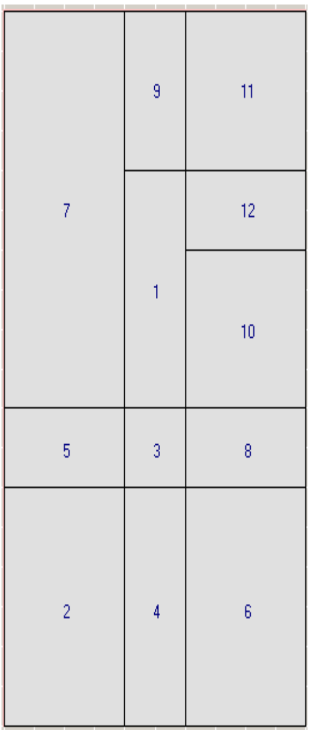


Figure 5.11 Scenario 2 for project layout

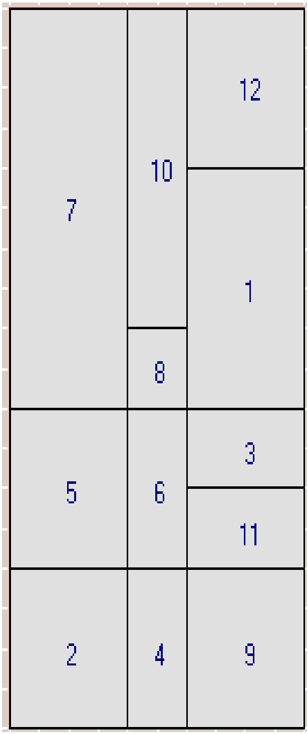


Figure 5.12 Scenario 2 for robust layout

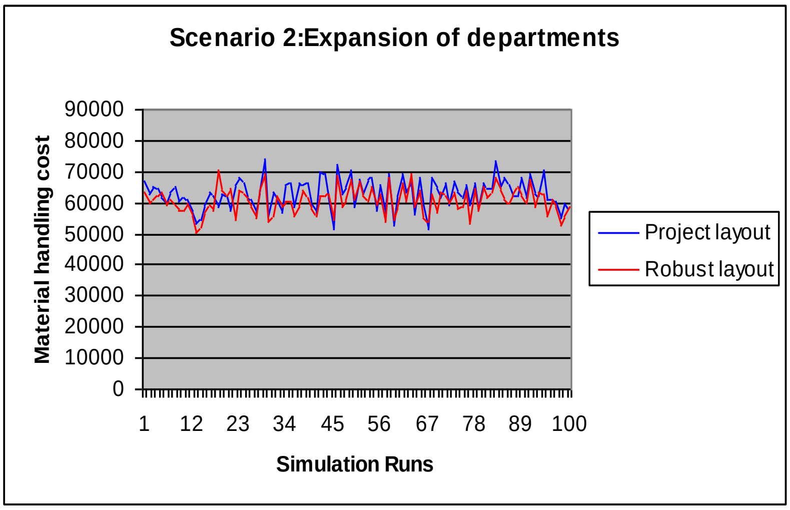


Figure 5.13 Results of the simulation method for scenario 2

Figure 5.13 shows how the robust layout provides high quality solution in terms of a low average total MHC ($60608) over time. This solution essentially gives savings of 3.6% when compared with the project layout ($62910).

5.3.1.3 Scenario 3: Deletion of department 12

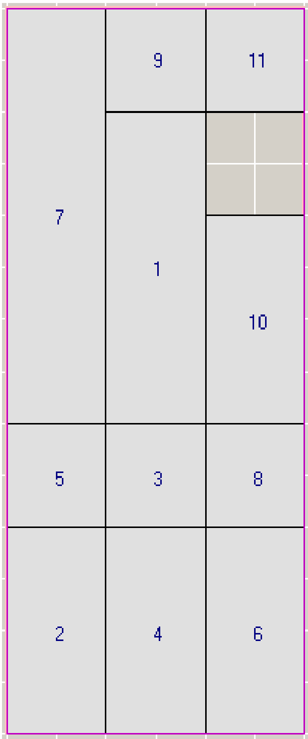


Figure 5.14 Scenario 3 for project layout

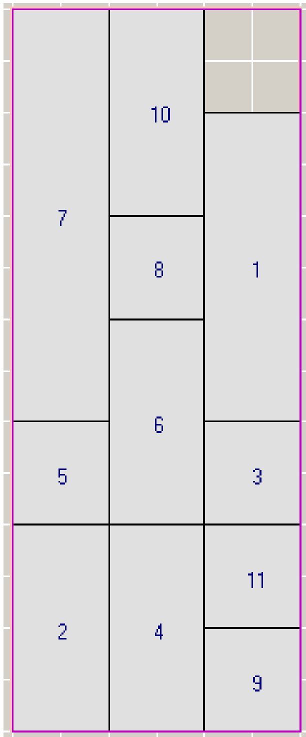


Figure 5.15 Scenario 3 for robust layout

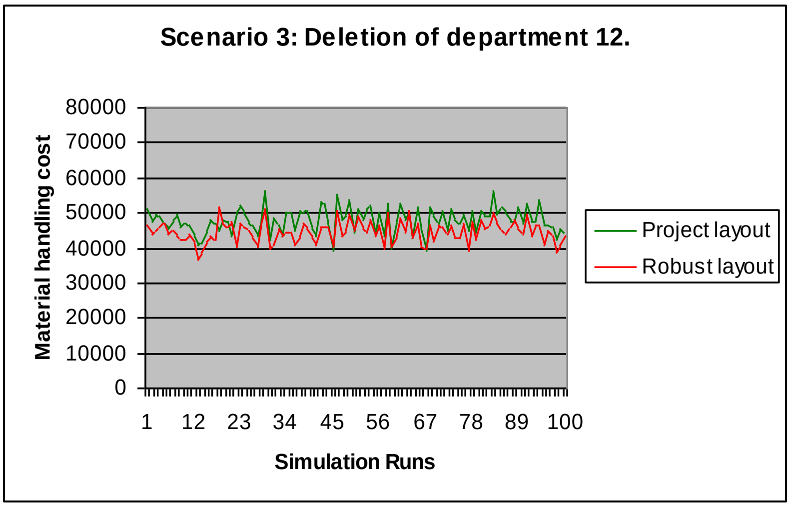


Figure 5.16 Results of the simulation method for scenario 3

Figure 5.16 shows how the robust layout provides high quality solution in terms of a low average total MHC ($44556) over time. This solution essentially gives savings of 6.9% when compared with the project layout ($47858).

5.3.1.4 Scenario 4: Deletion of departments 11 and 12

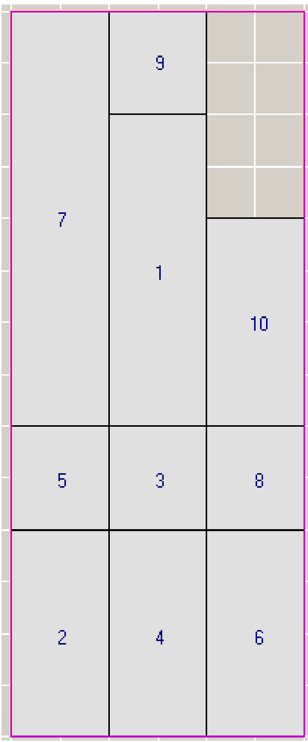


Figure 5.17 Scenario 4 for project layout

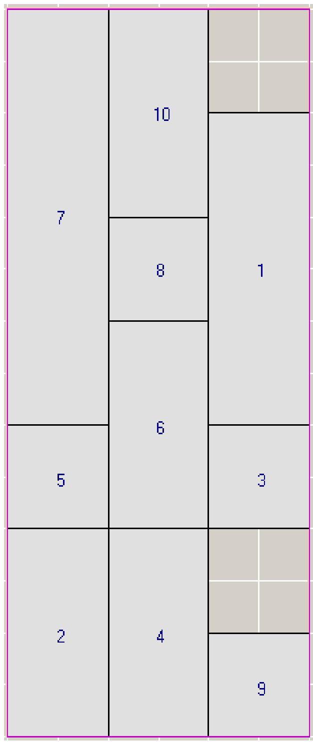


Figure 5.18 Scenario 4 for robust layout

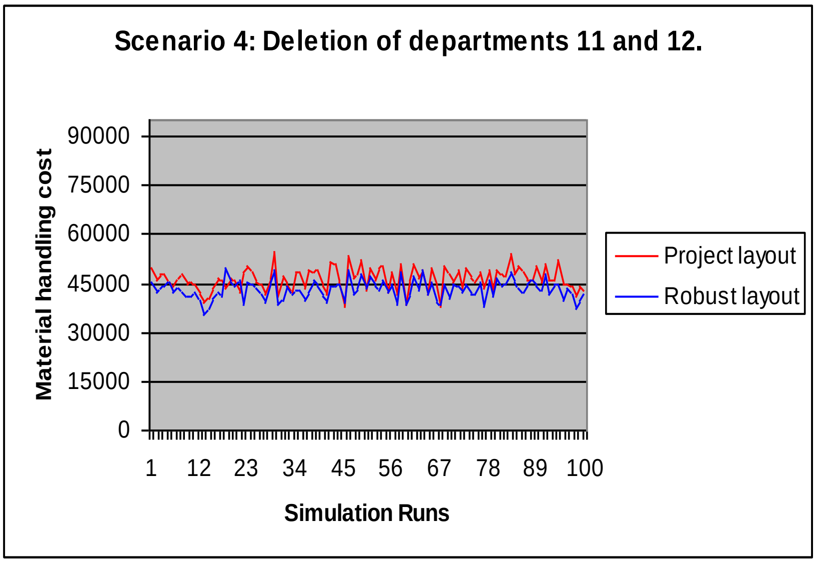


Figure 5.19 Results of the simulation method for scenario 4

Figure 5.19 shows how the robust layout provides high quality solution in terms of a low average total MHC ($43090) over time. This solution essentially gives savings of 7.05% when compared with the project layout ($46360.8).

Table 5.6 Comparisons of analytic indices for 12-department case study (Multi period)

Scenarios		Project layout		Robust layout			Analytic indices Reduction (-)	
		$MHC	$SD	$MHC	$SD	$MHC*	Robust index (column 5,7)	Stable index (column 4,6)
1	Project layout against robust layout	52850	3333.9	45900	2876.0	49200	-6.7	-13.7
2	Expansion of departments	67150	4292.4	60600	3939.8	62900	-3.65	-8.21
3	Deletion of department 12	51350	3279.5	44550	2841.2	47850	-6.89	-13.36
4	Deletion of departments 11 and 12	49550	3265.7	43050	2830.2	46350	-7.1	-13.33

* MHC for using project layout in state of robust layout

Table 5.7 Comparison of results both analytically and via simulation method for 12-department case study (Multi period)

Scenarios		Project layout		Robust layout		Comparison of robust, stable, MHC and SD indices Reduction (-)	
		$MHC	SD	$MHC	SD		
1	Analytic method	49200	3333.9	45900	2876.6	-6.7	-13.7
	Simulation method	49507.8	3693.4	46346.4	3175.3	-6.4	-14.02
	95% confidence interval	[48783.9,50231.72]		[45724,46968.77]			
2	Analytic method	62900	4292.4	60600	3939.8	-3.65	-8.21
	Simulation method	62909.93	4693.2	60608.37	4152.4	-3.6	-11.5
	95% confidence interval	[61990.1,63829.81]		[59794.5,61422.26]			
3	Analytic method	47850	3279.5	44550	2841.2	-6.89	-13.46
	Simulation method	47869.54	3570.3	44568.04	3052.7	-6.9	-14.5
	95% confidence interval	[47169.8,48569.32]		[43969.7,45166.36]			
4	Analytic method	46350	3265.7	43050	2825.2	-7.1	-13.46
	Simulation method	46360.83	3458.6	43090.37	2952.3	-7.05	-14.6
	95% confidence interval	[45682.9,47038.72]		[42511.74,43669.02]			

In the final phase of the proposed framework, the analysis of the case study is performed with respect to robust and stable indices for layouts based on PDF values and most robust layout. According to the results (Table 5.6, columns 8 and 9), the project layout performs worst in all scenarios and did not provide any reduction in terms of MHC and SD when compared with the robust layout. As a result, the robust layout is selected as the best layout for the 12-department multi-period case study. In order to provide a more statistical insight into using the analytic and simulation methods, equation (4.7) is used to compute the 95% confidence interval of the simulation results. The values of MHC are examined, compared and illustrated in Table 5.7. In Table 5.7,through observation, all of the MHC values obtained by using analytic indices fall within the range of the 95% confidence interval of MHC values acquired via the simulation method. Hence, it can be concluded that the results show a good agreement between the two methods.

5.3.2 20-department case study (Multi period)

The constructed case study involves 20 departments of unequal areas and 10 products. The material handling cost is fixed at $1/unit distance. The size of the plant is 50m long and 90m wide. The area of the departments and the from-to charts showing mean and variance values for each period are given in Appendix F. Probability density functions of the product demands follow a normal distribution, are of continuous type and are independent. Distances between departments are rectilinear for robust, MHC and SD indices and SED for the stable index. The horizon planning is three periods. Product demand distribution and sequence of process are shown in Table 5.8.

Table 5.8 Product demand distribution and process sequence for 20-department case study (Multi period)

Product	Period 1		Period 2		Period 3		Process sequence
	PDF	Distribution Normal	PDF	Distribution Normal	PDF	Distribution Normal	
1	60	(50 200)	150	(75 1600)	100	(85 900)	1-3-4-9-15
2	40	(50 100)	80	(80 400)	390	(320 4300)	10-12-14-16
3	40	(25 225)	60	(50 225)	100	(75 225)	7-13-15-16
4	30	(25 64)	60	(50 64)	100	(75 304)	7-13-15
5	130	(100 2300)	275	(275 3600)	370	(225 4900)	2--5-7
6	108	(250 1900)	110	(100 400)	130	(100 400)	9-11-13-17-19
7	150	(150 1600)	145	(150 1600)	190	(150 1600)	2-13-18
8	160	(150 1600)	145	(150 1600)	140	(150 1600)	3-5-6-13-20
9	240	(200 1600)	230	(200 1600)	195	(200 1600)	2-4-6-8-10
10	130	(100 1600)	90	(60 900)	45	(50 900)	2-4-6-10

Similar to the 12-department multi-period case study, the first phase of the framework is used to generate the optimal project layouts based on the PDF matrix for each period of the planning horizon. The project layouts are shown in Figures 5.20, 5.21 and 5.22, respectively. The MHC of project layouts for each period of the planning horizon is provided in Table 5.9. Once the optimal layouts are determined, the second step is to generate the optimal project for the sum of the flow matrices and calculate its MHC value. Figure 5.23 shows the project (most robust) layout and its MHC value. This layout is applied to various periods of the planning horizon and the MHC of each period is aggregated to obtain the total MHC of the entire planning horizon. Equation (5.1) is used as criterion to test the suitability of the identified layout to be the robust layout for this case study. The MHC for using the project layout in various periods, the total MHC of the planning horizon and the TPC are provided in Table 5.10. Similarly, using the expected value matrix, the optimal layouts are shown in Figures 5.24, 5.25 and 5.26, respectively. The MHC of the robust layouts for each period of the planning horizon is provided in Table 5.11. The most robust layout and its MHC value are shown in Figure 5.27. The MHC for using the robust layout of each period, the total MHC of the planning horizon and the TPC are provided in Table 5.12.

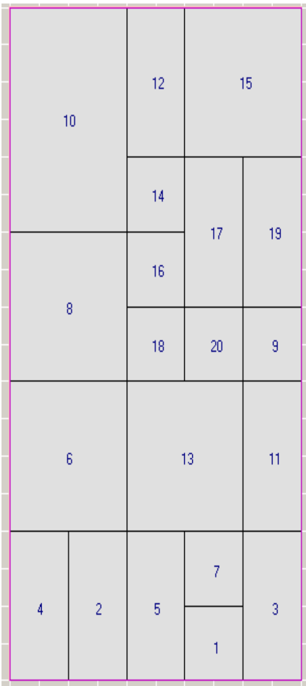


Figure 5.20 Project layout for Period 1

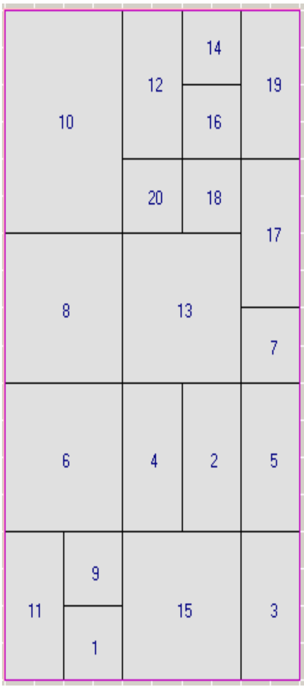


Figure 5.21 Project layout for Period 2

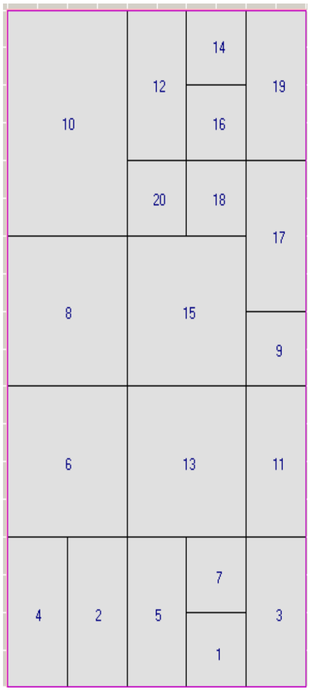
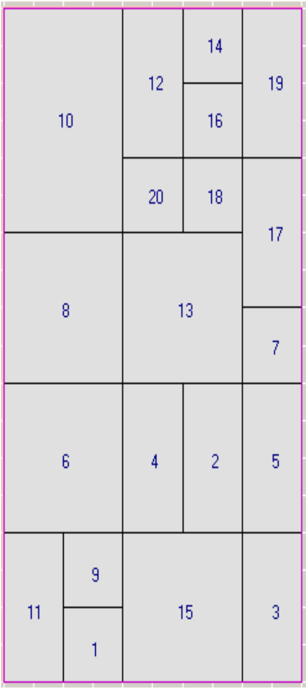


Figure 5.22 Project layout for Period 3

Table 5.9 MHC of optimal project layouts in various periods and total MHC of planning horizon

Periods	1	2	3	Total MHC of the planning horizon
$MHC	87400	103225	118700	309325



$103140

Figure 5.23 Project (most robust) layout and its MHC value

Table 5.10 MHC for using project (the most robust) layout in various periods, total MHC of planning horizon and TPC

Periods	1	2	3	Total MHC of the planning horizon
$MHC	87600	103225	119500	310325
TPC				.32%

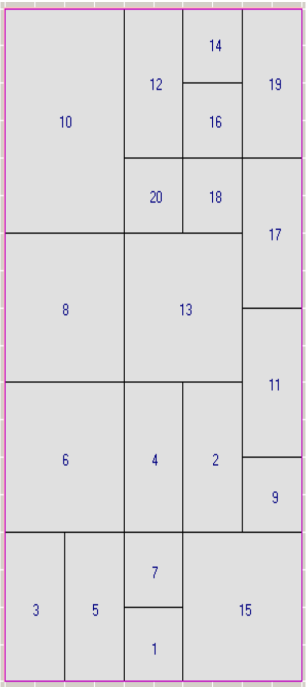


Figure 5.24 Robust layout for Period 1

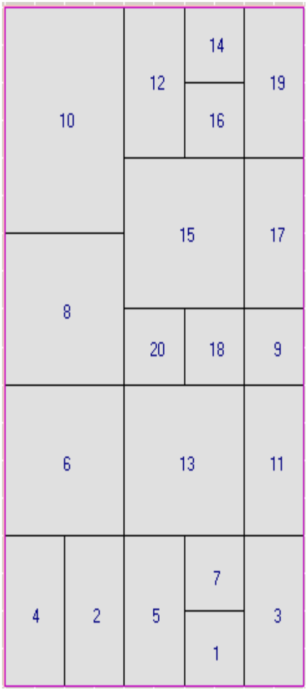


Figure 5.25 Robust layout for Period 2

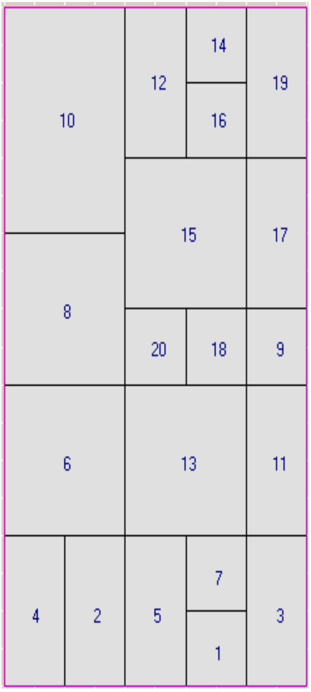
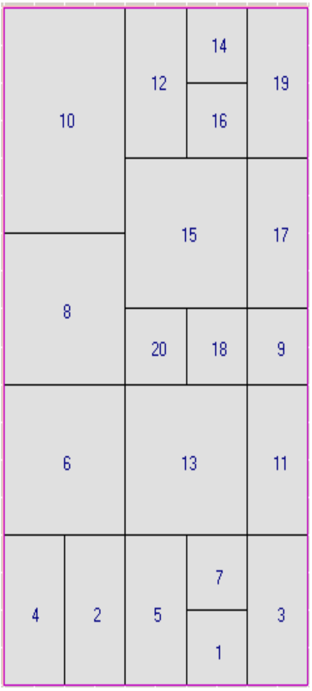


Figure 5.26 Robust layout for Period 3

Table 5.11 MHC of optimal robust layouts in various periods and total MHC of planning horizon

Periods	1	2	3	Total MHC of the planning horizon
$MHC	82750	81025	94625	258400



$87300

Figure 5.27 The most robust layout and its MHC value

Table 5.12 MHC for using the most robust layout in various periods, total MHC of planning horizon and TPC

Period	1	2	3	Total MHC of the planning horizon
MHC	86000	81025	94625	261650
TPC				1.24%

Once the most robust layouts are identified, the analytic and hybrid approaches of the second phase are used to evaluate these layouts under different scenarios. The configuration of project and robust layouts for different scenarios are shown in Figures 5.23, 5.27, 5.29, 5.30, 5.32, 5.33, 5.35 and 5.36, respectively The computation results from using the simulation method for different scenarios are shown in Figures 5.28, 5.31, 5.34 and 5.37. The computation results from using robust and stable indices and the results of the simulation indices are compared and illustrated in Table 5.13.

5.3.2.1 Scenario 1: Evaluation of project layout against robust layout

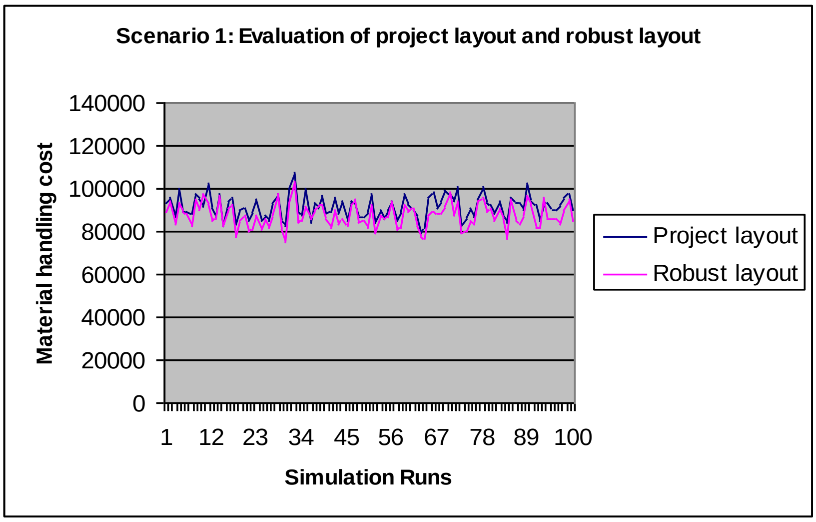


Figure 5.28 Results of the simulation method for scenario 1

Figure 5.28 shows how the robust layout provides high quality solution in terms of a low average total MHC ($87440.8) over time. This solution essentially gives savings of 4.46% when compared with the project layout ($91533.6).

5.3.2.2 Scenario 2: Expansion of departments

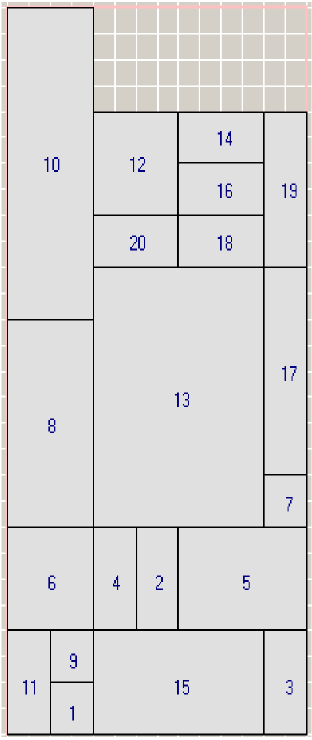


Figure 5.29 Scenario 2 for project layout

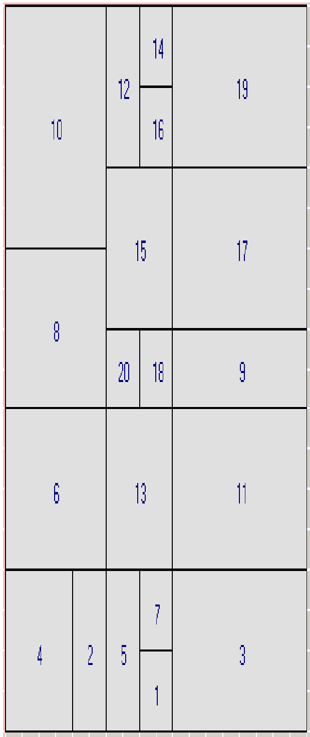


Figure 5.30 Scenario 2 for robust layout

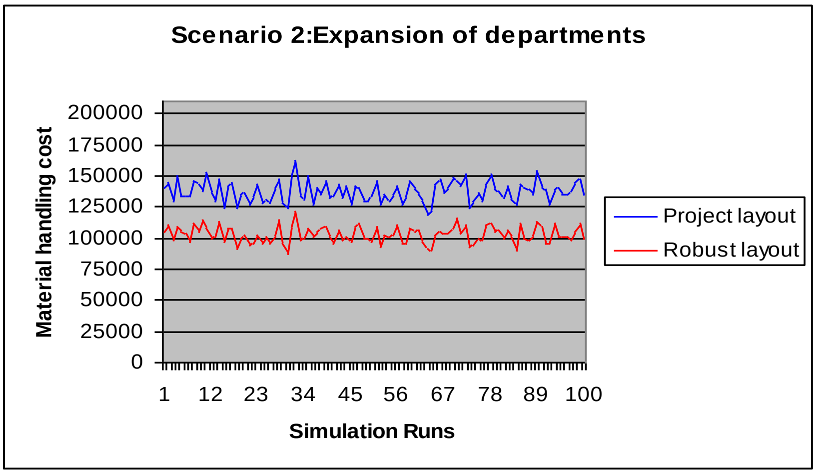


Figure 5.31 Results of the simulation method for scenario 2

Figure 5.31 shows how the robust layout provides high quality solution in terms of a low average total MHC ($102700) over time. This solution essentially gives savings of 25.1% when compared with the project layout ($137300).

5.3.2.3 Scenario 3: Deletion of department 20

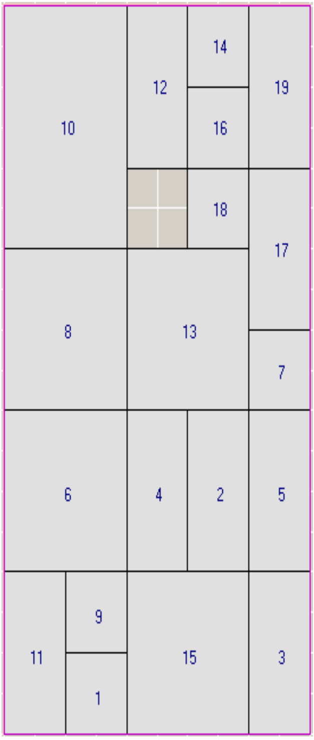


Figure 5.32 Scenario 3 for project layout

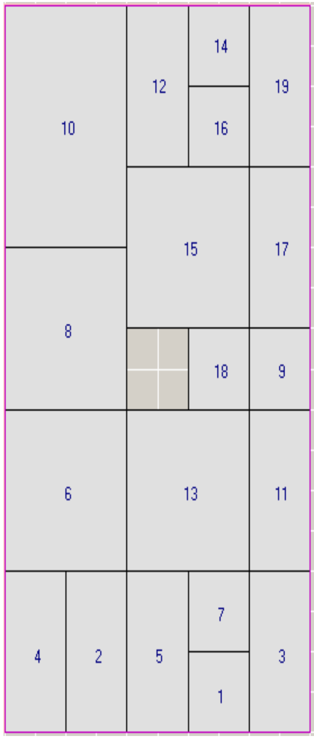


Figure 5.33 Scenario 3 for robust layout

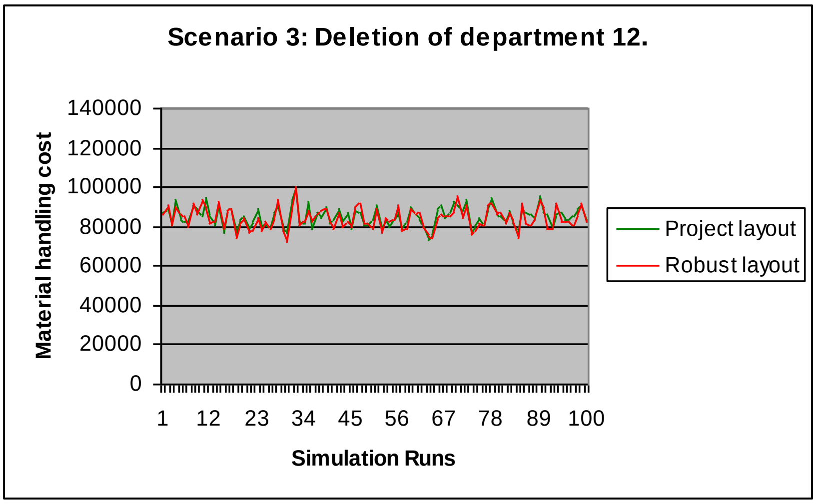


Figure 5.34 Results of the simulation method for scenario 3

Figure 5.34 shows how the robust layout provides high quality solution in terms of a low average total MHC ($84500) over time. This solution essentially gives savings of 4.3% when compared with the project layout ($88303).

5.3.2.4 Scenario 4: Deletion of departments 19 and 20

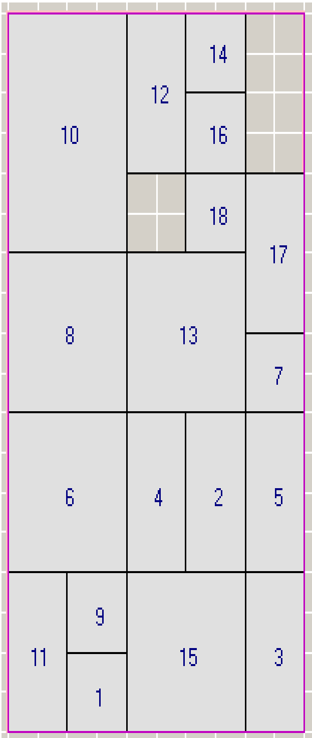


Figure 5.35 Scenario 4 for project layout

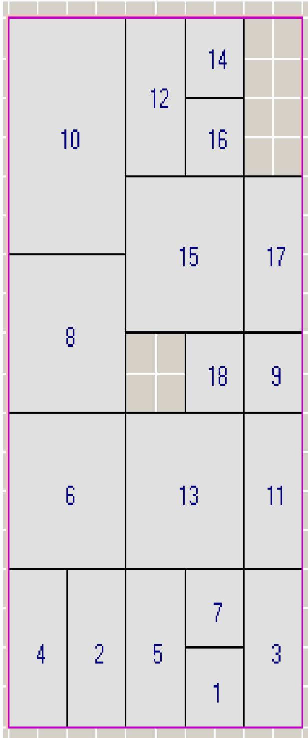


Figure 5.36 Scenario 4 for robust layout

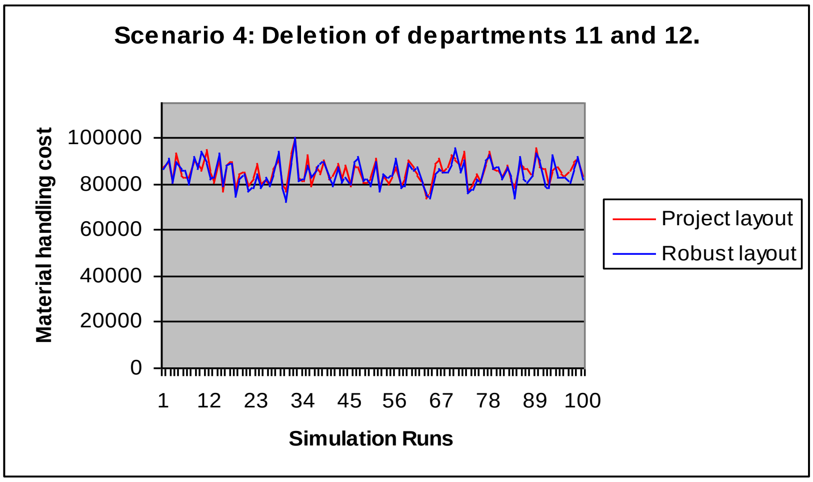


Figure 5.37 Results of the simulation method for scenario 4

Figure 5.37 shows how the robust layout provides high quality solution in terms of a low average total MHC ($81232.5) over time. This solution essentially gives savings of 4.5% when compared with the project layout ($85126.3).

Table 5.13 Comparison of results both analytically and via simulation method

Scenarios		Project layout		Robust layout		Analytic results Reduction (-)		Simulation results Reduction (-)	
		$MHC	$SD	$MHC	$SD	Robust Index %	Stable Index %	MHC Index %	SD Index %
1	Project layout against robust layout	103140	4250.0	87300 (91300)*	4140.0	-4.38	-2.58	-4.46	-4.4
2	Expansion of departments	155815	6553.8	102550 (137250)	5062.7	-25.3	-22.7	-25.1	-18.1
3	Deletion of department 20	98180	4205.6	84300 (88300)	4099.9	-4.53	-2.51	-4.32	-4.2
4	Deletion of departments 19 and 20	96180	4162.6	81300 (85700)	4055.7	-5.13	-2.57	-4.57	-4.24

*Number in parenthesis indicates MHC of using project layout in state of robust layout

In the final phase of the proposed framework, the analysis of the 20-department case study is done with respect to the robust and stable indices for layouts based on PDF values and the most robust layout. Table 5.13 shows a comparison of robust, stable, MHC and SD indices both analytically and via the simulation method for project and robust layouts under different scenarios. Based on the results (Table 5.13, columns 7 and 8), for scenario one, the robust layout resulted in a reduction of MHC by $4000 (4.38% reduction) and SD by $110 (2.58% reduction). For scenario two, the project layout performed worst and incurred an additional 25.3% increase in terms of MHC and an additional 22.7% increase in terms of variability when compared with the robust layout. On the other hand, for both scenarios three and four, the project layout did not provide any reduction in terms of MHC and SD when compared with the robust layout. Therefore, the layout based on product demand distribution values is selected as the best layout that is robust and stable to changing market demands for the 20-department multi-period case study.

5.3.3 30-department case study (Multi period)

The constructed case study involves 30 departments of unequal areas and 17 products. The layout is a process layout-type. The material handling cost is fixed at $1/unit distance. The size of the plant is 50m long and 120m wide. The area of the departments and the from-to charts showing mean and variance values for each period are given in Appendix G. Probability density functions of the product demands follow a normal distribution, a uniform distribution, a triangular distribution, are of continuous type and are independent. Distances between departments are rectilinear for the robust, MHC and SD indices and SED for the stable index. The horizon planning is three periods. Product demand distribution and sequence of process are shown in Table 5.14.

Table 5.14 Product demand distribution and process sequence for 30-department case study (Multi period)

Product	Period 1		Period 2		Period 3		Process sequence
	PDF	Distribution	PDF	Distribution	PDF	Distribution	
1	60	T* (25,50,90)	50	T(25,50,,100)	50	T(25,50,80)	1-3-4-9-15
2	30	U* (10 40)	50	U(10 80)	80	U(10 90)	10-12-14-16
3	30	N* (25 64)	25	N (25 64)	40	N (40 64)	7-13-15-16
4	20	N (25 36)	25	N (25 36)	40	N(40 36)	7-13-15
5	55	N (50 64)	200	N(200 1764)	270	N (270 1600)	2--5-7
6	55	N (50 3 6)	50	N (50 144)	100	N (100 900)	2-5-7-30
7	130	U(40 160)	100	U(40 160)	190	U(40 220)	9-11-13-17-19-21
8	50	N (50 64)	600	N (600 19600)	50	N (50 64)	14-23-25
9	50	N(50 36)	100	N (100 900)	50	N (50 36)	14-23-25-28
10	175	U(100 200)	50	U(40 360)	190	U(100 340)	2-13-18
11	186	T(60,150,240)	150	T(50,150,250)	150	T(100,150,200)	3-5-6-13-20
12	140	T(60,150,240)	450	T(90,450, 780)	850	T(300,600,930)	25-27-29
13	250	N (200 2500)	300	N(300 3600)	320	N (300 10000)	2-4-6-8-10
14	100	N(100 900)	200	N(200 2500)	260	N(260 900)	2-4-6-10
15	260	T(100,200, 300)	500	T(120,500,820)	650	T(230,500,800)	16-18-20-22
16	205	U(150 650)	200	U(100 300)	230	U(200 250)	24-26-28-30
17	60	U(50 750)	600	U(200 750)	510	U(200 1800)	1-30

*N, *U and *T indicate Normal, Uniform and Triangular distributions, respectively

For the 30-department case study, the first phase of the proposed methodology is used to generate the optimal project layouts based on the PDF matrix for each period of the planning horizon. The project layouts are shown in Figures 5.38, 5.39 and 5.40, respectively. The MHC of project layouts for each period of the planning horizon is illustrated in Table 5.15. These layouts represent a lower bound on the optimal solution for multiple periods. Once the lower bound is identified, the second step is to identify an upper bound on the optimal solution by using the sum of the flow matrices and generating its optimal layout. Figure 5.41 shows the project (most robust) layout and its MHC value. This layout configuration is utilised through each period of the planning horizon and the MHC of each period is aggregated to obtain the upper bound on the optimal solution. Once the lower and upper bounds are identified, equation (5.1) is used to compute the TPC value. This value indicates that the performance of the proposed robust layout is very high and falls within .772% of the optimal solution. The MHC for using the most robust layout in various periods, the total MHC of the planning horizon and the TPC are provided in Table 5.16. Similarly, using the expected value matrix, the optimal layouts for each period of the planning horizon are shown in Figures 5.42, 5.43 and 5.44, respectively. The MHC of the robust layouts for each period of the planning horizon is illustrated in Table 5.17. The most robust layout and its MHC value are shown in Figure 5.45. This layout configuration is utilised through each period of the planning horizon and the MHC of each period is aggregated to obtain the total MHC of the entire planning horizon. Then, equation (5.1) is used to compute the TPC value and this value indicates that the performance of the proposed layout is very high and falls within .846% of the optimal solution. The MHC for using the robust layout in various periods, the total MHC of the planning horizon and the TPC are provided in Table 5.18.

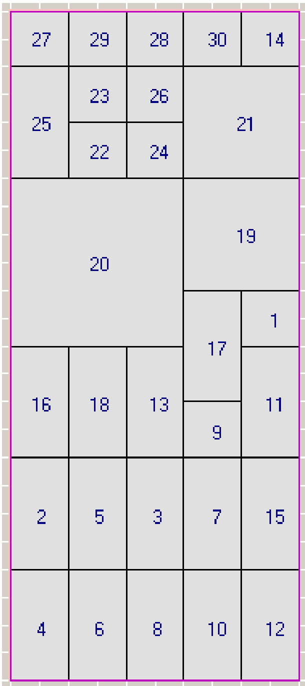


Figure 5.38 Project layout for Period 1

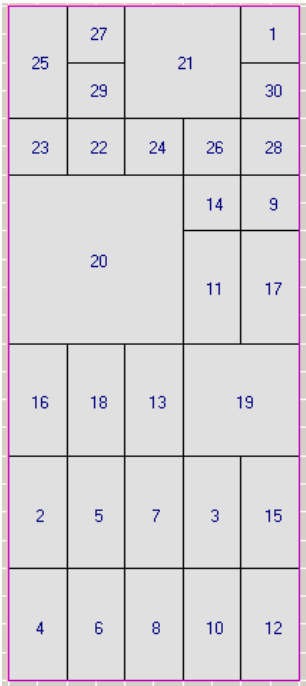


Figure 5.39 Project layout for Period 2

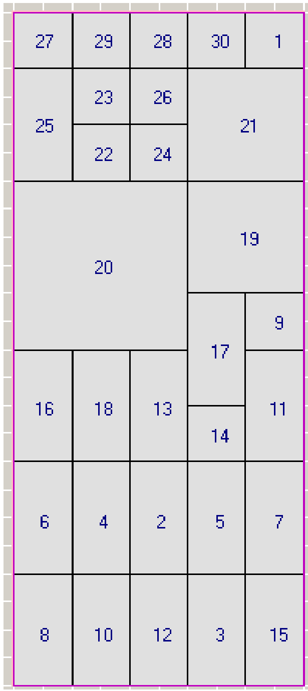
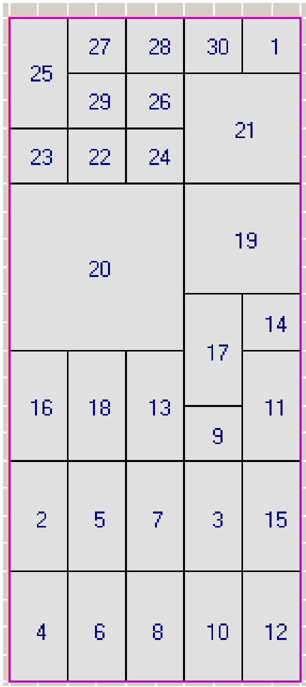


Figure 5.40 Project layout for Period 3

Table 5.15 MHC of project layouts in various periods and total MHC of planning horizon

Periods	1	2	3	Total MHC of the planning horizon
$MHC	120515	20100	201750	523265



$175940

Figure 5.41 Project layout (most robust) and its MHC value

Table 5.16 MHC for using project layout in various periods, total MHC of planning horizon and TPC

Periods	1	2	3	Total MHC of the planning horizon
$MHC	120625	204000	202450	527075
TPC				.722%

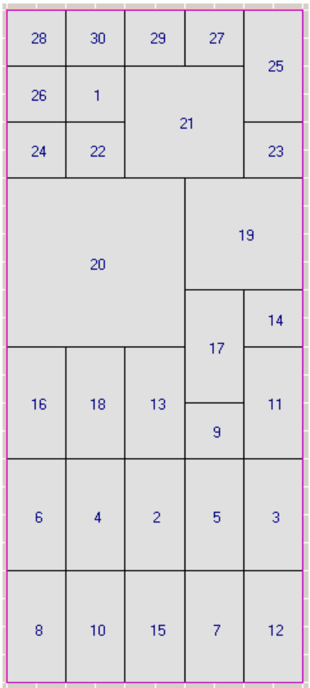


Figure 5.42 Robust layout for Period 1

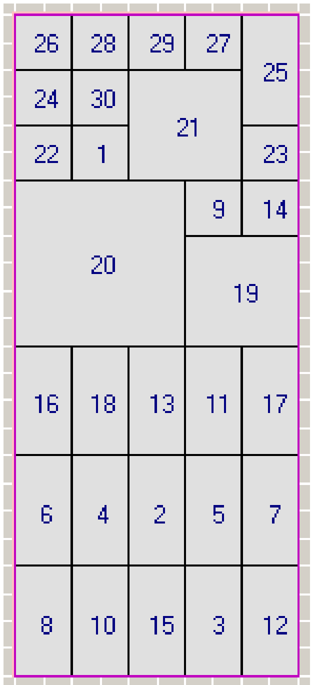


Figure 5.43 Robust layout for Period 2

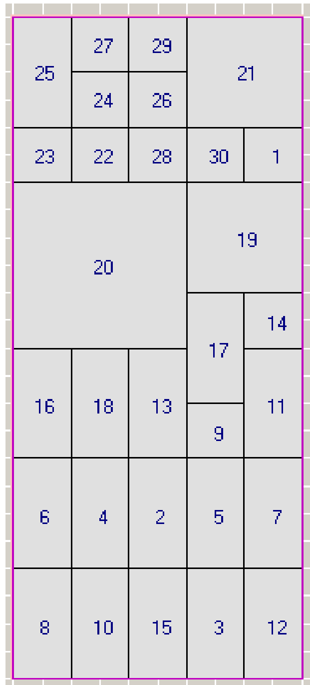
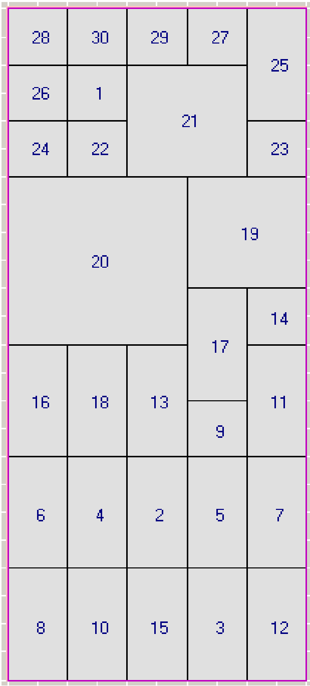


Figure 5.44 Robust layout for Period 3

Table 5.17 MHC of robust layouts in various periods and total MHC of planning horizon

Periods	1	2	3	Total MHC of the planning horizon
$MHC	118250	176450	179600	474300



$158720

Figure 5.45 The most robust layout and its MHC value

Table 5.18 MHC for using the most robust layout in various periods, total MHC of planning horizon and TPC

Periods	1	2	3	Total MHC of the planning horizon
$MHC	118750	178500	181100	478350
TPC				.846%

Once the most robust layouts are identified, the second phase of the proposed methodology is applied by using analytic approaches to evaluate these layouts under different scenarios. The configuration of project and robust layouts for different scenarios are shown in Figures 5.41, 5.45, 5.47, 5.48, 5.50, 5.51, 5.53 and 5.54, respectively. The computation results from using the simulation method for different scenarios are shown in Figures 5.46, 5.49, 5.52 and 5.55. The computation results from using the analytic robust and stable indices and the results of the simulation method are compared and provided in Table 5.19.

5.3.3.1 Scenario 1: Evaluation of project layout against robust layout

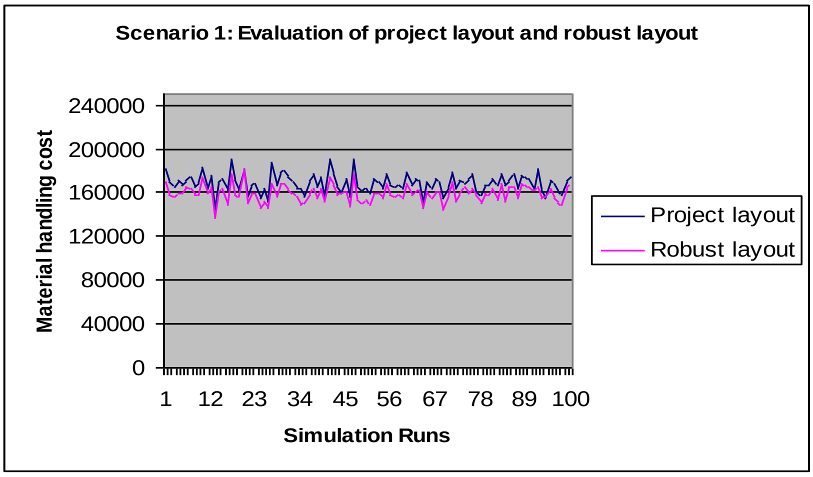


Figure 5.46 Results of the simulation method for scenario 1

Figure 5.46 shows how the robust layout provides high quality solution in terms of a low average total MHC ($159189.8) over time. This solution essentially gives savings of 5.6% when compared with the project layout ($168697.7).

5.3.3.2 Scenario 2: Expansion of departments

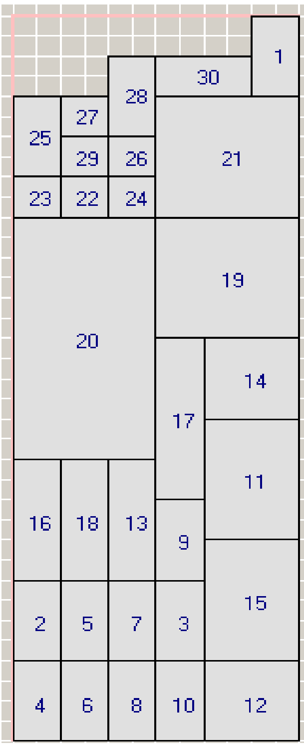


Figure 5.47 Scenario 2 for project layout

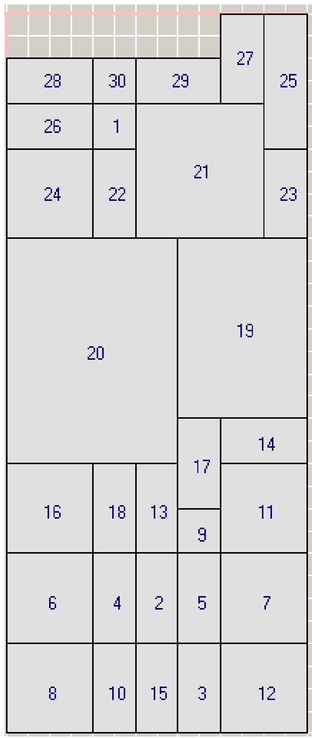


Figure 5.48 Scenario 2 for robust layout

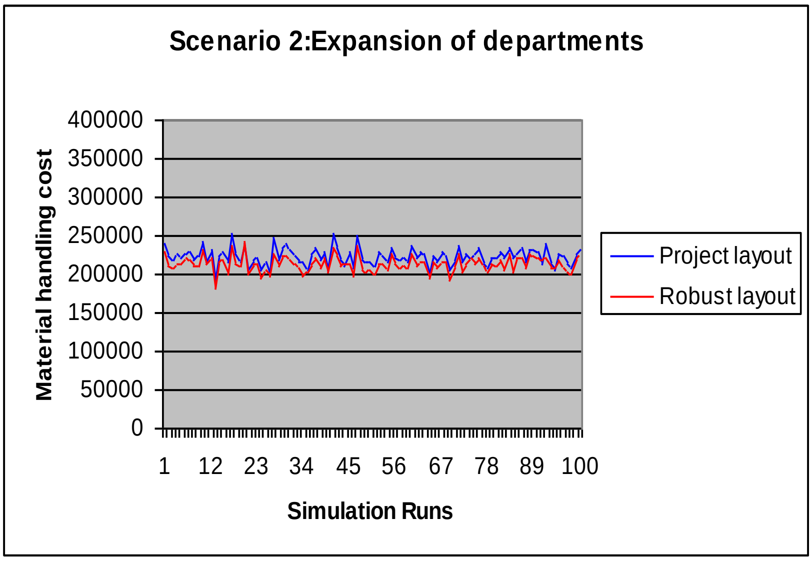


Figure 5.49 Results of the simulation method for scenario 2

Figure 5.49 shows how the robust layout provides high quality solution in terms of a low average total MHC ($213314.3) over time. This solution essentially gives savings of 4.27% when compared with the project layout ($222844.6).

5.3.3.3 Scenario 3: Deletion of department 30

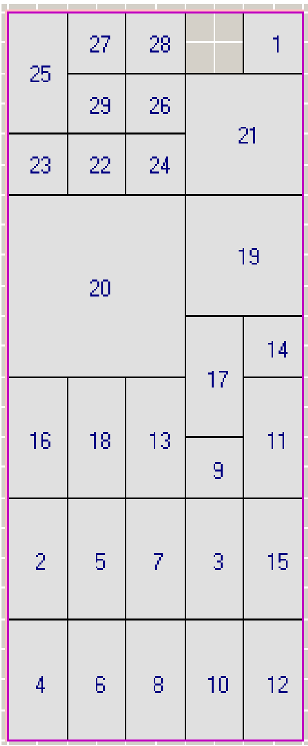


Figure 5.50 Scenario 3 for project layout

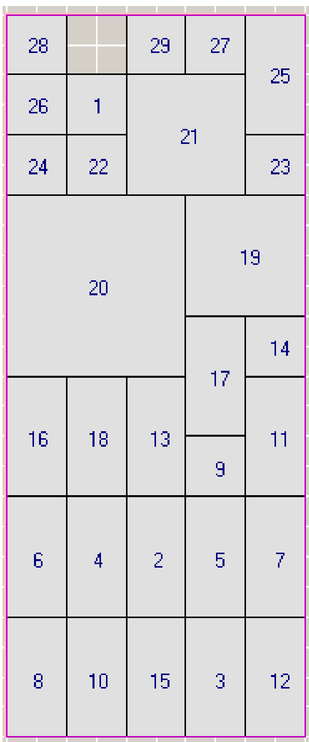


Figure 5.51 Scenario 3 for robust layout

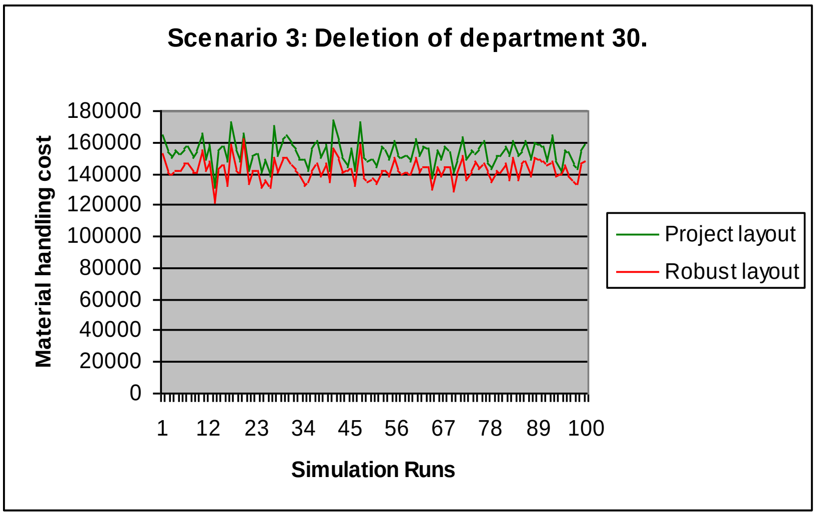


Figure 5.52 Results of the simulation method for scenario 3

Figure 5.52 shows how the robust layout provides high quality solution in terms of a low average total MHC ($142315.7) over time. This solution essentially gives savings of 7.2% when compared with the project layout ($153346.2).

5.3.3.4 Scenario 4: Deletion of departments 29 and 30

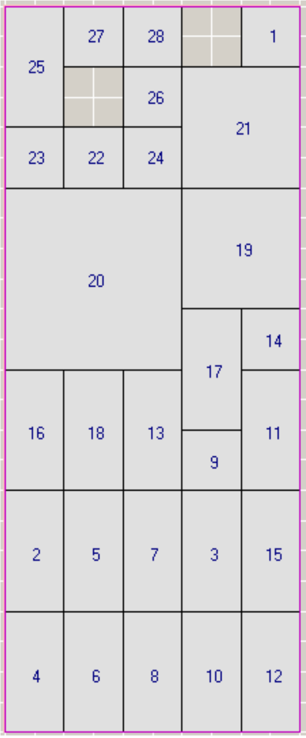


Figure 5.53 Scenario 4 for project layout

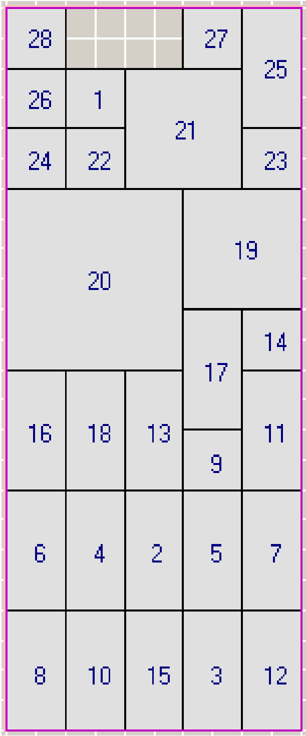


Figure 5.54 Scenario 4 for robust layout

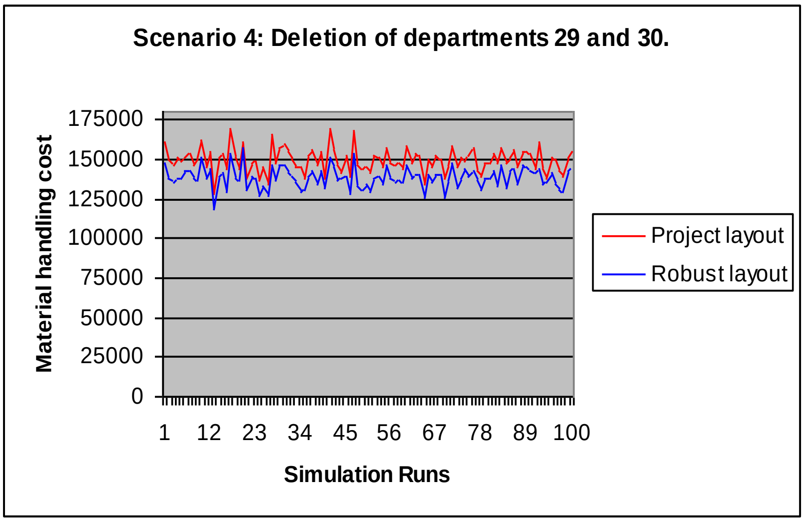


Figure 5.55 Results of the simulation method for scenario 4

Figure 5.55 shows how the robust layout provides high quality solution in terms of a low average total MHC ($138336) over time. This solution essentially gives savings of 7.3% when compared with the project layout ($149297).

Table 5.19 Comparison of results both analytically and via simulation method

Scenarios		Project layout		Robust layout		Analytic results Reduction (-)		Simulation results Reduction (-)	
		$MHC	$SD	$MHC	$SD	Robust Index %	Stable Index %	MHC Index %	SD Index %
1	Project layout against robust layout	175940	7381.2	158720 (168740)*	6758.2	-5.93	-9.21	-5.63	-10.7
2	Expansion of departments	232435	10247.5	212925 (222785)	9126.8	-4.42	-10.93	-4.27	-9.51
3	Deletion of department 30	163460	6466.5	142015 (153375)	5962.5	-7.4	-7.79	-7.19	-12.2
4	Deletion of departments 29 and 30	158660	6385.5	138015 (149375)	5874.5	-7.6	-8.00	-7.34	-12.4

*Number in parenthesis indicates MHC of using project layout in state of robust layout

In the final phase, the analysis of the case study is done with respect to robust and stable indices for layouts based on project demand values and the robust layout. Based on the results (Table 5.19, columns 7 and 8), the project layout did not provide any reduction in terms of MHC or SD as compared with the robust layout. Therefore, the layout based on product demand distribution is selected as the best layout that is robust and stable to changing market demands for the 30-department case study.

5.4 Application of the developed robust and stable indices for solving multi-period stochastic FLP

In this section, a 30-department case study is developed to demonstrate the application of the robust and stable indices for solving multi-period stochastic FLP and evaluating the most robust layout against the most stable layout effectively.

5.4.1 30-department case study (evaluation of robust layout against stable layout)

The constructed case study involves 30 departments of unequal areas and 17 products. The layout is a process layout-type. The material handling cost is fixed at $1/unit distance. The size of the plant is 50m long and 120m wide. The area of the departments and from-to charts can be found in Appendix H. Probability density functions of the product demands follow a normal distribution, are of continuous type and are independent. Distances between departments are rectilinear for the robust, MHC and SD indices and SED for the stable index. The horizon planning is six periods. Product demand distribution and sequence of process are shown in Table 5.20.

Table 5.20 Product demand distribution and process sequence for 30-department case study (Multi period)

Product	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Process
1	(500 1559)	(550 537)	(500 99)	(580 2304)	(1100 7398)	(520 2304)	1-3-4-9-15
2	(500 399)	(250 225)	(450 312)	(450 1224)	(500 399)	(500 1599)	10-12-14-16
3	(300 192)	(250 192)	(250 192)	(250 192)	(400 192)	(400 192)	7-13-15-16
4	(200 108)	(250 108)	(250 108)	(250 108)	(400 108)	(400 108)	7-13-15
5	(500 192)	(500 192)	(2000 10800)	(2000 5292)	(3000 4800)	(2700 4800)	2-5-7
6	(500 108)	(500 108)	(500 300)	(500 432)	(1000 1200)	(1000 1200)	2-5-7-30
7	(1500 5001)	(1000 3600)	(1800 8451)	(1000 3600)	(1300 1800)	(1300 1800)	9-11-13-17-19-21
8	(500 192)	(500 192)	(6000 67500)	(6000 58800)	(500 192)	(500 192)	14-23-25
9	(500 108)	(500 108)	(1000 1875)	(1000 1875)	(500 108)	(500 108)	14-23-25-28
10	(200 75)	(1530 3444)	(1500 16899)	(2000 25599)	(1500 2448)	(2200 14400)	2-13-18
11	(1500 7200)	(1500 4050)	(1500 2499)	(1500 5001)	(1500 6048)	(1500 2448)	3-5-6-13-20
12	(3500 62499)	(1500 4050)	(8400 28800)	(6400 291600)	(2500 11250)	(6100 48051)	25-27-29
13	(2000 10800)	(2000 7500)	(2500 7500)	(3000 10800)	(1500 7500)	(3000 24300)	2-4-6-8-10
14	(1000 1875)	(1000 1200)	(1000 675)	(2000 7500)	(500 1200)	(2600 14700)	2-4-6-10
15	(500 900)	(2000 5001)	(8600 12801)	(1000 6399)	(5000 19998)	(5100 39201)	16-18-20-22
16	(1800 6051)	(2000 9999)	(2000 16899)	(2000 9999)	(3100 44100)	(2250 7812)	24-26-28-30
17	(8000 20001)	(4000 122499)	(2600 20001)	(4750 37812)	(300 399)	(10000 5001)	1-30

In the 30-department case study, the framework discussed in section 5.2 is utilised to evaluate the performance of robust and stable layouts by replacing the data of the PDF matrix with the data of the variance matrix. Stable layouts are defined as those that can effectively handle changes in variability of product demands over various periods of the planning horizon. In order to show how the proposed methodology is efficient in addressing this type of problem, the first phase is utilised to generate the optimal robust layouts based on the expected value matrix for each period of the planning horizon. These robust layouts are shown in Figures 5.56 to 5.61, respectively. The MHC of the robust layouts for each period of the planning horizon is provided in Table 5.21. Once the optimal layouts are determined, the second step is to generate the most robust layout for the sum of the expected value matrices over various periods of the planning horizon and calculate its MHC value. Figure 5.62 shows the most robust layout and its MHC value. Using equation (5.1), the TPC value indicates that the most robust layout falls within 1% of the optimal solution. The MHC for using the most robust layout in various periods, the total MHC of the planning horizon and the TPC are provided in Table 5.22. Similarly, using the variance matrix, the optimal stable layouts are shown in Figures 5.63 to 5.68, respectively. The SD of stable layouts for each period of the planning horizon is given in Table 5.23. The most stable layout and its SD value are shown in Figure 5.69. The TPC value indicates that the most stable layout falls within 4.75% of the optimal solution. The SD for using the most stable layout in various periods, the total SD of the planning horizon and the TPC are provided in Table 5.24.

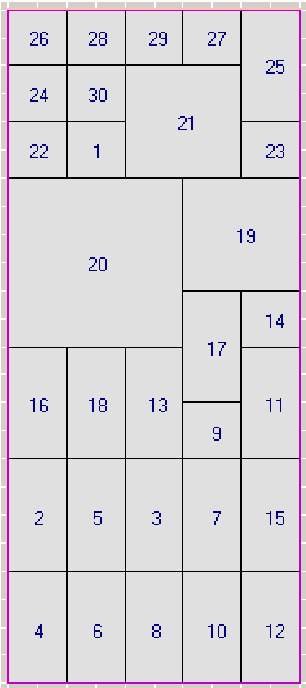


Figure 5.56 Robust layout for Period 1

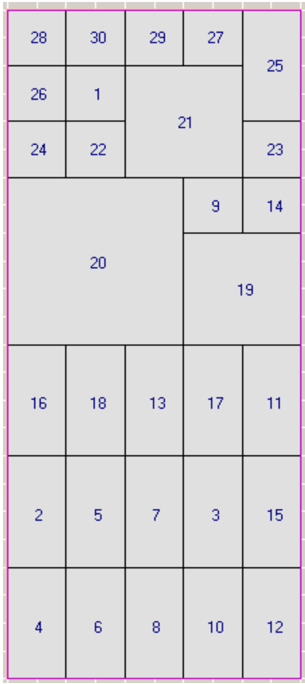


Figure 5.57 Robust layout for Period 2

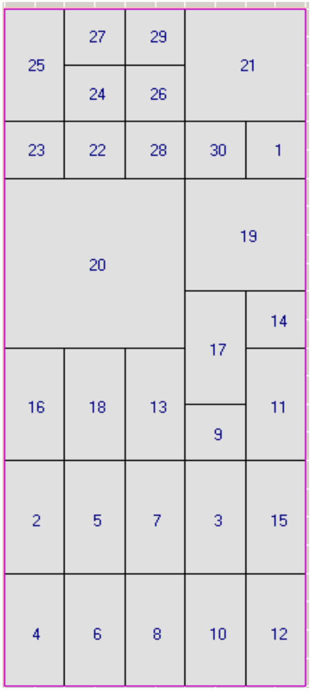


Figure 5.58 Robust layout for Period 3

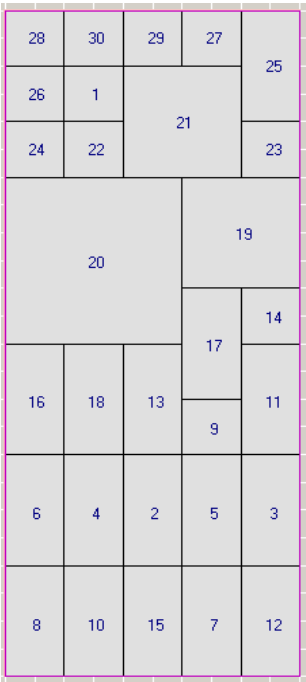


Figure 5.59 Robust layout for Period 4

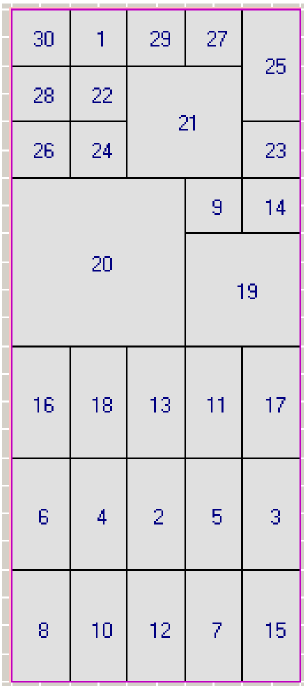


Figure 5.60 Robust layout for Period 5

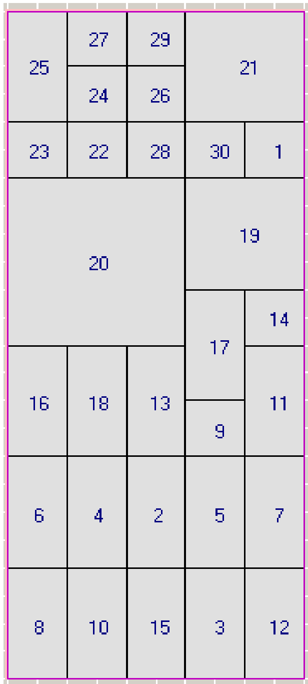
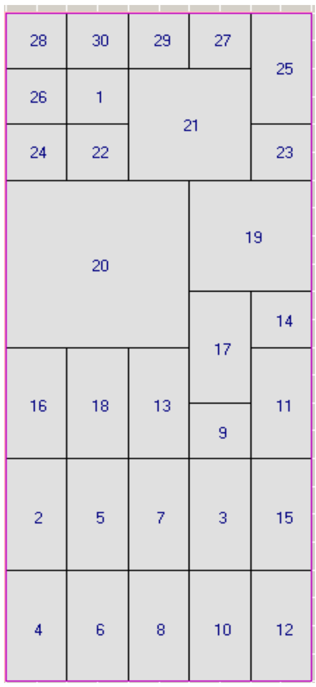


Figure 5.61 Robust layout for Period 6

Table 5.21 MHC of optimal robust layouts in various periods and total MHC of the planning horizon

Periods	1	2	3	4	5	6	Total MHCs
$MHC	1049000	2050500	1565000	1183400	1631400	1808300	9287600



$155970
Figure 5.62 The most robust layout and its MHC value

Table 5.22 MHC for using the most robust layout in various periods, total MHC of the planning horizon and TPC

Periods	1	2	3	4	5	6	Total MHCs
$MHC	1064000	2078500	1572000	1189000	1656800	1821700	9382000
TPC				1.006%			

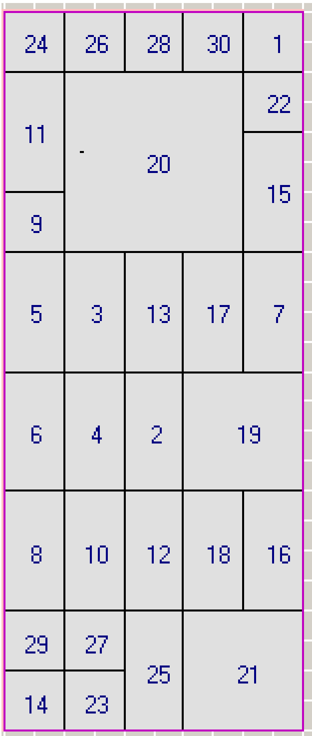


Figure 5.63 Stable layout for Period 1

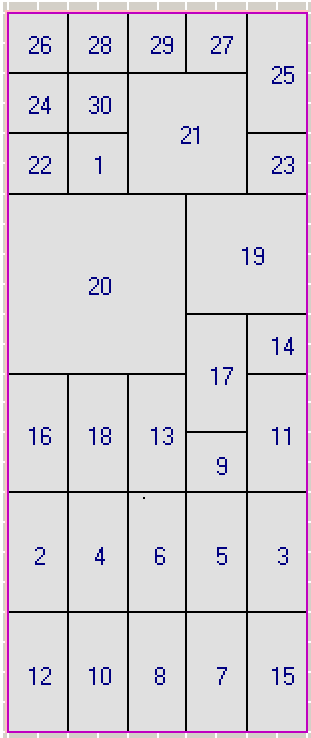


Figure 5.64 Stable layout for Period 2

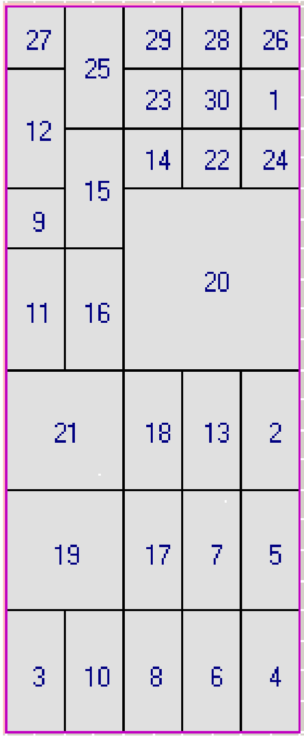


Figure 5.65 Stable layout for Period 3

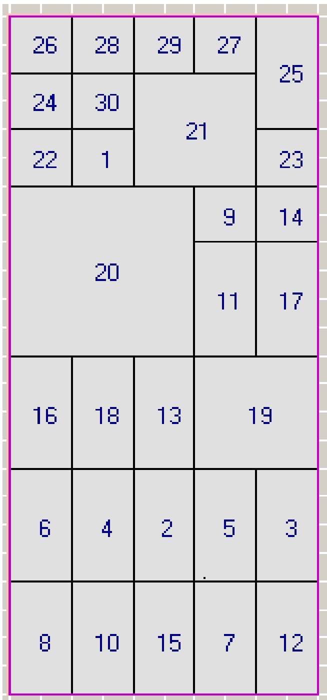


Figure 5.66 Stable layout for Period 4

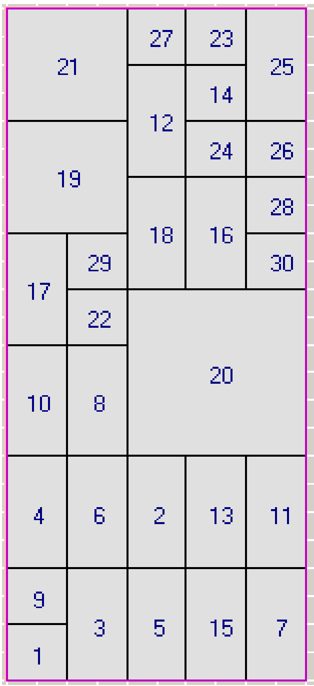


Figure 5.67 Stable layout for Period 5

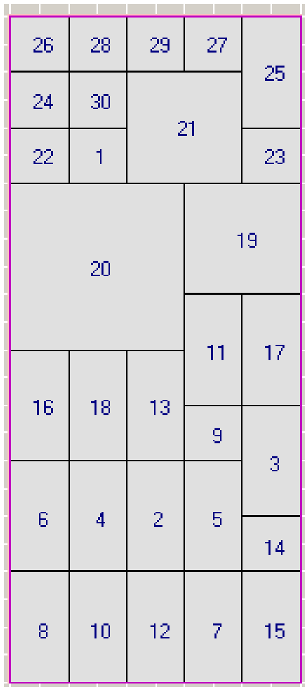
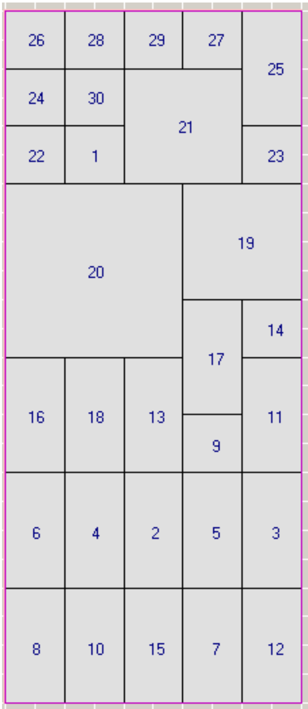


Figure 5.68 Stable layout for Period 6

Table 5.23 SD of optimal stable layouts in various periods, total SD of the planning horizon and TPC

Periods	1	2	3	4	5	6	Total SDs
$SD	8833.91	7218.65	11428.34	14526.38	11252.48	10611.23	26664.33



$6723.2

Figure 5.69 The most stable layout and its SD value

Table 5.24 SD for using the most stable layout in various periods, total SD of the planning horizon and TPC

Periods	1	2	3	4	5	6	Total SDs
$SD	8851.47	7404.12	12480.92	15103.65	12269.80	10779.36	27996.53
TPC	4.75%						

Once the most robust layout and the most stable layout for multiple periods are identified, the analytic approach of the second phase is applied to quantify the impact of uncertainty for all layouts in terms of MHC and SD values. Table 5.25 shows a comparison of MHC and SD values for all layouts in various periods of the planning horizon.

Table 5.25 Comparison of MHC and SD values for all layouts in various periods of the planning horizon

Optimal layouts in various periods	$MHC	$SD
Optimal robust layout in period 1	1586780	6795.04
Optimal robust layout in period 2	1606890	7156.21
Optimal robust layout in period 3	1647190	7616.55
Optimal robust layout in period 4	1573790	6810.00
Optimal robust layout in period 5	1675890	7303.43
Optimal robust layout in period 6	1672290	7589.14
The most robust layout	1559700	6913.90
Optimal stable layout in period 1	1875060	8131.81
Optimal stable layout in period 2	1674780	6906.72
Optimal stable layout in period 3	1839240	8317.07
Optimal stable layout in period 4	1677900	7128.67
Optimal stable layout in period 5	23241400	12937.75
Optimal stable layout in period 6	1744270	8661.27
The most stable layout	1591200	6723.29

In the final phase, based on data provided in Table 5.25, the analysis of the case study is done with respect to MHC and SD values for all layouts. Based on the results (Table 5.25, rows 8 and 15) and the use of equations (4.4) and (4.5), the most robust layout resulted in a reduction of MHC by $31500 (1.7% reduction) and also incurred an additional $190.61 in terms of variability (2.76% increase). Therefore, the most stable layout is selected as the best layout for this case study because the additional increase in MHC is not high enough when compared with reduction in variability.

5.5 Conclusion driven from case studies

Four case studies were developed to demonstrate the proposed methodology to design the most robust layout and ensure its efficiency over time, both analytically and via the simulation method. Through the analysis of case studies, the following results were obtained:

- Using the TPC value alone as criterion to evaluate and select layouts may lead to an inefficient layout. For instance, the TPC value of the most stable layout is higher than the most robust layout in the last case study but the performance of the most stable layout is better than the most robust layout;
- The optimality of project and robust layouts is not changing over time under different scenarios when the same departments are deleted or added and expanded. In addition, increasing the number of departments increases the MHC and SD values whilst reducing the number of departments reduces the MHC and SD values;
- Depending on the type of data, the most robust layout for multi-period stochastic FLP may or may not be optimal in all periods of the planning horizon. For instance, in the 30-department case study, the most robust layout is not optimal in any periods but the performance of this layout is better than any layout;
- Depending on the type of data, the most robust layout performs best in terms of MHC and SD values in three case studies and incurred an additional 2.7% in terms of variability when compared with the stable layout in the last case study. Therefore, the selection in such scenarios depends on the layout designer, the actual area site and the economic level of the manufacturing facility;
- The MHC for using the project layout in state of the robust layout is equivalent to the results of the simulation method to evaluate the project layout and robust layout over time. Therefore, any optimisation approach that has the ability to use one layout in a different state will result in reducing the computation time of the simulation method by factor 1/n where n is the number of simulation periods.

However, the simulation method can provide close results in terms of MHC and SD as compared with analytical results and can overtake the complexity of the analytic indices in the cases where such optimisation approaches are not available, especially for larger-sized problems.

5.6 Conclusion

This chapter presents the framework for the solution of multi-period stochastic FLP using analytic and hybrid approaches. The framework consists of three phases and aims to design, evaluate and select a single robust layout when product demand is subjected to variability. It also aims to evaluate any set of layouts with practical assumptions, such as complex distributions, the addition, deletion and expansion of departments and to deliver solutions that can incorporate uncertainty and variability in product demands under a variety of scenarios. Several case studies are developed to validate and strengthen the proposed framework. A 30-department case study is also developed to demonstrate the application of the proposed framework for solving multi-period stochastic FLP and evaluating the most robust layout against the most stable layout effectively. Through experimentation, the proposed framework has proven to be effective for assessing the impact of uncertainty of product demands to facility layout in terms of expected MHC and SD values. In the next chapter, the application of the developed general framework to address the stochastic FLP with equal area is presented.

CHAPTER 6

APPLICATION OF THE FRAMEWORK FOR STOCHASTIC FLP WITH EQUAL AREA

6.1 INTRODUCTION

In the previous three chapters, the analytic and hybrid approaches for single period and multi-period cases were presented along with several case studies for the validation procedure. In those case studies, unequal departmental areas are assumed to represent practical assumptions. However, in the literature, the FLP is commonly formulated as a QAP. In this chapter, a set of problems, ranging in size from six departments to 30 departments, is used to test the performance of VIPPLANOPT 2006 software to address the QAP. The computation results are compared to 10 other heuristics and indicate that the performance is competitive in generating new optimal, optimal and near-optimal solutions for a set of data taken from the literature. Based on the results, VIPPLANOPT 2006 software is utilised for the first time to address the discrete and the continuous stochastic FLP with equal area simultaneously. The following sections present the evaluation of VIPPLANOPT to address the QAP and the application of the proposed framework to address this type of hard optimisation problem as well.

6.2 Evaluation of VIPPLANOPT 2006 software for solving FLP with equal area departments

As mentioned earlier, VIPPLANOPT 2006 software was originally developed for solving unequal area FLP in an open field. In this section, the software is used to solve the QAP that has shown to be NP-hard and it provides high quality solutions. The comparison to some publications and the computational results are given in the following sections respectively.

6.2.1 Comparison to some publications

The set of problems, offered by Nugent et al. (1968), ranging in size from six departments to 30 departments, is used to evaluate the performance of VIPPLANOPT. This set has been used by different researchers for comparing different solution techniques (Rosenblatt and Golany, 1992; Hu and Wang, 2005). The first five problems are taken from Rosenblatt and Krupp (1992), the second two problems are taken from Golany and Rosenblatt (1989) and the last four problems are taken from the QAP Library (www.seas.upenn.edu/qaplib).

1- For Rosenblatt and Kropp's (1992) problem, VIPPLANOPT generates the same optimal (1,3,5,6,4,2) layout with a total MHC of 12822. This is given in Figure 6.1.

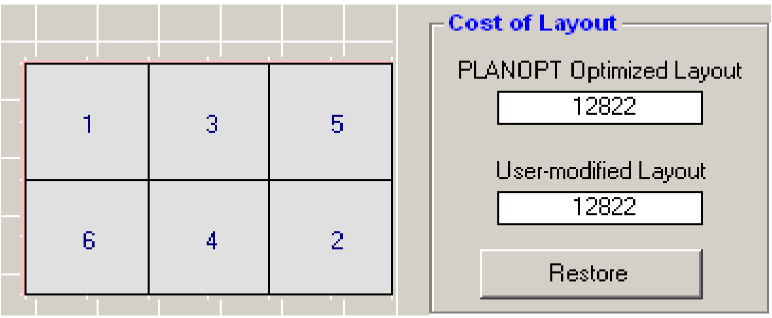


Figure 6.1 Optimal layout for Rosenblatt's problem (1992)

2- For Rosenblatt and Kropp's (1992) problem, VIPPLANOPT generates the same optimal (1, 4, 2, 5, 3, 6) layout with a total MHC of 14853. This is given in Figure 6.2.

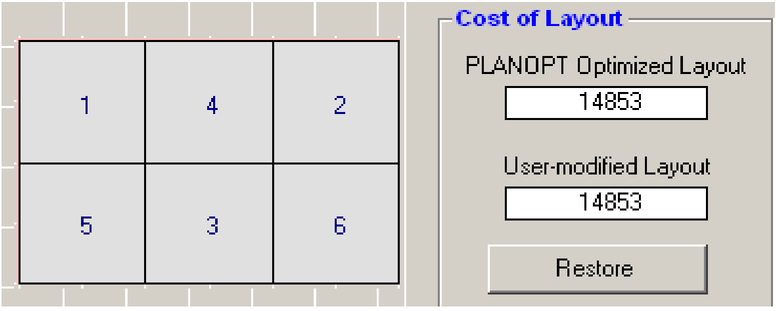


Figure 6.2 Optimal layout for Rosenblatt's problem (1992)

3- For Rosenblatt and Kropp's (1992) problem, VIPPLANOPT generates the same optimal (1, 5, 3, 2, 4, 6) layout with a total MHC of 13172. This is given in Figure 6.3.

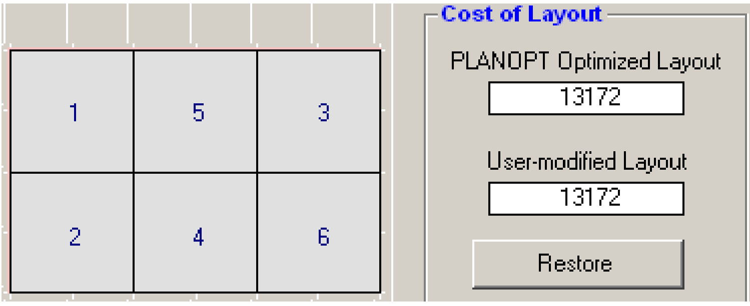


Figure 6.3 Optimal layout for Rosenblatt's problem (1992)

4- For Rosenblatt and Kropp's (1992) problem, VIPPLANOPT generates the same optimal (1, 6, 4, 2, 5, 3) layout with a total MHC of 13032. This is given in Figure 6.4.

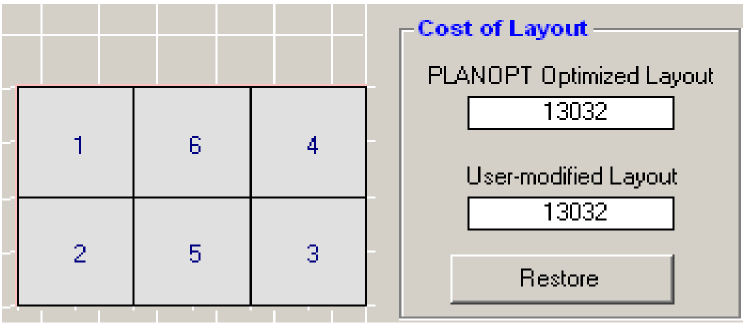


Figure 6.4 Optimal layout for Rosenblatt's problem (1992)

5- For Rosenblatt and Kropp's (1992) problem, VIPPLANOPT generates the same optimal (3, 2, 6, 4, 1, 5) layout with a total MHC of 12819. This is given in Figure 6.5.

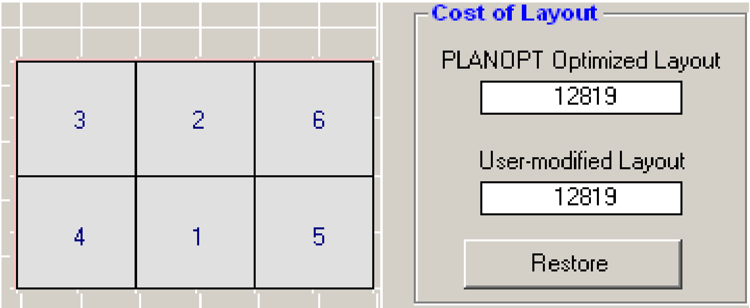


Figure 6.5 Optimal layout for Rosenblatt's problem (1992)

6- For Nugent et al.'s (1968) problem—six departments—VIPPLANOPT generates the same optimal (1, 2, 3, 4, 5, 6) layout with total MHC of 43. This is given in Figure 6.6.

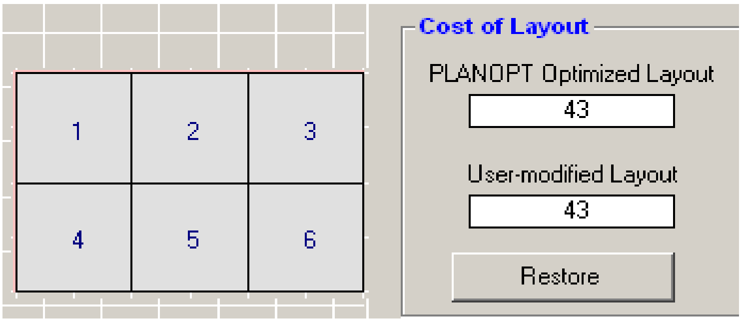


Figure 6.6 Optimal layout for Nugent et al.'s problem (1968)

7- For Nugent et al.'s (1968) problem—8 departments—VIPPLANOPT generates the same optimal (3, 8, 7, 6, 2, 1, 4, 5) layout with a total MHC of 107. This is given in Figure 6.7.

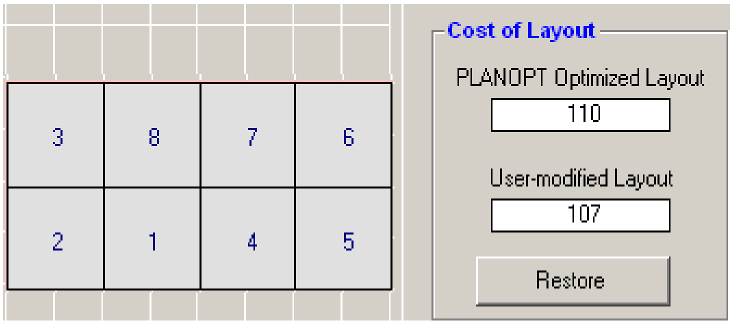


Figure 6.7 Optimal layout for Nugent et al.'s problem (1968)

8- For Nugent et al.'s (1968) problem—12 departments—VIPPLANOPT generates the same optimal (12, 7, 9, 3, 4, 8, 11, 1, 5, 6, 10, 2) layout with a total MHC of 289. This is given in Figure 6.8. In addition, for Hiller's problem—12 departments—VIPPLANOPT also generates a new layout for this problem with a total MHC of 297. This is given in Figure 6.9.

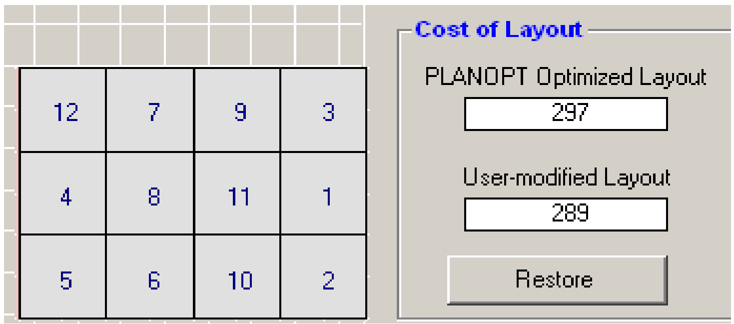


Figure 6.8 Optimal layout for Nugent et al.'s problem (1968)

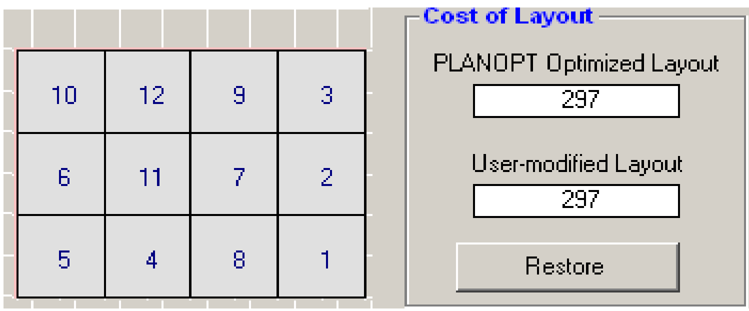


Figure 6.9 A new optimal layout for Hiller's problem (1963)

9- For Nugent et al.'s (1968) problem—15 departments—VIPPLANOPT generates the same optimal (1, 2, 13, 8, 9, 4, 3, 14, 7, 11, 10,15,6, 5, 12) layout with a total MHC of 575. This is given in Figure 6.10.

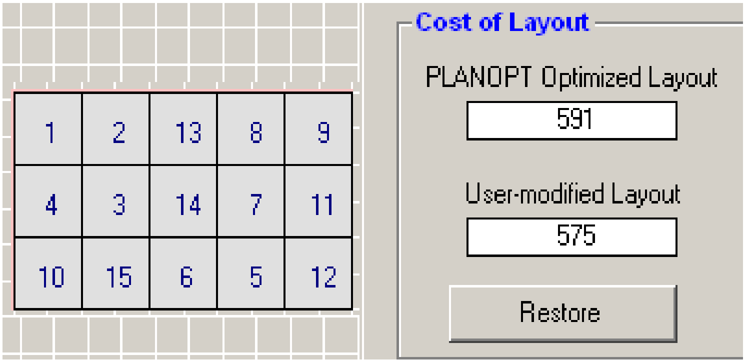


Figure 6.10 Optimal layout for Nugent et al.'s problem (1968)

10- For Nugent et al.'s (1968) problem—20 departments—VIPPLANOPT generates the same optimal (6, 1, 7, 5, 17, 13, 8, 20, 15, 19, 16, 11, 12, 2, 4, 9, 3, 10, 14, 18) layout with a total MHC of 1285. This is given in Figure 6.11.

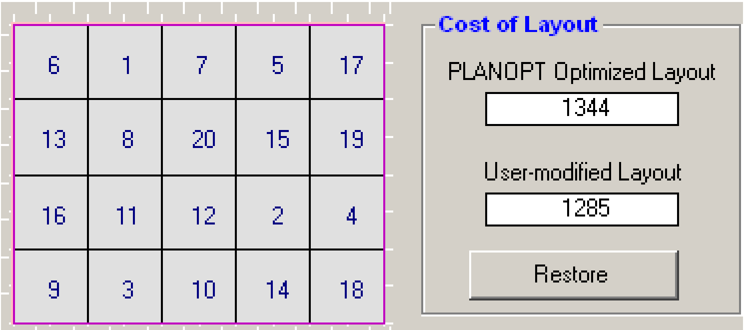


Figure 6.11 Optimal layout for Nugent et al.'s problem (1968)

11- For Nugent et al.'s (1968) problem—30 departments—VIPPLANOPT generates the same optimal layout with a total MHC of 3062. This is given in Figure 6.12.

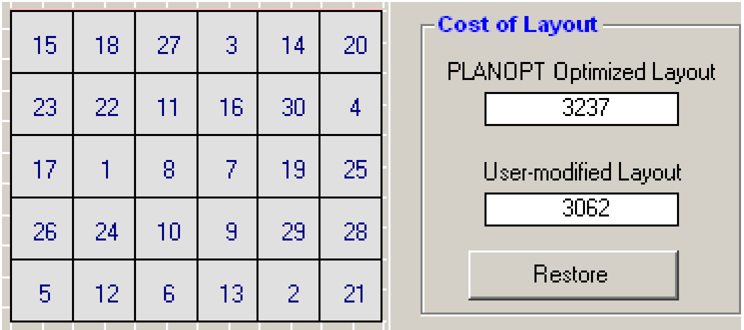


Figure 6.12 Optimal layout for Nugent et al.'s problem (1968)

6.2.2 Computational results

The set of problems offered by Nugent et al. (1968) became an acceptable benchmark and it is widely used by researchers for evaluating different solution techniques. This set is selected to evaluate the performance of VIPPLANOPT. The results of various heuristics are taken from Rosenblatt and Golany (1992) and Hu and Wang (2004). The computation results of the VIPPLANOPT 2006 software are compared to 10 other heuristics and are illustrated in Table 6.1. In order to provide further statistical insight into comparison data, the average deviation (from best known results) of each heuristic over test problems is computed and compared and also provided in Table 6.1.

Table 6.1 The testing results for VIPPLANOPT and existing heuristics

n	H63	H63-66	CRAFT	Biased sampling	FLAC	DISCON	FATE	TAA	GESA	GA	VIPPLANOPT-2006	Mean	Best Known
6	44.2	44.2	44.2	43.6	43	47.5	50.6	43	43	43	43	43	43
8	114	110.2	113.4	107	107	118.8	126.7	116	107	107.8	107-110	108.5	107
12	317	310.2	296.2	293	289	322.2	326.2	314	289.36	290.6	289-297	293	289
15	633	600.2	606	580.2	585	630.8	660.8	596	575.18	576.4	575-591	583	575
20	1400	1345	1339	1313	1303	1416	1436.3	1414	1287.4	1290.5	1285-1339	1314.5	1285
30	3267	3206.8	3189.6	3189.6	3079	3436	3390.6	3326	3079.3	3075.1	3062-3237	3149.5	3062
AV	962.7	936.1	931.4	921.1	901	995.3	998.5	968.3	896.8	897.2		915.2	893.5
D* %	7.7	4.7	4.2	3.0	.84	11.4	11.7	8.3	.37	.42		2.4	0

Based on the comparison data provided in Table 6.1, the performance of VIPPLANOPT 2006 software outperforms seven of 10 heuristics for solving equal area FLP. However, the computation time requirement for solving these problems is not provided by authors in this comparison but VIPPLANOPT 2006 software generates the solution for each problem in a reasonable amount of time. Through observation, VIPPLANOPT is competitive and capable of providing good results for the QAP.

6.3 Performance analysis

In order to illustrate that the VIPPLANOPT 2006 software is effective in solving discrete as well as continuous stochastic FLP with equal area, the following case study is taken from Rosenblatt and Kropp (1992) for discrete stochastic FLP.

6.3.1 Stochastic single period FLP with equal area

In the literature, the stochastic FLP is modelled by using a discrete set of product demand scenarios with known probability of occurrence. In order to show how the proposed approach is effective in solving this type of problem, the QAP formulation of Rosenblatt and Kropp's (1992) approach is given below and used to solve the same published case study. In addition, the QAP formulation of continuous stochastic FLP can be found in Bragilia et al. (2003).

$$\text{Min } Z(S) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{m=1}^{n} A^{s}{}_{ijkm} \times X^{s}{}_{ij} \times X^{s}{}_{km} \qquad (6.1)$$

Subject to

$$\sum_{i=1}^{n} X^{s}{}_{ij} = 1 \qquad j = 1,\ldots\ldots,n$$

$$\sum_{j=1}^{n} X^{s}{}_{ij} = 1 \qquad\qquad i = 1,\ldots\ldots, n$$

$$X^{s}{}_{ij} = 0 \text{ or } 1, \qquad\qquad i = 1,\ldots.. n, \; j = 1,\ldots\ldots n$$

Where

$$X^{s}{}_{ij} = \begin{cases} 1 & \text{if facility i is assigned to site j for scenario s} \\ 0 & \text{otherwise} \end{cases}$$

$$A^{s}{}_{ijkm} = \begin{cases} \mathrm{f}^{\,s}{}_{ik}\, \mathrm{d}_{jm} & \text{if } \mathrm{i} \neq \mathrm{k} \text{ or } \mathrm{j} \neq \mathrm{m} \\ \mathrm{c}_{ij} & \text{if } \mathrm{i} = \mathrm{k} \text{ and } \mathrm{j} = \mathrm{m} \end{cases}$$

c_{ij} is fixed location cost associated with assigning facility i to location j.

d_{jm} is the distance between site j and site m (proportional to travel cost between sites),

d_{jj} =0.

$f^{s}{}_{jk}$ is the flow of materials between facilities i and k for scenario s.

s is the number of scenarios (states), s =1,2,……s.

n is the number of departments.

The objective function of stochastic FLP is to minimise the expected MHC and can be expressed as follows:

$$\text{Min } \overline{Z} = \sum_{s=1}^{s} P_s Z(s)$$

Where

$$\sum_{s=1}^{s} P_s = 1 \text{ And } P_s > 0 \quad \text{and} \quad \overline{F} = \sum_{s=1}^{s} P_s \; F_s \qquad (6.2)$$

6.3.2 Stochastic case study from Rosenblatt and Kropp (1992)

The following case study is adapted from Rosenblatt and Kropp (1992) to illustrate how VIPPLANOPT can generate the same results as Rosenblatt and Kropp obtained. Consider six departments with five from-to charts (contained in Appendix I) representing five demand states. The probability of occurrence of each from-to chart is 0.3, 0.1, .05, .015 and 0.4, respectively. Input data and optimal solutions for this example are provided in Appendix I. Given this data, using equations (6.1) and (6.2), Tables 6.2 and 6.3 summarise the results. The idea of Rosenblatt's approach is to derive the layout for state $\overline{F}$ by using equation (6.2) and compute the weighted average flow matrix. Once the weighted average flow matrix is obtained, the second step is to find its best layout and apply this layout for the various demand states to obtain various layout costs. The final step is to use the TFP criterion that is developed by Shore and Tompkins (1980) to evaluate the layouts and compare the results with the optimal layout of the weighted average flow matrix.

Table 6.2 MHC for using layout designed for state i in state j (Rosenblatt and Kropp, 1992)

Layout designed for state	MHC for using layout designed for state i in state j					Expected cost
	1	2	3	4	5	
1:(1,3,5,6,4,2)	12822	15328	15612	16490	16358	15177
2:(1,4,2,5,3,6)	12964	14853	14962	16165	15193	14625
3:(1,5,3,2,4,6)	13962	16978	13172	14849	15455	14954
4:(1,6,4,2,5,3)	15548	18520	15370	13032	15866	15586
5:(3,2,6,4,1,5)	15305	17718	16748	15920	12819	14716
$\overline{F}$:(2,1,5,4,3,6)	13694	16269	17046	15711	14072	14573

Table 6.3 Total expected penalties for the various layouts (Rosenblatt and Kropp, 1992)

Layout designed for state	State which occurs					Total Facility Penalty(TFP)
	1	2	3	4	5	
1:(1,3,5,6,4,2)	0	475	2440	3458	3539	2104
2:(1,4,2,5,3,6)	142	0	1790	3133	2374	1552
3:(1,5,3,2,4,6)	1140	2125	0	1817	2636	1881
4:(1,6,4,2,5,3)	2726	3668	2198	0	3074	2513
5:(3,2,6,4,1,5)	2483	2865	3576	2888	0	1643
$\overline{F}$:(2,1,5,4,3,6)	872	1416	3874	2679	1253	1500

Based on the results of Table 6.3 (column 7), using the TFP criterion, the layout designed for state two is selected as the most robust layout with a total TFP of 1552. However, this layout incurred an additional 3.5% increase when compared with the most robust layout based on $\overline{F}$ state. Therefore, the layout based on $\overline{F}$ values is selected as the most robust layout for this problem.

Through observation, the design of a robust layout for discrete stochastic FLP requires a large number of calculations and the problem is solved 30 times in order to select the most robust layout. However, computation time increases as the number of departments and number of layouts increase. In order to reduce the computation time and obtain the same results, an alternative method is developed using the proposed three steps:

- Derive the layout for state $\overline{F}$ by using equation (6.2) to design the most robust layout;
- Calculate the MHC of using the optimal layouts designed for states one, two, three, four and five in state $\overline{F}$;
- Evaluate the MHCs of all layouts in state $\overline{F}$ and select the most robust in terms of minimum MHC.

To illustrate the application of an alternative method, VIPPLANOPT is utilised once again to solve the same problem and the results are given in Figures 6.13 to 6.18.

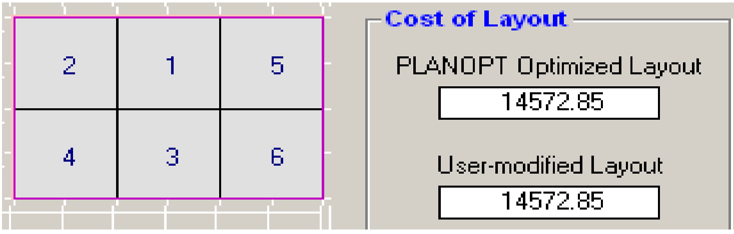


Figure 6.13 MHC for optimal layout for $\overline{F}$

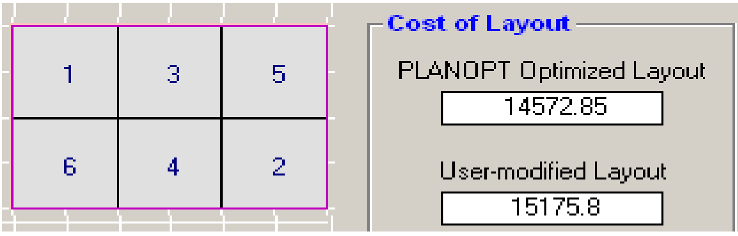


Figure 6.14 MHC for using layout designed for state 1 in state $\overline{F}$

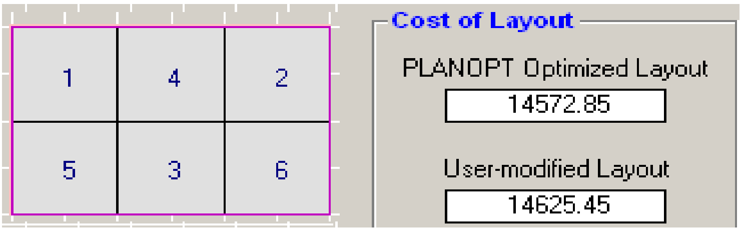


Figure 6.15 MHC for using layout designed for state 2 in state $\overline{F}$

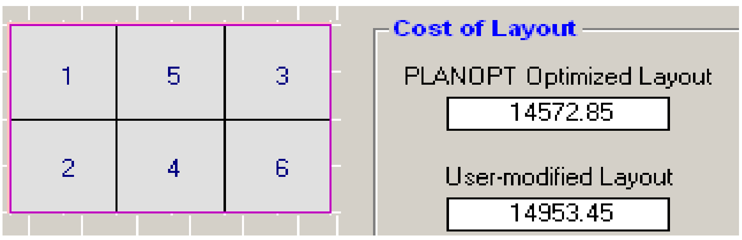


Figure 6.16 MHC for using layout designed for state 3 in state $\overline{F}$

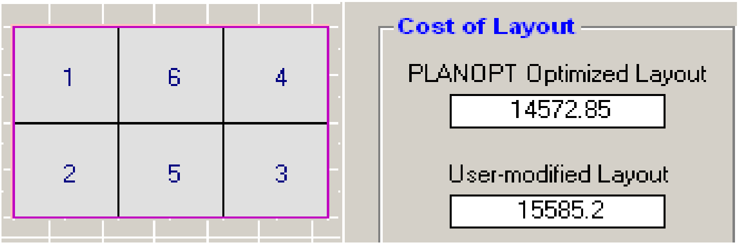


Figure 6.17 MHC for using layout designed for state 4 in state $\overline{F}$

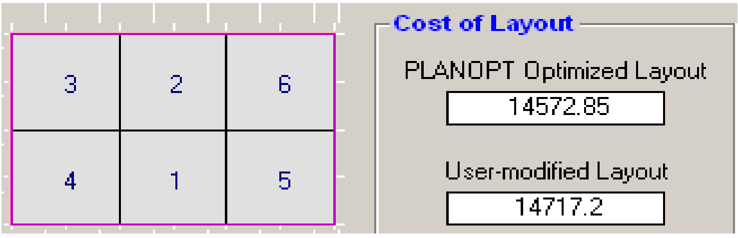


Figure 6.18 MHC for using layout designed for state 5 in state $\overline{F}$

From the results of the previous figures, it is clear that the same results are obtained by solving the problem only six times instead of 30 times. Therefore, a high reduction in computation time of 80% is obtained. Based on the previous results, it is possible to formulate a robust index that reduces the computation time for discrete stochastic FLP and validates the development of robust and stable indices for continuous stochastic FLP as well.

Robust index for discrete stochastic FLP =

$$= \frac{MHC \;\; of \;\; using \;\; Layout_n \;\; in \;\; state \;\; \overline{F} - MHC \;\; of \;\; using \;\; optimal \;\; \overline{F}}{MHC \;\; of \;\; using \;\; Layout_n \;\; in \;\; state \;\; \overline{F}} \times 100$$

$$\text{Robust Index} = \frac{\left(\sum_{i=1}^{N}\sum_{j=i+1}^{N} f_{ij} d_{ij}\right)_n - Optimal \left(\sum_{i=1}^{N}\sum_{j=i+1}^{N} \overline{F} d_{ij}\right)}{\left(\sum_{i=1}^{N}\sum_{j=i+1}^{N} f_{ij} d_{ij}\right)_n} \times 100 \qquad (6.3)$$

Where

$$\overline{F} \quad \sum_{s=1}^{s} P_s \; F_s$$

f_{ij} is the total flow between department i and department j.

d_{ij} is the distance between department i and department j in the layout configuration to be evaluated.

$\left(\sum_{i=1}^{N} \sum_{j=i+1}^{N} f_{ij} d_{ij} \right)_n$ is the number of layouts to be compared.

The proposed robust index aims to evaluate the robustness of facility layout designs and compute the percentage of decrease or increase in terms of MHC with or without respect to the most robust layout. To illustrate how to evaluate the performance of layout two with the most robust layout, the results from Figures 6.17 and 6.18 are used as follows:

$$\text{MHC index} = \frac{14625.45 - 14572.85}{14625.45} \times 100 = 3.5\%$$

The most robust layout resulted in a reduction of 3.5% when compared with layout two, which is the same value as Rosenblatt and Kropp (1992) obtained and published.

6.4 The application of the framework to address the FLP with equal area

To further generalise and enhance the range of applications of the proposed framework, this section presents the development of two case studies (30 departments) to gauge the effectiveness of the proposed framework for solving the single period stochastic FLP and multi-period stochastic FLP with equal area.

6.4.1 30-department case study (Single period)

For the 30-department single period case study, the same assumptions used in the thirty department single period case study (Chapter Four) were applied. However, all departments are assumed to have equal areas (40m × 40m).

Using the information presented in Table 4.9, the first phase of the framework that is presented in Figure 5.1 is utilised by eliminating time periods to generate the optimal layouts for PDF and expected value matrices. These layouts are shown in Figures 6.19 and 6.20, respectively. Once the optimal layouts are determined, the analytic and hybrid approaches are utilised to evaluate the robustness and stability of these layouts under different scenarios. Four scenarios are considered for uncertainty analysis. The first scenario includes evaluation of optimal layouts. The second scenario includes deletion of departments. The third scenario includes doubling the area of the project layout and tripling the area of the robust layout. The final scenario includes moving the first column 40 square units up and moving the last column 40 square units down. The configuration of project and robust layouts for different scenarios are shown in Figures 6.19, 6.20, 6.22, 6.23, 6.25, 6.26, 6.28 and 6.29, respectively. The computation results from using the simulation method for different scenarios are shown in Figures 6.21, 6.24, 6.27 and 6.30. The computation results from using robust and stable indices and the results of the simulation method are compared and provided in Table 6.4.

6.4.1.1 Scenario 1: Evaluation of project layout against robust layout

10	8	20	22	14	23
12	6	18	16	21	25
7	4	13	17	19	27
5	2	11	9	15	29
3	1	30	28	26	24

Figure 6.19 Scenario 1 for project layout

10	21	19	23	25	27
8	3	17	22	1	29
6	5	7	20	30	28
4	2	13	18	16	26
12	9	11	15	14	24

Figure 6.20 Scenario 1 for robust layout

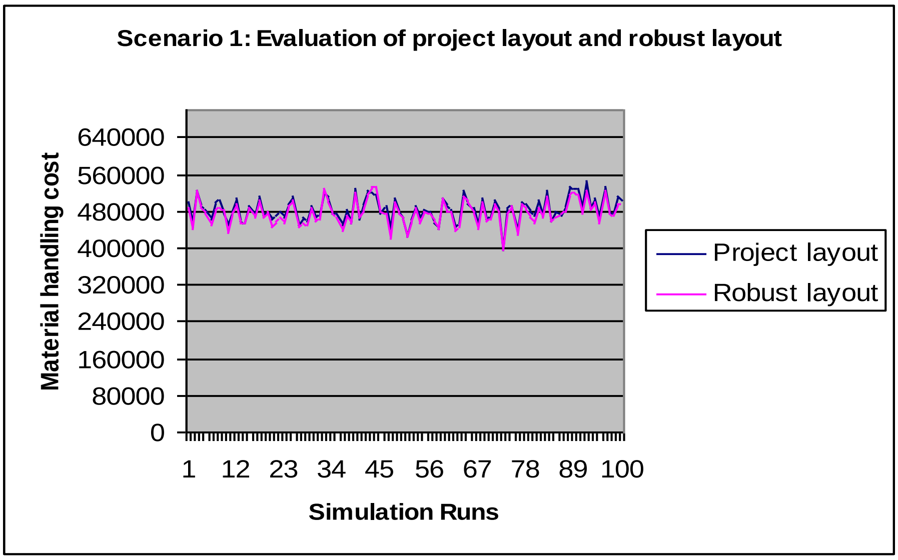


Figure 6.21 Results of the simulation method for scenario 1

Figure 6.21 shows how the robust layout provides high quality solution in terms of a low average total MHC ($476434) over time. This solution essentially gives savings of 1.47% when compared with the project layout ($483544).

6.4.1.2 Scenario 2: Deletion of departments

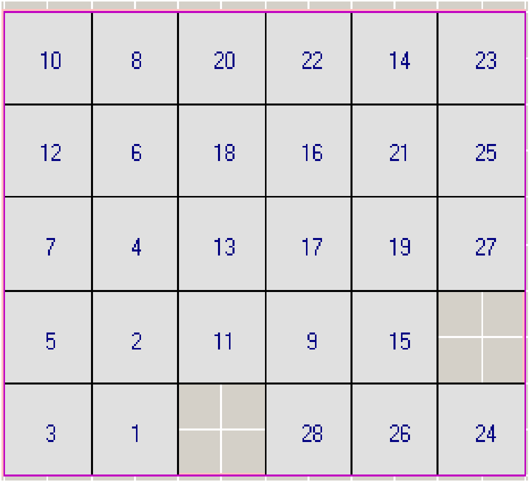


Figure 6.22 Scenario 2 for project layout

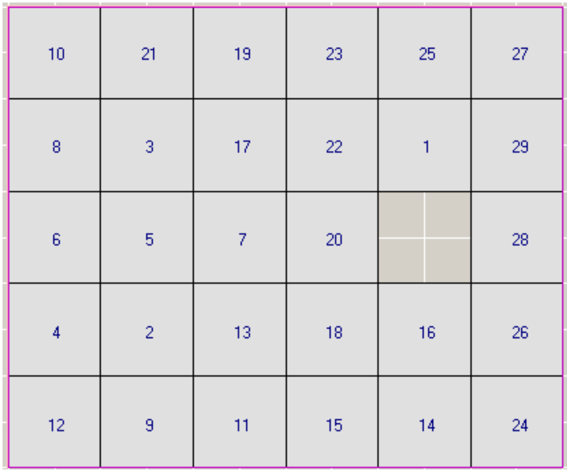


Figure 6.23 Scenario 2 for robust layout

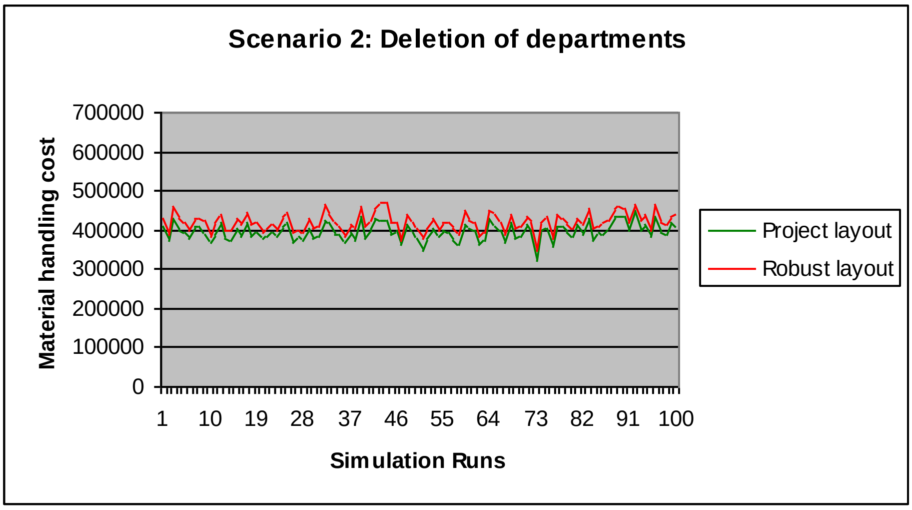


Figure 6.24 Results of the simulation method for scenario 2

Figure 6.24 shows how the project layout provides high quality solution in terms of a low average total MHC ($395207) over time. This solution essentially gives savings of 5.83% when compared with the robust layout ($419487).

6.4.1.3 Scenario 3: Doubling area for project layout and tripling area for robust layout

10	8	20	22	14	23
12	6	18	16	21	25
7	4	13	17	19	27
5	2	11	9	15	29
3	1	30	28	26	24

Figure 6.25 Scenario 3 for project layout

10	21	19	23	25	27
8	3	17	22	1	29
6	5	7	20	30	28
4	2	13	18	16	26
12	9	11	15	14	24

Figure 6.26 Scenario 3 for robust layout

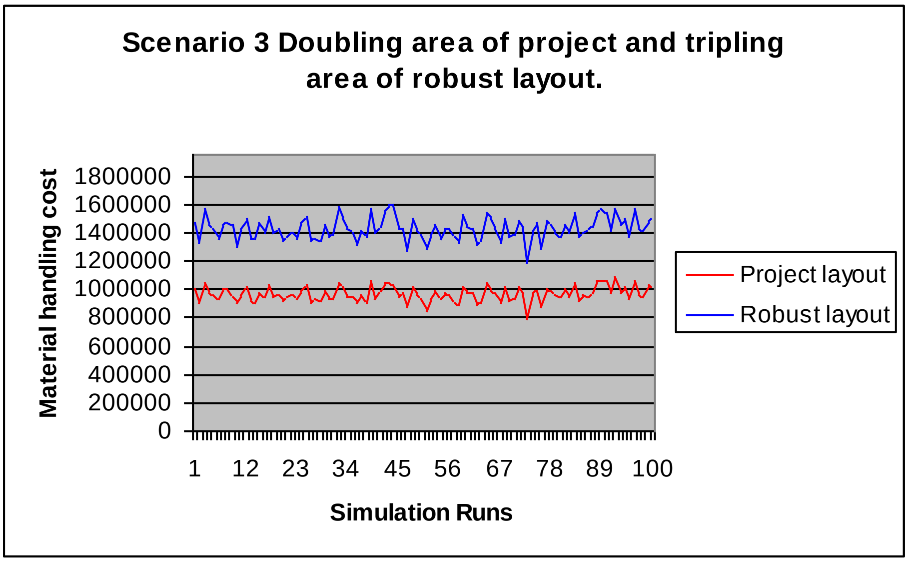


Figure 6.27 Results of the simulation method for scenario 3

Figure 6.27 shows how the project layout provides high quality solution in terms of a low average total MHC ($967088) over time. This solution essentially gives savings of 32.3% when compared with the robust layout ($1429301).

6.4.1.4 Scenario 4: Moving the first column 40 square units up and moving the last column 40 square units down for project and robust layouts

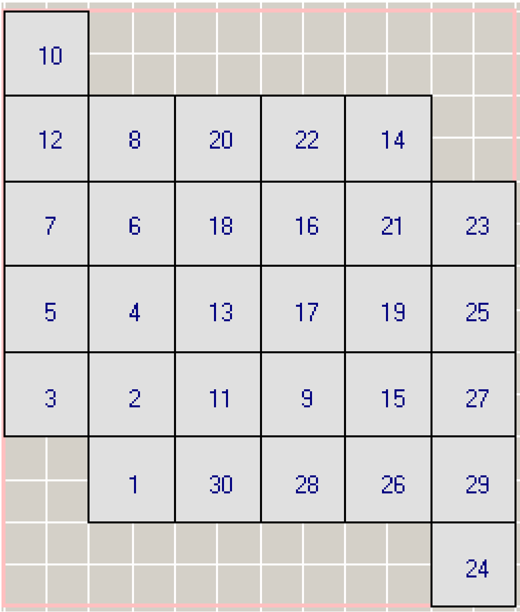


Figure 6.28 Scenario 4 for project layout

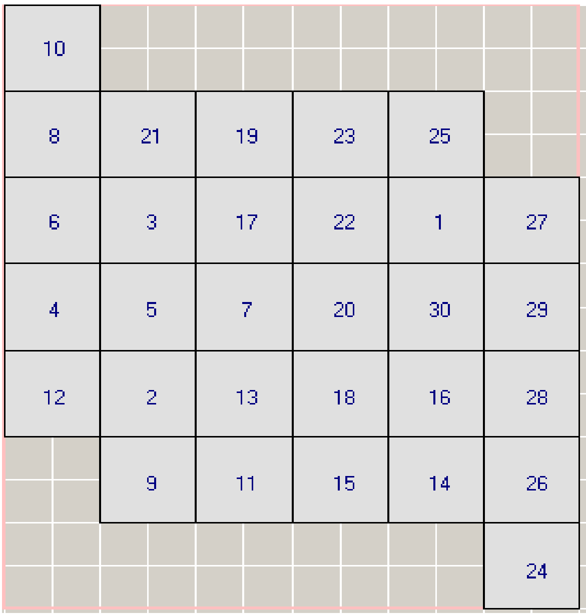


Figure 6.29 Scenario 4 for robust layout

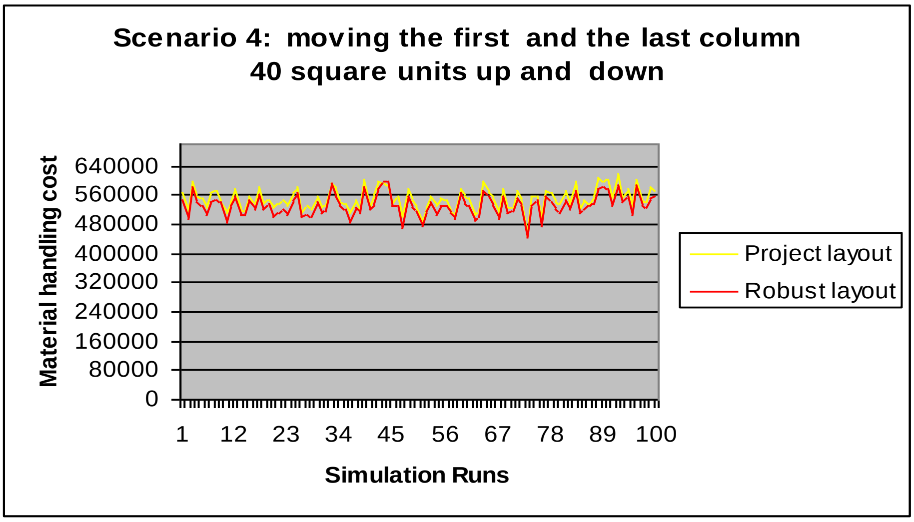


Figure 6.30 Results of the simulation method for scenario 4

Figure 6.30 shows how the robust layout provides high quality solution in terms of a low average total MHC ($532467) over time. This solution essentially gives savings of 3.1% when compared with the project layout ($549589).

Table 6.4 Comparison of results both analytically and via simulation method (single period)

Scenarios		Project layout		Robust layout		Analytic results Reduction (-)		Simulation results Reduction (-)	
		$MHC	$SD	$MHC	$SD	Robust Index %	Stable Index %	MHC Index %	SD Index %
1	Project layout against robust layout	429200	25902.3	477440 (485000)*	26536.8	-1.558	2.391	-1.47	+0.16
2	Deletion of departments	371600	16810.1	419800 (395840)	18657.4	+5.7	+9.9	+5.8	+7.2
3	Doubling area for project and tripling area for robust	858400	51804.6	1432320 (970000)	79610.4	+33.3	+34.9	+32.3	+33.4
4	Moving first column 40 square units up and last column down.	463600	26970.8	532600 (549440)	27700.8	-3.06	+2.6	-3.1	+1.45

*Number in parenthesis indicates MHC of using project layout in state of robust layout

In the final phase of the proposed framework, the analysis of the case study is performed with respect to robust and stable indices for layouts based on project demand values and the robust layout. Based on the results (Table 6.4, columns 7 and 8), for scenarios one and four, the robust layout performs best and resulted in a reduction of MHC by -1.5%, and -3.07%, respectively, and performs worst in terms of variability when compared with the project layout. On the other hand, the project layout performs best in scenarios two and three and resulted in a reduction of MHC by 5.7%, 33.3% and variability by 9.9% and 35% when compared with the robust layout. Under such situations, using the first scenario as a criterion, the project layout is selected as the best layout for this case study because the increase in MHC is not high enough when compared with the reduction in variability.

6.4.2 30-department case study (Multi period)

For the 30-department multi-period case study, the same assumptions used in the thirty - department multi period case study (Chapter Five) were applied. However, all departments are assumed to be equal in size (40m × 40m).

Using the information presented in Table 5.14, the first phase of the framework is used to generate the optimal project layouts based on the PDF matrix for each period of the planning horizon. The project layouts are shown in Figures 6.31, 6.32 and 6.33, respectively. The MHC of project layouts based on the PDF matrices for each period of the planning horizon is illustrated in Table 6.5. Once the optimal layouts are determined, the second step is to generate the optimal project (most robust) for the sum of the flow matrices and calculate its MHC value. Figure 6.34 shows the project (most robust) layout and its MHC value. Equation (5.1) is used to test the suitability of the identified layout to be the robust layout for this case study. The MHC for using the project (most robust) layout in various periods, the total MHC of the planning horizon and the TPC are provided in Table 6.6. Similarly, using the expected value matrix, the optimal layouts are shown in Figures 6.35, 6.36 and 6.37, respectively. The MHC of robust layouts for each period of the planning horizon is illustrated in Table 6.7. The most robust layout and its MHC value are shown in Figure 6.38. The MHC for using the most robust layout in various periods, the total MHC of the planning horizon and the TPC are provided in Table 6.8.

30	28	15	26	24	29
1	9	11	16	25	27
3	4	2	18	23	14
5	6	13	20	22	12
7	8	10	17	19	21

Figure 6.31 Project layout for Period 1

3	1	30	28	26	24
5	2	4	10	12	29
7	22	6	8	21	27
18	20	13	17	19	25
16	15	11	9	14	23

Figure 6.32 Project layout for Period 2

10	19	21	23	25	27
8	3	17	22	1	29
6	5	7	20	30	28
4	2	13	18	16	26
12	15	9	11	14	24

Figure 6. 33 Project layout for Period 3

Table 6.5 MHC of optimal project layouts in various periods and total MHC of planning horizon

Periods	1	2	3	Total MHC of the planning horizon
$MHC	284760	441000	545200	1270960

3	1	30	28	26	24
5	2	4	10	12	29
7	22	6	8	21	27
18	20	13	17	19	25
16	15	11	9	14	23

$425800

Figure 6.34 Project (most robust) layout and its MHC value

Table 6.6 MHC for using project (the most robust) layout in various periods, total MHC of planning horizon and TPC

Periods	1	2	3	Total MHC of the planning horizon
$MHC	288640	441000	545200	1274840
TPC%				0.3

29	1	30	28	26	24
27	21	19	3	17	22
25	8	6	5	7	20
23	10	4	2	13	18
14	12	15	9	11	16

Figure 6.35 Robust layout for Period 1

22	4	6	8	10	12
20	2	5	3	21	1
18	13	7	19	17	30
16	11	14	27	29	28
15	9	23	25	24	26

Figure 6.36 Robust layout for Period 2

10	8	20	22	14	23
12	6	18	16	21	25
7	4	13	17	19	27
5	2	11	9	24	29
3	15	1	30	28	26

Figure 6.37 Robust layout for Period 3

Table 6.7 MHC of optimal robust layouts in various periods and total MHC of the planning horizon

Periods	P=1	P=2	P=3	Total MHC of planning horizon
$MHC	307000	450000	474000	1231000

22	4	6	8	10	12
20	2	5	3	21	1
18	13	7	17	19	30
16	11	9	27	29	28
15	14	23	25	24	26

$405920

Figure 6.38 The most robust layout and its MHC value

Table 6.8 MHC for using the most robust layout in various periods, total MHC of the planning horizon and TPC

Periods	1	2	3	Total MHC of planning horizon
$MHC	309000	450000	474240	1233240
TPC%				.018

Once the most robust layouts are identified, the analytic and hybrid approaches of the second phase are utilised to evaluate these layouts under different scenarios. The computation results from using the simulation method for different scenarios are shown in Figures 6.39, 6.42, 6.45 and 6.48. The configuration of project and robust layouts for different scenarios are shown in Figures 6.34, 6.38, 6.40, 6.41, 6.43, 6.44, 6.46 and 6.47, respectively. The computation results from using robust and stable indices and the results of the simulation method are compared and provided in Table 6.9.

6.4.2.1 Scenario 1: Evaluation of project layout and robust layout

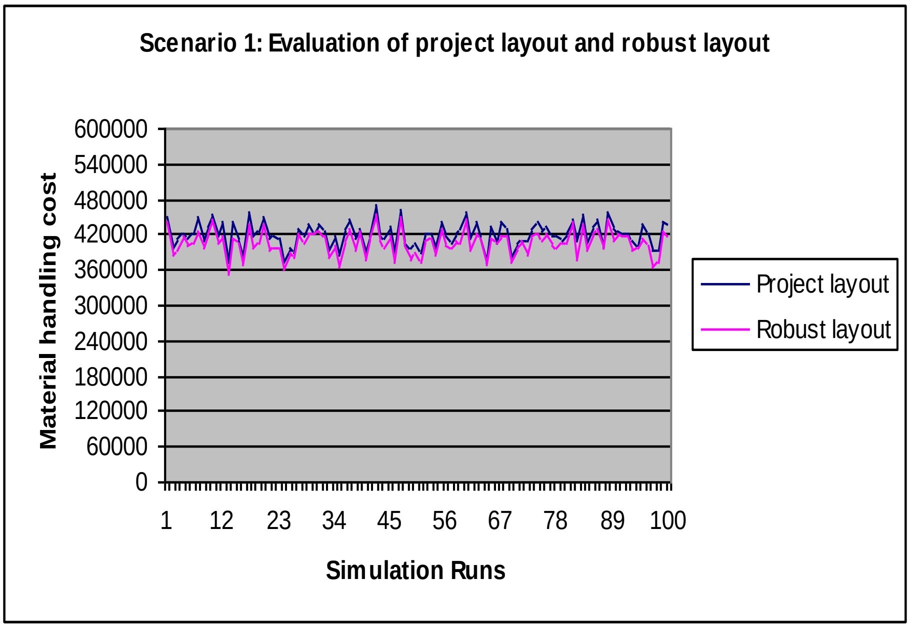


Figure 6.39 Results of the simulation method for scenario 1

Figure 6.39 shows how the robust layout provides high quality solution in terms of a low average total MHC ($406214) over time. This solution essentially gives savings of 3.2% when compared with the project layout ($420038).

6.4.2.2 Scenario 2: Deletion of departments

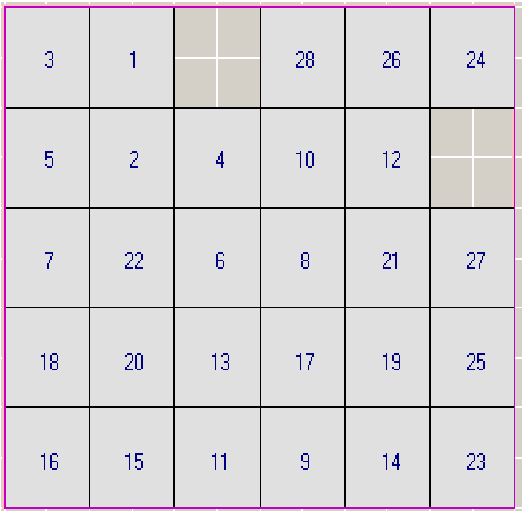


Figure 6.40 Scenario 2 for project layout

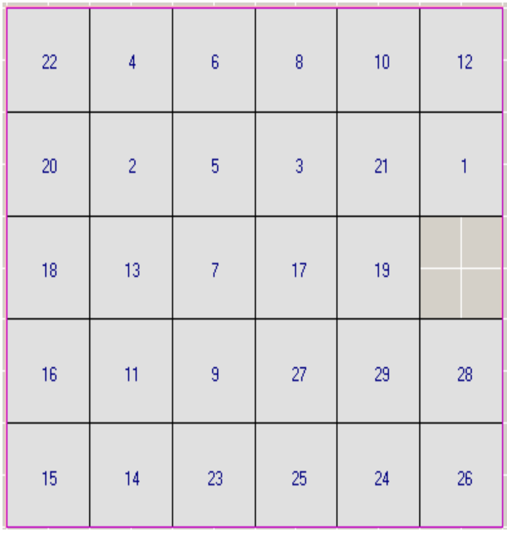


Figure 6.41 Scenario 2 for robust layout

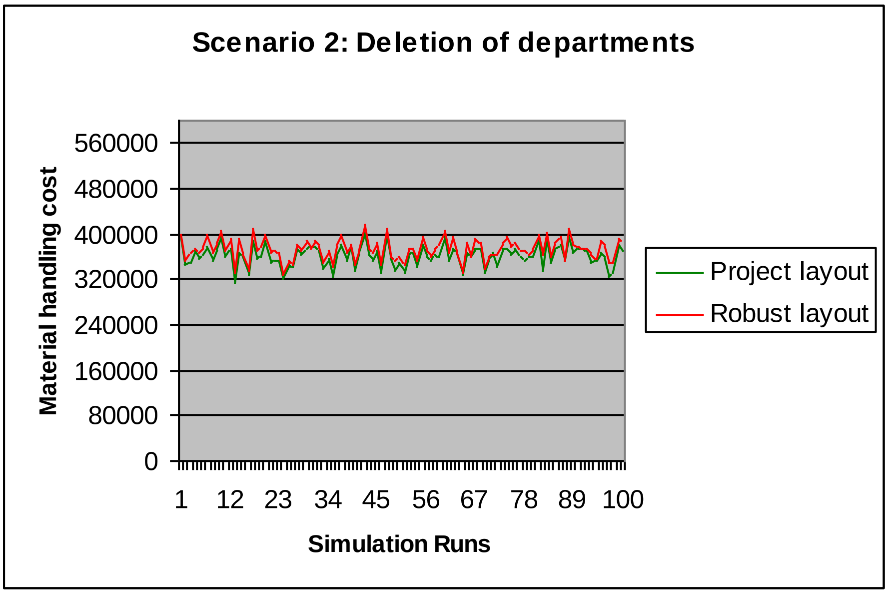


Figure 6.42 Results of the simulation method for scenario 2

Figure 6.42 shows how the project layout provides high quality solution in terms of a low average total MHC ($357189) over time. This solution essentially gives savings of 1.2% when compared with the robust layout ($361639).

6.4.2.3 Scenario 3: Doubling area of project layout and tripling area of robust layout

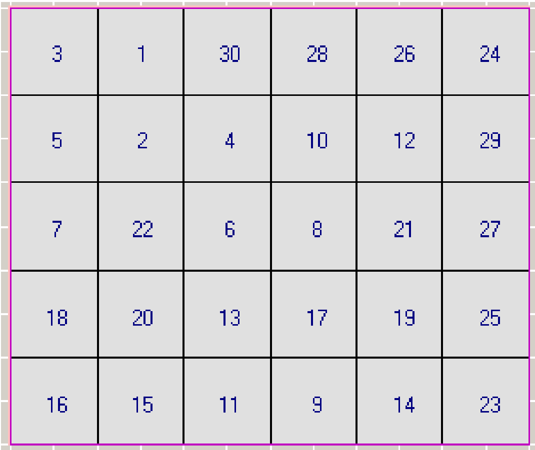


Figure 6.43 Scenario 3 for project layout

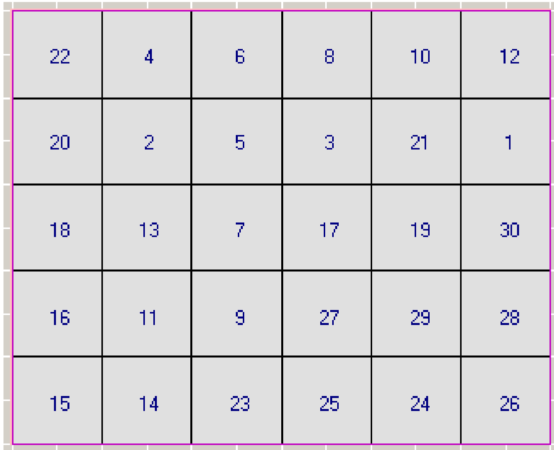


Figure 6.44 Scenario 3 for robust layout

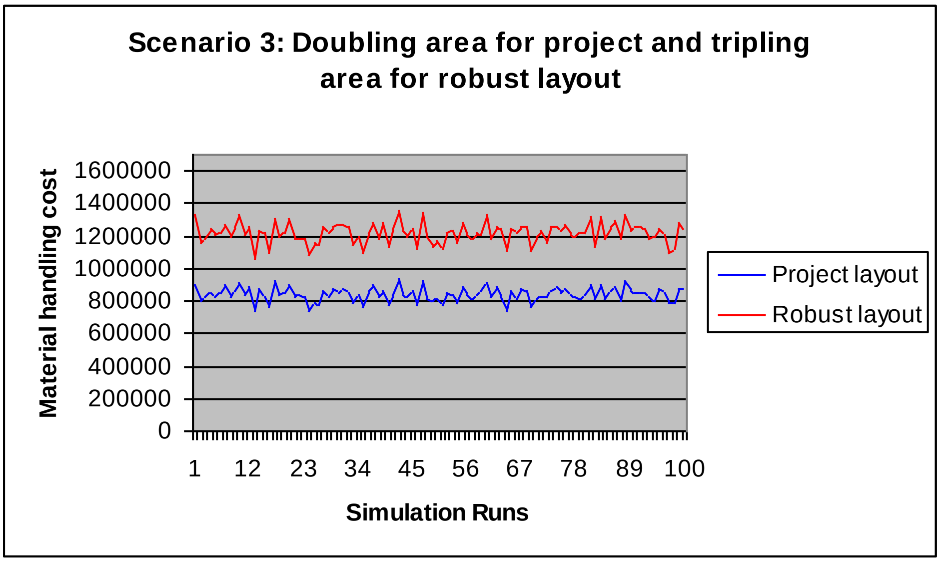


Figure 6.45 Results of the simulation method for scenario 3

Figure 6.45 shows how the project layout provides high quality solution in terms of a low average total MHC ($840893) over time. This solution essentially gives savings of 30.9% when compared with the robust layout ($1218422).

6.4.2.4 Scenario 4: In figure 6.46, moving the first column 40 square units up and moving the last column 40 square units down for project layout. In figure 6.47, shifting the first row 40 square units left and moving the last row 40 square units right for robust layout.

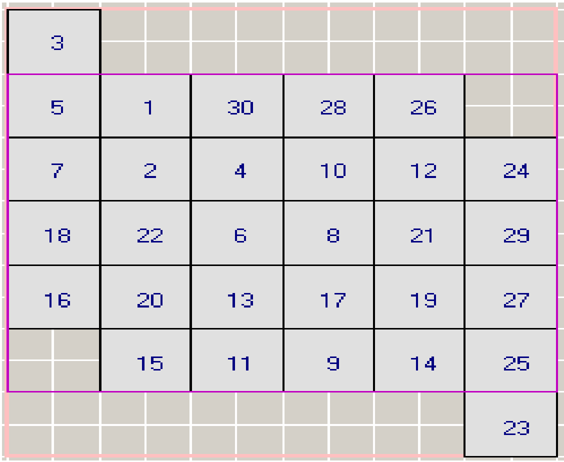


Figure 6.46 Scenario 4 for project layout

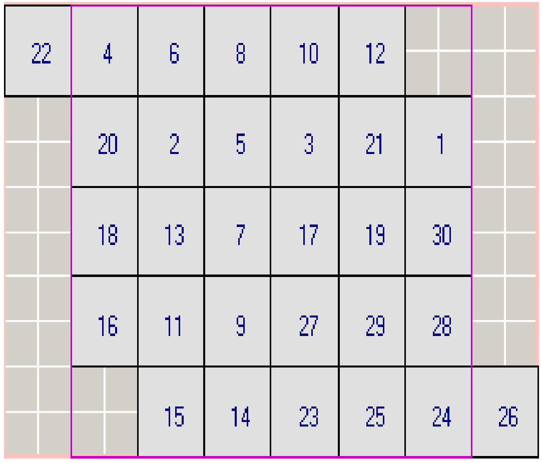


Figure 6.47 Scenario 4 for robust layout

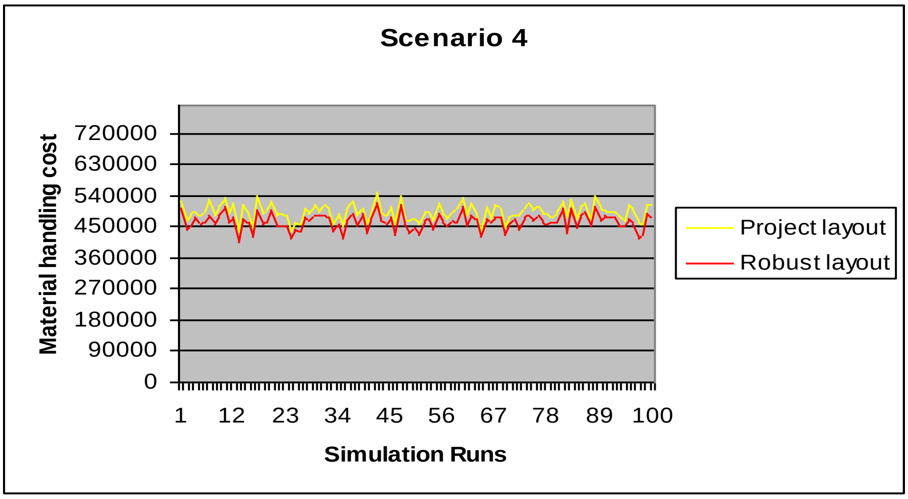


Figure 6.48 Results of the simulation method for scenario 4

Figure 6.48 shows how the robust layout provides high quality solution in terms of a low average total MHC ($463892) over time. This solution essentially gives savings of 5.5% when compared with the project layout ($491234).

Table 6.9 Comparison of results both analytically and via simulation method

Scenarios		Project layout		Robust layout		Analytic results Reduction (-)		Simulation results Reduction (-)	
		$MHC	$SD	$MHC	$SD	Robust Index %	Stable Index %	MHC Index %	SD Index %
1	Project layout against robust layout	425800	19965.3	405920 (419960)*	19344.2	-3.34	-3.13	-3.2	-2.05
2	Deletion of departments	371640	15811.5	361880 (357240)	15551.4	1.28	1.64	1.2	2.5
3	Doubling area for project and tripling area for robust	851600	39930.6	1217760 (839920)	58032.6	31.0	31.2	30.9	31.93
4	Shifting 40 square units for project and robust layouts.	496800	21045.0	463600 (491360)	20567.0	-5.64	-2.3	-5.5	-4.3

*Number in parenthesis indicates MHC of using project layout in state of robust layout

In the final phase, the analysis of the multi-period stochastic FLP case study is done with respect to robust and stable indices for layouts based on project demand values and the robust layout. Table 6.9 shows a comparison of MHC and SD indices both analytically and via the simulation method for project and robust layouts under different scenarios. According to the results (Table 6.9, columns 7 and 8), for scenarios one and four, the project layout did not provide any reduction in terms of MHC or SD when compared with the robust layout. On other hand, for scenarios two and three, the project layout performed best in terms of MHC and SD when compared with the robust layout. Therefore, using the first scenario as criterion, the layout based on product demand forecast values is selected as the best layout for the 30-department multi-period case study.

6.5 Conclusion driven from case studies

Through investigation of Rosenblatt and Kropp's (1992) methodology for solving discrete stochastic FLP, a new robust index is developed and can be used effectively to:

- Eliminate the need to use any manual calculations for both discrete and continuous stochastic FLPs;
- Compare any set of layouts in terms of MHC with or without respect to the most robust layout and eliminates the need to use TFP as criterion to select the most robust layout for discrete stochastic FLP. As a result, the computation time is reduced by 1/n factor where n is the number of solution times;
- Validate the formulation of the robust index to compare any set of layouts in terms of MHC with respect to the most robust layout for continuous stochastic FLP by replacing $\overline{F}$ state with optimal layout for expected value matrix and reduce the computation time by 1/n factor where n is the number of simulation periods;
- Validate the development of the stable index to compare any set of layouts in terms of SD with respect to the most stable layout for continuous stochastic FLP by replacing $\overline{F}$ state with optimal layout for variance matrix and reduce the computation time by 1/n factor where n is the number of simulation periods;
- Compare any set of layouts with or without respect to the most robust layout. This type of comparison is preferred in a real-life scenario where the layout designer is interested in selecting a single layout from a set of limited layouts.

The analysis of case studies highlight that the proposed framework is effective in solving the QAP both analytically and via the simulation method, and also in ensuring the efficiency of project and robust layouts over time. Through analysis of the case studies, the following results are obtained:

- Comparing the project layout and robust layout based on their minimum MHC without ensuring its efficiency over time via analytic indices or the simulation method may lead to the selection of an inefficient layout—for instance, the first scenario for the 30-department case study (single period);
- The results of the simulation method are close to the analytic indices in terms of MHC and SD and using both methods will result in selecting the same layouts. Therefore, the simulation method can provide an alternative method when solving robust and stable indices is prohibitive;
- The optimality of project and robust layouts is drastically changing when different parameters and predefined scenarios are used for evaluation; for instance, doubling the area for project layout and tripling the area for robust layout scenarios. Therefore, the layout designer can develop a large number of scenarios based on the actual area and analyse each scenario separately to select the best one. In addition, designing the most robust layout with or without consideration of the SD index may lead to different results and should be identified a priori.

6.6 Conclusion

As stated earlier, the QAP is a mathematical model for assigning n equal area departments to n equal area locations such that the distance of material travel is minimised. In this chapter, VIPPLANOPT is used for the first time to address the QAP. The performance of VIPPLANOPT is tested using data taken from literature and the computation results show significant improvements compared to existing approaches to solve the QAP. A new robust index is also developed that can be used effectively to reduce the computation time by 1/n factor where n is the number of solution times for discrete stochastic FLP. In addition, the validity of the proposed framework is verified using single and multiple period case studies. The results of the case studies show that the proposed framework is efficient in evaluating the robustness and stability of facility layout designs with equal area under different scenarios and outcomes. In the next chapter, the achievements of the research documented in this thesis with respect to the objectives initially stated in Chapter One, along with the conclusion of this research, contributions of this research to the FLP area and future work, are presented.

CHAPTER 7

CONCLUSION, CONTRIBUTIONS AND FUTURE WORK

7.1 Introduction

This chapter reviews the achievements of the research work performed with respect to the objectives initially stated in Chapter One and presents the author's contributions in the field of facility layout problem areas. It also provides a conclusion and possible future work.

7.2 Review of objectives and achievements

In Chapter One, the aim of this thesis was to present a systematic methodology in the form of a framework that allows the layout designer to incorporate uncertainty in product demands into the design of a facility layout, show how to assess product demand forecasts; design robust layouts; evaluate robust layouts over time; and how to perform uncertainty analysis to select the optimal layout design under consideration.

In order to demonstrate that the aim has been achieved, the objectives that are initially stated in section 1.6 are reviewed:

- **Objective 1**

Develop a simulation model to generate random variables with known mean and Standard Deviation (SD) and integrate this model with VIPPLANOPT 2006 to evaluate the generated layouts and to quantify the impact of product demand uncertainty to facility layout designs in terms of robustness (MHC) and variability (SD).

- **Achievements**

A new hybrid (simulation) approach is constructed in which a simulation model is developed and integrated with VIPPLANOPT 2006 to quantify the impact of product demand uncertainty to facility layout designs in terms of robustness (MHC) and variability (SD). Section 3.3.2 describes the steps required to develop a simulation model whereas section 3.3.3 presents the integration of VIPPLANOPT 2006 with the simulation model. The flow chart of the integration of VIPPLANOPT software with the simulation model is shown in Figure 3.1. To gauge the effectiveness of the simulation method, numerous case studies with practical assumptions were developed for procedure validation in sections 3.5.1, 4.4, 5.3, 6.3.3 and 6.3.4. Computation results indicate that the proposed simulation approach is effective in evaluating the robustness and stability of any set of facility layout designs with hard constraints, such as the addition, deletion and expansion of departments under different scenarios in a stochastic environment, performing uncertainty analysis to select a single layout, providing very close results to analytic indices over 100 simulation periods, validating the developed analytic indices and transforming the static FLP to DFLP. However, computation time to execute the simulation approach due to the import and export of files is required.

In summary: the first objective, i.e., to develop a new hybrid (simulation) approach for stochastic FLP, was met in full.

- **Objective 2**

Develop new analytic robust and stable indices to evaluate any set of layouts and to quantify the impact of product demand uncertainty to facility layout designs in terms of robustness (MHC) and variability (SD) when the flow changes stochastically with known mean and variance.

- **Achievements**

In section 4.3, two new analytic indices were developed to quantify the impact of product demand uncertainty to facility layout designs in terms of robustness (MHC) and variability (SD). The first index is referred to as the robust index whereas the second index is referred to as the stable index. Section 4.3.1 presents the mathematical formulation of analytic robust and stable indices based on the results of integration of a simulation model with VIPPLANOPT and Rosenblatt and Kropp’s (1992) methodology for discrete stochastic FLP. To gauge the effectiveness of the proposed robust and stable indices, several case studies with practical assumptions were developed for procedure validation in sections 4.4, 5.3, 6.3.3 and 6.3.4. Through experimentation, the proposed indices have shown to be effective in evaluating any set of facility layout designs with hard constraints under different scenarios in a stochastic environment, performing uncertainty analysis to select a single layout, validating the results of simulation approach, transforming the stochastic FLP to static FLP and reducing the computational time by 1/n factor where n is the number of simulation periods and assisting the layout designer or practitioners to quantify the impact of uncertainty with a high reduction in computation time and eliminating the need for manual calculations.

In summary: the second objective, i.e., to develop new analytic robust and stable indices to quantify the impact of uncertainty in terms of MHC and SD, was met in full.

- **Objective 3**

Apply the developed analytic indices and simulation approach to address the single period stochastic FLP with unequal area and validate the effectiveness and efficiency of the proposed approaches via small, medium and large case studies (12, 20 and 30 departments).

- **Achievements**

Chapter Four presents the application of the proposed analytic and simulation approaches to assess product demand forecasts at the early stage of the design process and to address the single period stochastic FLP. In section 4.4, small, medium and large case studies (12, 20 and 30 departments) were developed to gauge the effectiveness of the proposed robust and stable indices and simulation approach for solving the single period stochastic FLP with unequal area. Computation results indicate that the proposed approaches are effective in quantifying the impact of uncertainty to the efficiency of facility layout designs under different scenarios. The computation results from using robust and stable indices and the results of the simulation indices are compared and illustrated in Tables 4.6, 4.8 and 4.10, respectively. The computation results are also used to draw conclusions driven from the case studies in section 4.7.

In summary: the third objective, i.e., to apply the analytic and simulation approaches to address the single period stochastic FLP and validate the results via case studies, was met in full.

- **Objective 4**

Develop a framework to enhance the application of the developed analytic indices and simulation approach to address the multi-period stochastic FLP with unequal area and validate the effectiveness and efficiency of the proposed framework via small, medium and large case studies (12, 20 and 30 departments)

- **Achievements**

To enhance the application of the proposed analytic and simulation approaches, section 5.2 presents the steps required to develop a framework for the design of optimal robust layout design for multi-period stochastic FLP. Figure 5.1 shows the three phases of the proposed framework to address different aspects of stochastic FLPs. In sections 5.3.1, 5.3.2, and 5.3.3, three case studies were constructed to validate the performance of the proposed framework for solving different aspects of multi-period stochastic FLP. The computation results from using robust and stable indices and the results of the simulation indices are compared and illustrated in Tables 5.7, 5.13 and 5.19, respectively. In addition, a 30-department case study was also developed to demonstrate the application of analytic robust and stable indices for solving the multi-period stochastic FLP where the most robust layout is evaluated against the most stable layout. The computation results from using robust and stable indices were compared and illustrated in Table 5.25. The results of the case studies showed that the proposed framework is effective in quantifying the impact of uncertainty under different scenarios, evaluating the robustness and stability of facility layout designs with practical assumptions in a stochastic environment and in applying the analysis results to make better decisions.

In summary: the fourth objective, i.e., to develop and enhance the framework to address different aspects of stochastic FLPs, was met in full.

- **Objective 5**

Evaluate the performance of the VIPPLANOPT 2006 software to address the QAP for the first time via a set of data that are taken from the literature and develop a new robust index to reduce the computation time for discrete stochastic FLP with equal area.

- **Achievements**

In the literature, the FLP is commonly formulated as a QAP. In section 6.2, a set of problems ranging in size from six departments to 30 departments were used to test the performance of the VIPPLANOPT 2006 software to address the QAP for the first time. This set of problems became an acceptable benchmark and is used by researchers for evaluating the performance of different solution optimisation approaches. Based on comparison data provided in Table 6.1, the performance of VIPPLANOPT 2006 outperforms seven of 10 heuristics for solving the QAP. Therefore, the VIPPLANOPT 2006 software is a new effective tool to address this type of hard optimisation problem. Once VIPPLANOPT 2006 software had proved to be effective in addressing the QAP, Rosenblatt and Kropp's (1992) methodology for discrete stochastic FLP was investigated in order to improve and explore new solutions that eliminate the need for manual calculations and the use of TFP as criteria to evaluate the robustness of facility layouts in terms of MHC (single objective). Section 6.3.2 presents the mathematical formulation of a new robust index for discrete stochastic FLP and the validation of the proposed robust index via a numerical example from Rosenblatt and Kropp (1992). Computation results indicate that the robust index can be used effectively to reduce the solution time by 80% for discrete stochastic FLP and this reduction increases as the number of departments or layouts increases.

In summary: the fifth objective, i.e., to evaluate the performance of VIPPLANOPT 2006 software to address the QAP for the first time and develop a new robust index for discrete stochastic FLP, was met in full.

- **Objective 6**

Apply the developed framework to address the single period stochastic FLP and multi-period stochastic FLP with equal area and validate the framework via two case studies (30 departments).

- **Achievements**

To further generalise and enhance the range of applications of the proposed framework, in sections 6.4.1 and 6.4.2, two case studies (30 departments) were developed to gauge the effectiveness of the proposed framework for solving the single period stochastic FLP and multi-period stochastic FLP with equal area. The computation results from using robust and stable indices and the results of the simulation method were compared and provided in Tables 6.4 and 6.9, respectively. The computation results were also used to draw conclusions driven from the case studies in section 6.5. The results of the case studies confirmed that the proposed framework is effective in evaluating the robustness and stability of facility layout designs with equal area under stochastic product demands.

In summary: the sixth objective, i.e., to apply the proposed framework to address stochastic FLP with equal area and validate the framework via case studies, was met in full.

7.2 Conclusion

The manufacturing environment is characterised by a high degree of volatility and variability. The ability to design and operate layouts that are robust and stable against changing market demands is becoming increasingly important to the success of any manufacturing organisation. In general, FLP is concerned with the allocation of the departments or machines in a facility with an objective to minimise the total MHC of moving the required materials between pairs of departments. Most FLP approaches assume the flow between departments is deterministic, certain and constant over the entire time-planning horizon. However, changes in product demand and product mix in a dynamic environment invalidate these assumptions where product demands are highly volatile and uncertain. Therefore, there is a need for stochastic FLP approaches that aim to minimise the impact of uncertainty and accommodate any possible changes in future product demands.

From the literature surveys, most FLP approaches are designed to generate a single layout and not to use the same layout with the same configuration in various periods of the planning horizon. Therefore, these approaches may fall short in designing and evaluating robust layouts that can handle uncertain production environments. In addition, the major drawback of most previous research on stochastic FLP is limited in applicability in practice because of the underlying assumptions, such as the single objective function, the assignment of a probability value to the from-to chart, equal area departments and the analysis of only small-sized problems. Therefore, by considering the complexity of FLP and the importance of quantifying the impact of uncertainty on facility layout designs, an attempt was made to present a practical methodology in the form of a framework with fully computerised stochastic approaches to answer the research question and address different aspects of stochastic FLPs as well.

In addition, the proposed methodology, along with the use of the proposed stochastic approaches, are validated via numerical examples and numerous case studies in order to assist the layout designers or practitioners to evaluate the robustness and stability of facility layout designs with realistic assumptions, such as the addition, deletion and expansion of departments, in a stochastic environment where product demands are subjected to variability. Through experimentation, the results of the case studies showed that the mean and variance of the flow between departments do not depend on the type of layout. Once these values are obtained, the layout designer can evaluate different types of layouts that are preferred by changing the input data of the proposed framework. In other words, the solution approaches are not restricted to certain types of layouts or certain types of distribution. For instance, the layout designer can evaluate product layout against process layout, stable layout against initial layout, robust layout against initial layout and so on. This leads to the importance and practicability of the proposed methodology to evaluate different types of layouts and can be applied in real-life scenarios for assessing the influence of uncertainty on facility layout designs in terms of MHC and SD and making better decisions faster. Finally, the methodology is presented in a simple form to enable those who are interested in this area to evaluate a set of new layouts at the early stage of the design process or to improve the efficiency of existing layouts under a variety of different scenarios and outcomes.

7.3 Contributions

Throughout this thesis, both theoretical as well as practical aspects of the stochastic FLP are discussed with an objective to take the body of knowledge one step further by:

- Presenting a systematic methodology with fully computerised stochastic approaches for solution validation. The proposed methodology can be used effectively to design robust layouts, evaluate any set of layout designs with hard constraints, such as the addition of departments; the deletion of departments; the expansion of departments; the simultaneous solving of larger FLPs with equal and unequal areas in a stochastic environment and perform uncertainty analysis in terms of robustness and stability to select the optimal layout design under consideration;
- Developing new analytic robust and stable indices to evaluate the robustness and stability of facility layout designs with hard constraints in a stochastic environment. These indices help to reduce the computation time and eliminate the need for manual calculations for any given FLP;
- Developing a new analytic robust index for discrete stochastic FLP that could be used effectively to compare and evaluate the robustness of facility layout designs in terms of MHC, eliminate the use of manual calculations and TFP to select the most robust layout and reduce the computation time by 1/n where n is the solution time;
- Applying VIPPLANOPT 2006 software for the first time to generate optimal layouts for QAP formulation and obtain the same results as published in the literature. Therefore, the VIPPLANOPT 2006 software is a new and effective tool in solving this type of hard combinatorial optimisation problem as well.

7.4 Future research

The proposed methodology is proven to be effective in incorporating the uncertainty of product demands and designing, evaluating and selecting the optimal layout designs under a stochastic environment. It can also be extended within the following different aspects:

- The use of the proposed methodology, along with solution approaches, to design, evaluate and select detailed optimal robust layouts in a stochastic environment by considering aisles; for instance, the effect of locations of aisles and types of aisles under different scenarios is a potential area of research;
- The use of the proposed methodology to address the scenarios where the deletion, addition and expansion of departments between periods and duplication of the same departments are allowed;
- Through experimentation, VIPPLANOPT software is utilised to generate the optimal adaptive layout that is published in Rosenblatt (1986). However, the relocation costs are added manually to obtain the same results in this case. Therefore, extension of the proposed methodology to design the adaptive layout with practical assumptions by combining the VIPPLANOPT software with auto CAD software or other software to calculate automatically the relocation costs. This is a new area of research;
- The use of the proposed methodology to address the machine layout problem by considering the effect of internal source of uncertainty such as machine breakdowns and the significant role of maintenance strategy for improving the performance and handling cost analysis.

- The use of the VIPPLANOPT 2006 software to solve large-sized QAPs; for instance, 150 or 200 departments;

- The results of the case studies showed a good agreement between the analytic and simulation approaches. Therefore, the simulation model is effective and can be applied in other applications of the production and operation management.

REFERENCES

Afentakis, P., Millen, R. A. and Solomon, M. M. (1990). Dynamic layout strategies for flexible manufacturing systems. International Journal of Production Research, 28, 311-323.

Aleisa, E. E., and Lin, L. (2005). For effectiveness facilities planning: Layout optimization then simulation, or vice versa? In Proceedings of the 2005
Winter Simulation Conference

Aiello, G., Enea, M. and Galante, G. (2002).An integrated approach to the facilities and material handling system design. International Journal of Production Research, 40(15), 4007-4017.

Amaral, A.R. S.(2006).On the exact solution of facility layout problem. European Journal of Operational Research, 173(2), 508-518.

Armour, G.C. and BuffaE.S. (1963).A heuristic algorithm and simulation approach to relative location of facilities. Management science, 9,294-309.

Balakrishnan, J., Cheng C. H. and Wong K. F. (2003).FACTOPT: a user friendly

Azdivar, F. and Wang J. (2000). Facility layout optimization using simulation and genetic algorithms. International Journal of Production Rresearch, 38(17), 4396-4383.

Balakmurugan, K., Selladurai, V. and Llamathi, B. (2006).Design and optimization of manufacturing facilities layouts. Journal of Engineering Manufacturing, 220 part B.

Balakrishnan, J., Jacobs, F. R. and Venkataramanan, M. A. (1992). Solutions for the constrained dynamic facility layout problem. European Journal of Operational Research, 57,280-286.

Balakrishnan, J., and Cheng, C. H. (1998) .Dynamics layout algorithms: A state-of-the art survey .International Journal of Management Science, 26(4), 507-521.

Batta, R. (1987). Comments on the dynamics of plant layout. Management Science, 33(8), 1065.

Balakrishnan, J., and Cheng, C. H. (2009).The dynamic plant layout problem: incorporating rolling horizons and forecast uncertainty. International Journal of Management Science.37, 165-177.

Balakrishnan, J., Cheng, C. H, and Conway, D. G. (2000). An Improved pair wise exchange heuristic for the dynamic plant layout problem. International Journal of Production Research, 38(13), 3067-3077.

Balakrishnan, J., Cheng C. H. and Wong K. F. (2003).FACTOPT: a user friendly FACilty layout OPTimization system. Computers and Operation Research, 30, 1625-1641.

Balakrishnan, J., Jacobs, F. R. and Venkataramanan, M. A. (1992). Solutions for the constrained dynamic facility layout problem. European Journal of Operational Research, 57,280-286.

Barabosa-Povoa, A.B., Mateus, R. and Novais, A. (2002).Optimal 3D layout of industrial facilities. International Journal of Production Research, 40(7), 1669-1698.

Baykasoglu, A.and Gindy, N. (2001). A simulated annealing algorithm for dynamic layout problem. Computers and Operations Research 28(14), 1403-1426.

Benajaafar, S. and Sheikhzadeh, S. (2000). Design of flexible plant layouts. IIE Transactions, 32,309-322.

Bozer, Y. A. and Meller, R. D.(1997). A re-examination of distance based facility layout problem. IIE Transactions, 29, 549-560.

Bozer, Y. A., MellerR. D. and Erlebachher, S. J. (1994). An improvement type layout algorithm for single and multiple floor facilities. Management Science, 40(7), 918-932.

Braglia, M., Simone, Z. and Zavanella, L. (2003). Layout design in dynamic environments: Strategies and quantitative indices. International Journal of Production Research, 41(5), 995-1016.

Braglia, M., Simone, Z. and Zavanella, L. (2005). Layout design in dynamic environments: analytical issues. International Transactions in Operational Research, 12, 1-19.

Braglia, M., Simone, Z. and Zavanella, L. (2005).Robust versus stable layout design in stochastic environments. International Journal of Production Planning and Control, 16, 71-80.

Burkard, R. E. and Derigs, U. (1980). Assignment and matching problems: solution methods with FORTRAN program, lecture notes in economics and mathematical system, 184, 99-148.

Chen, C. W. and Sha, D. Y. (2005).Heuristic approach for solving the multi objective facility layout problem. International Journal of Production Research, 43(21), 4493-4507

Chiang, W.C. (2001).Visual facility layout design. International Journal of Production Research, 39(9), 1811-1836.

Chiang, W. C. and kouvelis, P. (1996). An improved tabu search heuristic for solving facility layout design problems. International Journal of Production Research, 34(9), 2565-2585.

Chiang, W. C., Kouvelis, p. and Urban T. L. (2006).Single and multi objective facility layout with work flow interference considerations. European Journal of Operational Research, 174,144-1426

Conway, D. G. and Venkataramanan, M. A. (1994). Genetic search and the dynamic facility layout problem. Computers and Operations Research, 21(8), 955-960.

Cowan, D. F.,(2003) Informatics for the clinical laboratory: a practical guide, Springer, New York Inc.

Das, S. K. (1993).A facility layout method for flexible manufacturing systems. International Journal of Production Research, 31(2), 279-297.

Deb, S. K. and Bhattachaaryya, B. (2005) Fuzzy decision support systems for manufacturing facilities layout planning. Decision support systems, 40, 305-314.

Donaghey, C. E. and Pire, V. P. (1991) BLOCPLAN-90, user's manual, Industrial Engineering Department, university of Houston, USA

Drira, A., Pierreval, H. and Gabouj, S. H. (2007). Facility layout problem: A survey. Annuals Reviews in control, 31,255-267.

Dunker, T. Radons, G, and Westkamper, E. (2005). Combing evolutionary computation and dynamic programming for solving a facility layout problem. European Journal of Operational Research, 165, 55-69.

Dweeiri, F. and Meier, F. A. (1996).Application of fuzzy decision making in facilities layout planning. International Journal of Production Research, 34(11), 3207-3225

El-Baz, M. A. (2004).A genetic algorithm for facility layout problems of different manufacturing environments. Computers and Industrial Engineering, 47(2-30,233-246.

Elsayed, A. E. (2007). Optimal facility layout under different topologies and intra plant stochastic flow considerations. Proceeding of 37th International Conference on computers and Industrial Engineering, Alexandria – Egypt.

Elshafie, A. N. (1977). Hospital layout as quadratic assignment problem. Operation Research, 28(1), 167-179.

Engineerig.Optimization.Software,2006,VIPPLAN OPT2006, <http://www.planopt.com/>

Erel, E., Ghosh, J. B. and Simon, J. T. (2003). New heuristic for the dynamic layout problem. Journal of the Operational Research Society, 54(12), 1275-1282.

Evans, G. W., Wilhelm, m. R. and Karwowsky, W. (1987). A layout design heuristic employing the theory of fuzzy sets. International Journal of Production Research, 25, 1431-1450.

Ficko M., Brezoncnik, M. and Balic, J. (2004).Designing the layout of single and multiple-rows flexible manufacturing system by genetic algorithms. Journal of Materials processing Technology, 157-158: 150-158.

Foulds, L. R. and Robinson D. F. (1976).A strategy for solving the plant layout problem. Operation Research, 27, 845-855.

Harmonosky, C. M. and Tothero, G. K. (1992).A multi-factor plant layout methodology. International Journal of Production Research, 30(8), 1773-1789.

Hassan, M. M. D. (2002).Toward re-engineering models and algorithms of facility layout. International Journal of Management Science, 28, 711-723.

Hassan, M. M. D., Hogg, G. L. and Smith D. R. (1986). SHAPE: A construction algorithm for area placement evaluation. International Journal of Production Research, 24, 1283-1295.

Heragu, S. S. (1992).Recent models and techniques for solving the layout problem. European Journal of Operational Research, 57, 136-144.

Heragu, S. S. (2006). Facilities design. - 2nd ed. - New York: iUniverse, Inc.

Heragu S. S.and Kusiak A. (1988). Machine layout problem in flexible manufacturing systems. Operations Research, 36(2), 258-268.

Heragu S. S.and Kusiak A. (1991). Efficient models for facility layout problem. European Journal of Operation Research, 53(1), 1-13.

Houshyar, A. and White, B. (1992).Exact optimal solution for facility layout: deciding which pairs of locations should be adjacent. Computers and Industrial Engineering, 23(4), 287-290.

Houshyar, A. and White, B.(1997).Comparison of solutions procedure to the facility location problem. Computers and Industrial Engineering, 32(1), 77-87.

Hu, M. H. and Wang, M. J. (2004). Using genetic algorithms on facility layout problems. International Journal of Advanced Manufacturing Technology, 23,301-310.

Hunagund, I. B. and Madhusudanan, P (2006). Design of robust machine layout for cellular manufacturing systems.

Hunagund, I. B. and Madhusudanan Pillia V. (2008). Development of a heuristic for layout formation and design of robust layout under dynamic demand. Proceedings the International Conference on Digital Factory, ICDF, Coimbatore, India, August 11-13-2008

Islier, A. A. (1998).A genetic algorithm approach for multiple criteria facility layout design. International Journal of Production Research, 36(6), 1549-1569.

Jithavech, ID. And Krishnan, K., K. (2009). A simulation –based approach for risk assessment of facility layout designs under stochastic product demands. International Journal of Advanced Manufacturing Technology

Gopalakrishnan, B., Turuvekere, R. and Gupta, P. D. (2004).Computer integrated facilities planning and design. Emerland research, 22,199-209.

Gupta, R. M. (1986). Flexibility in layouts: a simulation approach .Material Flow, 3,243-250.

Jensen, P. a. and Bard, J. F. (2003). Operation research models and methods. John Wiley and Sons.

Kaku, B. K. and Mozzola, J., B. (1997). A tabu search heuristic for the dynamic plant layout problem. INFORMS Journal on Computing, 9(4), 374-383.

Kamaldeep, Singh, P. K.(2010).Multi-period in cellular manufacturing a: discussion, International Journal of Engineering studies,2(3),251-262

Kochhar, J. S. and Heragu, S. S. (1998). MULTI-HOPE: A tool for multiple floor layout problems. International Journal of Production Research, 36(12), 3421-3435.

Kochhar, J. S. and Heragu, S. S. (1999).Facility layout design in a changing environment . International Journal of Production Research, 37(11), 2429-2446.

Komarudin and Wong, K. W. (2009). Applying ant system for solving unequal area facility layout problems. European Journal of Operational Research.

Konak, S. K. (2007). Approaches to uncertainties in facility layout problem: perspectives at the beginning of the 21 century. Journal of Intelligent Manufacturing, 18,273-284.

Kouvelis, P., Kuawarwala, A. A. and Gutierrez, G. J. (1992). Algorithms for robust single and multiple period layout planning for manufacturing systems. European Journal of Operational Research, 63,287-303

Krishnan, K. K., Cheraghi, S. H. and Nayak, C. (2006). Dynamic from between chart: Anew tool for solving dynamic facility layout problems. International journals of Industrial and Systems Engineering, 3(2), 105-133.

Krishnan, K. K., Cheraghi, S. H. and Nayak, C. (2008).Dynamic facility layout design for multiple production scenarios in a dynamic environment. International journals of Industrial and Systems Engineering, 1,182-200.

Krishnan, K. K., Jithavech, I. d. and Liao, H. (2008). Mitigation of risk in facility layout design for single and multiple problems. International Journal of Production Research, 1-30.

Konak, S. K., Simith, A. E. and Norman, B. A (2007).Bi-objective facility expansion and re layout considering monuments. IIE Transactions, 39,747-761

Konak, S. K., Simith, A. E. and Norman, B. A (2004). Layout optimization considering production uncertainty and routing flexibility. International Journal of Production Research, 42(21), 4475-4493

Kusiak, A. and Heragu S. S. (1987). The facility layout problem. European Journal of Operational Research, 29,229-251.

Lacksonen, T. A. (1994). Static and dynamic layout problems with varying areas. Journal of the Operational Research Society, 45(1), 59-69.

Lacksonen, T. A. (1997). Pre-processing for static and dynamic facility layout problems. International Journal of Production Research, 35(4), 1095-1106.

Lacksonen, T. A. and Enscore E. E. (1993). Quadratic assignment algorithms for dynamic layout problems. International journal of production research, 31(3),503-517

Lahmar, M. and Benjaafar, S., (2005). Design of distributed layouts. IIE Transactions, 37,303–318.

Lawler, E. L. (1963).The quadratic assignment problem. Management science, 9(4), 586-599.

Lien, L., C., and Cheng, M., U.(2012). A hybrid AI based algorithm for facility layout optimization. Engineering with Computers,57-69

Liu, F., Dong, M., Hou,F and Chen, F.(2006). Facility optimization with stochastic logistic flows. IEEE

Liu, Q. and Russell, D. and Meller (2007). A sequence-pair representation and MIP-model-based heuristic for the facility layout problem with rectangular departments *IIE* Transaction*s* (2007) **39**, 377–394

Longo F., Giovanni M. and Enrico P.(2005) Material flow analysis and plant layout optimization of a manufacturing system. IEEE Workshop on Intelligent data Acquisition and Advanced Computing Systems, Sofia, Bulgaria

Madhusudanan Pillai, V., Hunagund, I.B., Krishnan, K.K. (2011). Design of robust layout for dynamic plant layout problems. Computers & Industrial Engineering

McKendall, A. R. and Hakobyan, A. (2010).Heuristics for dynamic facility layout problem with unequal area departments. European Journal of operation research 201, 171-182

McKendall, A. R. and Shang, J. (2006). Hybrid ant systems for the dynamic facility layout problem. Computers and Operations research, 33,790-803.

McKendall, A. R., Shang, J. and Kuppusamy, S. (2006). Simulated annealing heuristics for the dynamic facility layout problem. Computers and Operations research, 33, 2431-2444.

Meller, R. D. and Gau, K. Y. (1996). The facility layout problem: recent and emerging trends and perspectives. Journal of Manufacturing systems, 15,351-366.

Meller, R. D. and Bozer, Y. A. (1996) A new simulated annealing algorithm for the facility layout problem. International Journal of Production Research, 34, 1675-1692

Meng, G., Heragu, S. and Zijms H. (2004). Reconfigurable layout problem. International Journal of Production Research, 42(22), 4709-4729

Mohsen, J., Simon, J. E. and Young, T.(2010) Economics of modelling and simulation: reflections and implications for healthcare,, Proceedings of the 2010 Winter Simulation Conference

Montgomery R. H. (2007). Engineering statics, 4 editions, John Wiley &Sons.

Mote, J., Murthy, I. and Olson, D. L. (1988). On solving single constrained shortest path problems by generating pareto-optimal paths parametrically. Working paper

Montreuil, B., Brotherton, E. and Marcotte, S. (2002).Industrial Engineering Research conference may, Orlando, Florida

Montreuil, B. and Laforge, A. (1992). Dynamic layout design given a scenario tree of probable futures. European Journal of Operational Research, 63,271-286.

Moslemipour, G. and Lee, T. S. (2011). Intelligent design of a dynamic machine layout in uncertain environment of flexible manufacturing systems. International Journal of Advanced Manufacturing technology,10,.499-512

Moslemipour, G. , Lee, T. S. and Rilling D.(2011). A review of intelligent approaches for designing dynamic and robust layout in flexible manufacturing systems. International Journal of Advanced Manufacturing Technology,

Norman, B., A. and Smith, E. A. (2000). Considering uncertainty in unequal area block layout design

Nugent, C.E., Vollmann, T.E and Ruml, J.(1968) An experimental comparison of techniques for the assignment of facilities to locations, Journal of Operations Research, 16, 150–173

Palekar, U. S., Batta, R., Bosch, R. M. and Elhence, S. (1992). Modeling uncertainties in plant layout problems. European Journal of Operational Research, 63,347-359.

Panahi, H., Rabbani, M. and Moghaddam, R. T. (2008). A comparison of three meta heuristics for a closed loop layout problem with un equal area. Springer, 265-278.

Pooch U. W and James A. W. (2000). Discrete event simulation-Florida, CRC Press, INC.

Popescu, C. and Popescu D. E. (2005). Monte carlo simulation for predicting the reliability of a control system for a geothermal plant. Proceedings world geothermal, congress, Antalya Turkey, 24 -29 April 2005

QAPLIB Website: http://www.seas.upenn.edu/qaplib/inst.html

Rosenblatt, M. J. (1979). The facilities layout problem: a multi goal approach. International Journal of Production Research, 17,323-332.

Rosenblatt.M. J. (1986). The dynamics of plant layout. Management science, 32(1), 76-86.

Rosenblatt, M. J. and Golany, B. (1992). A distance assignment approach to facility layout problem. European Journal of Operation Research, 57,253-270.

Rosenblatt, M. J. and Kropp, D. H. (1992). The single period stochastic plant layout problem. IIE Transations, 24(2), 169-176.

Rosenblatt, M. J. and Lee, H. L. (1987). A robustness approach to facilities design. International Journal of Production Research, 25(4), 479-486.

Savsar, M. (1991).Flexible facility layout by simulation. Computers and Industrial Engineering, 20(1), 155-165.

Scholz D., Betrick A. and Domscke W. (2009). A slicing tree and tabu search heuristics for the unequal area facility layout problem . International Journal of Production Research, 197,166-178

Seehof, J. M. and Evans, W. O. (1967). Automated layout design program. Journal of Industrial Engineering, 18(2), 690-695.

Shayan, E. and Chittilappilli, A. (2004).Genetic algorithm for facilities layout problems based on slicing tree structure. International Journal of Production Research, 42(19), 4055-4067.

Shore, R. H. and Tompkins, J. A. (1980). Flexible facilities design. AIIE Transations, 12(2), 200-205.

Singh, S. P. and Sharama, R. K. (2006). A review of different approaches to facility layout problems. International Journal of Advanced manufacturing technologies, 30,425-433.

Smutkupt, U. and Wimonkasame , S. (2009).Plant layout design with simulation. Proceedings of the International Multi Conference of Engineers and Computer Scientists 2009 Vol II, IMECS 2009, March 18 - 20, 2009, Hong Kong

Solimanpur, M. and Jafari, A. (2008).Optimal solution for two dimensional facility layout problem using a branch and bound algorithm. Computers and Industrial Engineering.

Suo, X. H. and Liu, Z. Q. (2008). Relationship among SFLP, DFLP and robust layout. International Journal of Applied Mechanics and Materials, 10(12), 235-241.

Tam, K. Y. (1992) A simulated annealing algorithm for allocating space to manufacturing cells. International Journal of Production Research, 30, 63-87

Tam, K. Y. and Li S. G.(1991).A hierarchical approach to facility layout problem. . International Journal of Production Research, 29(1), 165-184.

Tate, D. M. and Smith A. E. (1995). Unequal area facility layout using genetic search. IIE Transactions, 27,465-472.

Tearwattanarattikal, P., Namphacharoen, S. and Chamraaspom, C.(2008). Using PROMODELl as a simulation tool to assist plant layout design and planning: case study plastic packaging factory. Songklanakarian Journal of Science and Technology

Tompkins, J. A. and Reed R. (1976). An applied model for the facilities design problem. International Journal of Production Research, 14(5)583-595.

Tompkins, J. A. White J. A., Bozer Y. A. and Tanchoco, J. M. A. (2003). Facilities planning. Third edition, John Wiley &. Sons.

Tompkins, J. A. White J. A., Bozer Y. A. and Tanchoco, J. M. A. (2010). Facilities planning. fourth edition, John Wiley &. Sons.

Tseng., H., and Lee H.,(2012). A hybrid system for facility layout by integrating simulation and ant colony optimization. Applied mathematics & information sciences, 6(2) 387-396.

Urban, T. L. (1992).Computational performance and efficiency of lower- bound procedures for dynamic facility layout problem. European Journal of Operation Research, 271-279.

Urban, T. L. (1993).A heuristic for the dynamic facility layout problem. IEE Transactiona, 25(4), 57-63.

Urban T. L. (1998). Solution procedures for the dynamic facility layout problem. Annals of operation Research, 76,323-342.

Van Camp, D. J., Carter, M. w. and Vannelli, A. (1991). A non linear optimization approach for solving facility layout problems. European Journal of Operational Research, 57,174-189.

Waghodekar. P. H. and Sahu, S. (1986). Facility layout with multiple objectives: MFLAP. Engineering Cost and Production Economics, 10,105-112.

Wang, M. J., Hu, M. H. and Ku, M.H. (2004).A solution to unequal area facilities layout problem by genetic algorithm. Computers in Industry 56(2), 207-222.

Waynel L. W (1994). Operations research applications and algorithms- 3 edition, Wadsworth Inc.

Welgama, P. S. and Gibson, P. R. (1995). Computer- aided facility layout: A status report. International Journal of Advanced manufacturing Technologies, 10, 66-77.

Wilsten, j. and Shayan E. (2007).Layout design of a furniture production line using formal methods. Journal of Industrial System Engineering, 1, 81-96.

Wu, Y. and Appleton, E. (2002).The optimization of block layout and aisle structure by a genetic algorithm. Computers and industrial Engineering, 41(4), 371-387.

Xie,,W. and Sshinidis, N. V. (2008). A branch and bound algorithm for continuous facility layout problem. Journal of Computer and Chemical Engineering, 32, 1016-1028

Yang, T. and Peters, B. A. (1998). Flexible machine layout design for dynamic and uncertain production environments. European Journal of Operational Research, 108, 49-64.

APPENDICES

Appendix A: Hypothesis tests for 10-department case study

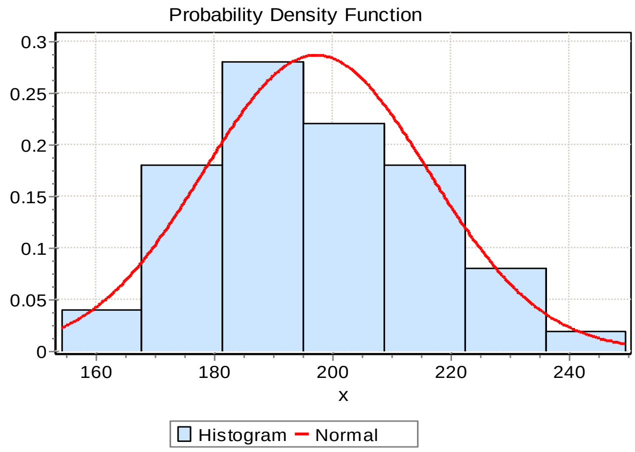


Fig.B.1. Sample data follow normal distribution for flow 5-10 Normal (200, 20).

Table B.1. Statistical hypothesis tests for flow 3-5

Normal [#43]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.05854 0.86289 25				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 0.31247 27				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 2.8328 0.82952 18				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	No	No	No	No	No

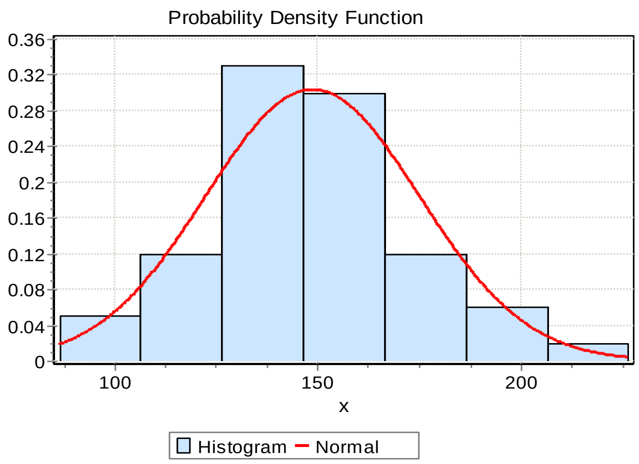


Fig.B.2. Sample data follow normal distribution for flow 1-5 Normal (150, 30).

Table B.2. Statistical hypothesis tests for flow 1-5

Normal [#43]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.0667 0.73955 13				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 0.4572 26				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 2.8872 0.82286 20				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	No	No	No	No	No

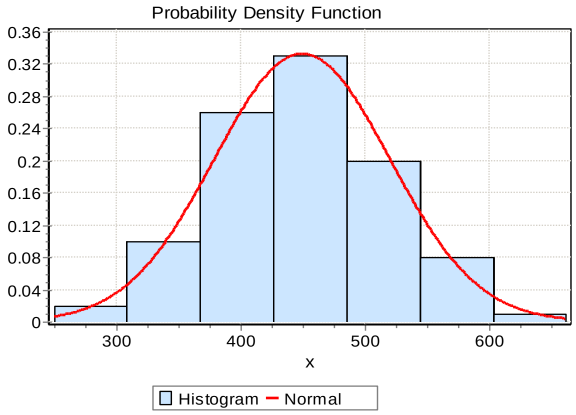


Fig.B.3. Sample data follow normal distribution for flow 5-8 Normal (450, 80).

Table B.3. Statistical hypothesis tests for flow 5-8

Normal [#43]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.05037 0.95038 18				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 0.22343 20				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 0.71137 0.99424 8				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	No	No	No	No	No

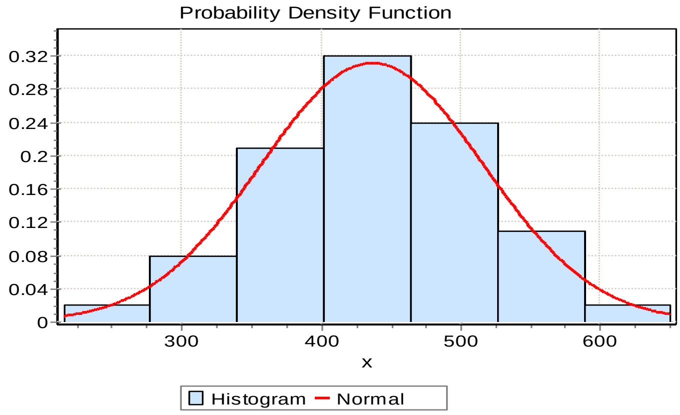


Fig.B.4. Sample data follow normal distribution for flow 8-7 Normal (450, 80).

Table B.4. Statistical hypothesis tests for flow 8-7

Normal [#43]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.04815 0.96592 8				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 0.255 7				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 1.8776 0.93061 7				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	No	No	No	No	No

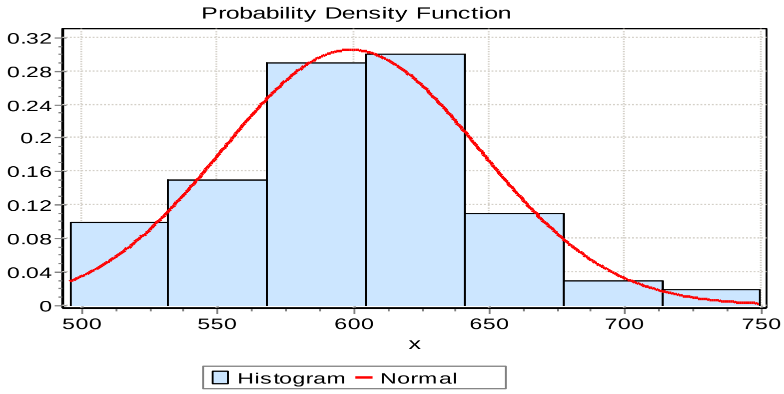


Fig.B.5. Sample data follow normal distribution for flow 2-9 Normal (600, 60).

Table B.5. Statistical hypothesis tests for flow 2-9

Normal [#43]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.06216 0.8113 24				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 0.31424 8				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 4.3765 0.62586 25				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	No	No	No	No	No

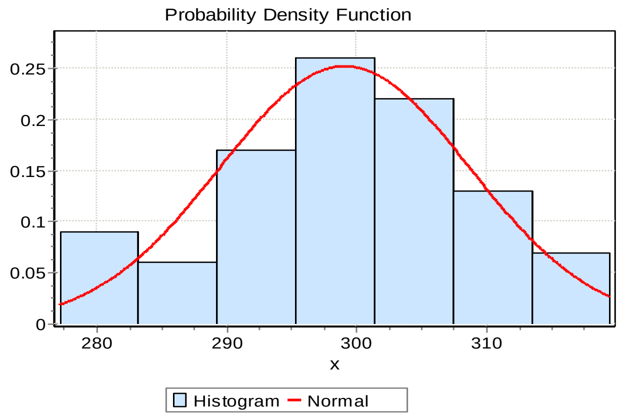


Fig.B.6. Sample data follow normal distribution for flow 2-9 Normal (300, 10).

Table B.6. Statistical hypothesis tests for flow 2-9

Normal [#43]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.04699 0.97263 1				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 0.3062 3				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 1.3785 0.96715 4				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	No	No	No	No	No

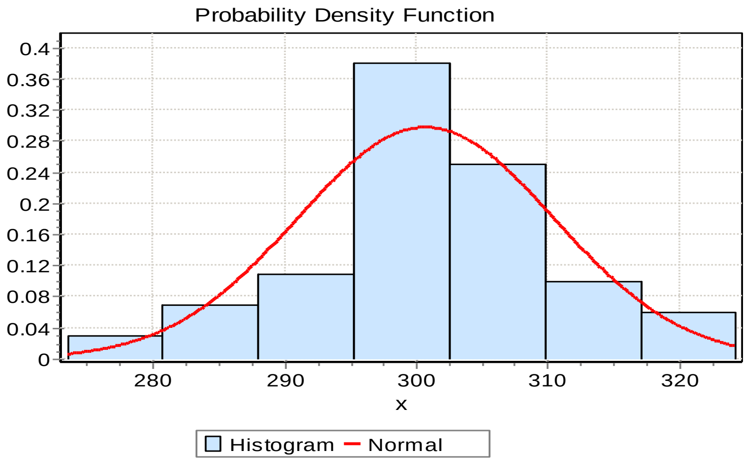


Fig.B.7. Sample data follow normal distribution for flow 6-4 Normal(300,10).

Table B.7. Statistical hypothesis tests for flow 6-4

Normal [#44]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	100 0.09478 0.31032 13				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 1.0386 13				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 7.8106 0.25231 18				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	No	No	No	No	No

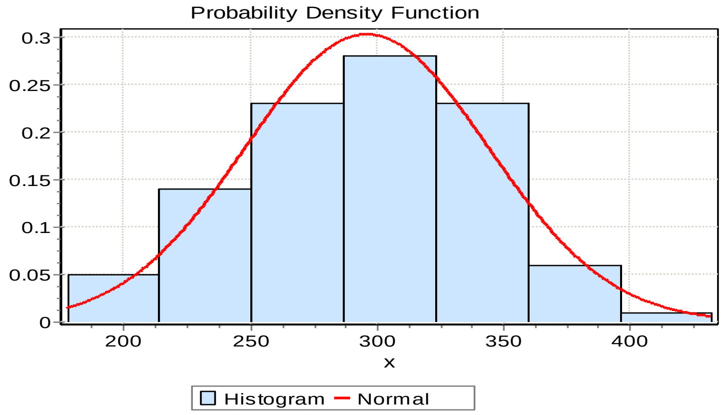


Fig.B.8. Sample data follow normal distribution for flow 9-5 Normal(300,10).

Table B.8. Statistical hypothesis tests for flow 9-5

<table>
<tr><td colspan="6">Normal [#43]</td></tr>
<tr><td colspan="6">Kolmogorov-Smirnov</td></tr>
<tr><td>Sample Size
Statistic
P-Value
Rank</td><td colspan="5">100
0.05408
0.91633
4</td></tr>
<tr><td>α</td><td>0.2</td><td>0.1</td><td>0.05</td><td>0.02</td><td>0.01</td></tr>
<tr><td>Critical Value</td><td>0.10563</td><td>0.12067</td><td>0.13403</td><td>0.14987</td><td>0.16081</td></tr>
<tr><td>Reject?</td><td>No</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td colspan="6">Anderson-Darling</td></tr>
<tr><td>Sample Size
Statistic
Rank</td><td colspan="5">100
0.26426
5</td></tr>
<tr><td>α</td><td>0.2</td><td>0.1</td><td>0.05</td><td>0.02</td><td>0.01</td></tr>
<tr><td>Critical Value</td><td>1.3749</td><td>1.9286</td><td>2.5018</td><td>3.2892</td><td>3.9074</td></tr>
<tr><td>Reject?</td><td>No</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td colspan="6">Chi-Squared</td></tr>
<tr><td>Deg. of freedom
Statistic
P-Value
Rank</td><td colspan="5">6
6.4639
0.37328
21</td></tr>
<tr><td>α</td><td>0.2</td><td>0.1</td><td>0.05</td><td>0.02</td><td>0.01</td></tr>
<tr><td>Critical Value</td><td>8.5581</td><td>10.645</td><td>12.592</td><td>15.033</td><td>16.812</td></tr>
<tr><td>Reject?</td><td>No</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
</table>

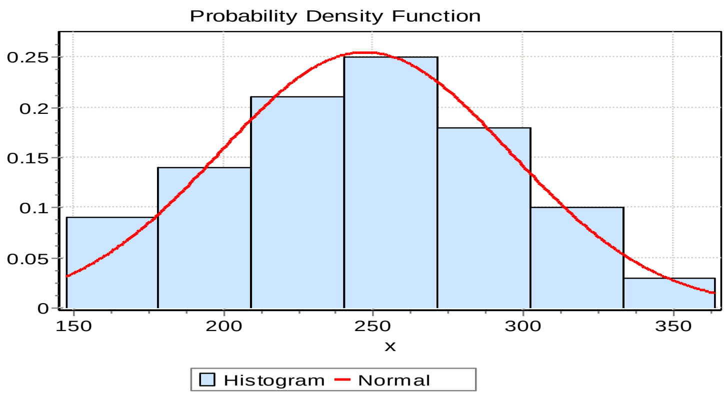


Fig.B.9. Sample data follow normal distribution for flow 2-7 Normal(250,50).

Table B.9. Statistical hypothesis tests for flow 2-7.

Normal [#43]					
KolmogorovSmirnov					
Sample Size Statistic P-Value Rank	100 0.0574 0.87779 7				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.10563	0.12067	0.13403	0.14987	0.16081
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	100 0.27413 6				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	6 2.798 0.83374 12				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	8.5581	10.645	12.592	15.033	16.812
Reject?	No	No	No	No	No

Appendix B: Twelve- department case study (single period)

Table B.1. Departmental areas

department	Area (m^2)	Length (m)	Width (m)	department	Area (m^2)	Length (m)	Width (m)
1	400	20	20	7	300	10	30
2	200	10	20	8	100	10	10
3	100	10	10	9	100	10	10
4	200	10	20	10	200	10	20
5	100	10	10	11	100	10	10
6	200	10	20	12	100	10	10

Table B.2. From to chart showing PDF values for twelve- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		50									
2		0		360	26							
3	50		0	50	48							
4		360	50	0		360			50			
5		26	48		0	48	26					
6				360	48	0		240		120		
7					26		0					
8						240		0		240		
9				50					0		50	
10						120		240		0		41
11									50		0	
12										41		0

Table B.2. From to chart showing mean values for twelve- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		50									
2		0		300	100							
3	50		0	50	50							
4		300	50	0		300			50			
5		100	50		0	50	100					
6				300	50	0		200		100		
7					100		0					
8						200		0		200		
9				50					0		50	
10						100		200		0		100
11									50		0	
12										100		0

Table B.3. From to chart showing variance values for twelve- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		1600									
2		0		2500	1600							
3	1600			1600	100							
4		2500	1600	0		2500			900			
5		1600	100		0	100	1600					
6				2500	100	0		1600		900		
7					1600		0					
8						1600		0		1600		
9				900					0		900	
10						900		1600		0		900
11									900		0	
12										900		0

Appendix C: Twenty- department case study (single period)

Table C.1. Area requirements for Twenty- department case study (single period)

department	Area square meter	Length (m)	Width (m)	department	Area square meter	Length (m)	Width (m)
1	100	10	10	11	200	10	20
2	200	10	20	12	200	10	20
3	200	10	20	13	400	20	20
4	200	10	20	14	100	10	10
5	200	10	20	15	400	20	20
6	400	20	20	16	100	10	10
7	100	10	10	17	200	10	20
8	400	20	20	18	100	10	10
9	100	10	10	19	200	10	20
10	600	20	30	20	100	10	10

Table C.2. From to chart showing mean values for twelve- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		65																	
2		0		270	225								150							
3	65		0	65	150															
4		270	65	0		270			65											
5		225	150		0	150	225													
6				270	150	0		200		70			150							
7					225		0						100							
8						200		0		200										
9				65					0		100				65					
10						70		200		0		200								
11									100		0		100							
12										200		0		200						
13		150				150	100				100		0		100		100	150		150
14												200		0		200				
15									65				100		0	50				
16														200	50	0				
17													100				0		100	
18													150					0		
19																	100		0	
20													150							0

Table C.3. From to chart showing PDF values for twelve- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		40																	
2		0		270	100								150							
3	40		0	40	150															
4		270	40	0		270			40											
5		100	150		0	150	100													
6				270	150	0		200		70			150							
7					100		0						100							
8						200		0		200										
9				40					0		100				40					
10						70		200		0		120								
11									100		0		100							
12										120		0		120						
13		150				150	100				100		0		100		100	150		150
14												120		0		120				
15									40				100		0	25				
16														120	25	0				
17													100				0		100	
18													150					0		
19																	100		0	
20													150							0

Table C.4. From to chart showing variance values for twelve- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		408																	
2		0		2500	10208								1600							
3	408		0	408	2500															
4		2500	408	0		2500			408											
5		10208	2500		0	2500	10208													
6				2500	2500	0		1600		900			2500							
7					10208		0						100							
8						1600		0		1600										
9				408					0		833				408					
10						900		1600		0		3333								
11									833		0		833							
12										3333		0		3333						
13		1600				2500	100				833		0		36		833	1600		2500
14												3333		0		3333				
15									408				36		0	64				
16														3333	64	0				
17													833				0		833	
18													1600					0		
19																	833		0	
20													2500							0

Appendix D: Thirty- department case study (single period)

Table D.1. Area requirements for Thirty- department case study (single period)

department	Area (m^2)	Length (m)	Width (m)	department	Area (m^2)	Length (m)	Width (m)
1	100	10	10	16	200	10	20
2	200	10	20	17	200	10	20
3	200	10	20	18	200	10	20
4	200	10	20	19	400	20	20
5	200	10	20	20	900	30	30
6	200	10	20	21	400	20	20
7	200	10	20	22	100	10	10
8	200	10	20	23	100	10	10
9	100	10	10	24	100	10	10
10	200	10	20	25	200	10	20
11	200	10	20	26	100	10	10
12	200	10	20	27	100	10	10
13	200	10	20	28	100	10	10
14	100	10	10	29	100	10	10
15	200	10	20	30	100	10	10

Table D.2. From to chart showing PDF values for thirty- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		50																											320
2		0		300	300								190																	
3	50		0	50	120																									
4		300	50	0		300			50																					
5		300	120		0	120	300																							
6				300	120	0		200		100			120																	
7					300		0						80																	100
8						200		0		200																				
9				50					0		190				50															
10						100		200		0		80																		
11									190		0		190																	
12										80		0		80																
13		190				120	80				190		0		80		190	190		120										
14												80		0		80							100							
15									50				80		0	40														
16														80	40	0		650												
17													190				0		190											
18													190			650		0		650										
19																	190		0		190									
20													120					650		0		650								
21																			190		0									
22																				650		0								
23														100									0		100					
24																								0		230				
25																							100		0		490	50		
26																								230		0		230		
27																									490		0		490	
28																									50	230		0		230
29																											490		0	
30	320						100																					230		0

Table D.3. From to chart showing mean values for thirty- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		52																											1000
2		0		560	370								223																	
3	52		0	52	150																									
4		560	52	0		560			52																					
5		370	150		0	150	370																							
6				560	150	0		300		260			150																	
7					370		0						80																	100
8						300		0		300																				
9				52					0		130				52															
10						260		300		0		50																		
11									130		0		130																	
12										50		0		50																
13		223				150	80				130		0		80		130	223		150										
14												50		0		50							100							
15									52				80		0	40														
16														50	40	0		510												
17													130				0		130											
18													223			510		0		510										
19																	130		0		130									
20													150					510		0		510								
21																			130		0									
22																				510		0								
23														100									0		100					
24																								0		230				
25																							100		0		610	50		
26																								230		0		230		
27																									610		0		610	
28																									50	230		0		230
29																											610		0	
30	1000						100																					230		0

Table D.4. From to chart showing variance values for thirty- department case study (single period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		126																											213333
2		0		14900	2500								2606																	
3	126		0	126	417																									
4		14900	126	0		14900			126																					
5		2500	417		0	417	2500																							
6				14900	417	0		10000		4900			417																	
7					2500		0						100																	900
8						10000		0		10000																				
9				126					0		3333				126															
10						4900		10000		0		533																		
11									3333		0		3333																	
12										533		0		533																
13		2606				417	100				3333		0		100		3333	2606		417										
14												533		0		533							100							
15									126				100		0	64														
16														533	64	0		13550												
17													3333				0		3333											
18													2606			13550		0		13550										
19																	3333		0		3333									
20													417					13550		0		13550								
21																			3333		0									
22																				13550		0								
23														100									0		100					
24																								0		5633				
25																							100		0		16550	36		
26																								5633		0		5633		
27																									16550		0		16550	
28																									36	5633		0		5633
29																											16550		0	
30	213333						900																					5633		0

Appendix E: Twelve-department case study (multi-period)

Table E.1. Area requirements for twelve-department multi-period case study

department	Area (m^2)	Length (m)	Width (m)	department	Area (m^2)	Length (m)	Width (m)
1	300	10	30	7	400	40	10
2	200	20	10	8	100	10	10
3	100	10	10	9	100	10	10
4	200	20	10	10	200	10	20
5	100	10	10	11	100	10	10
6	200	20	10	12	100	10	10

Table E.2. From to chart showing PDF values for twelve-department multi-period case study (first period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		140									
2		0		310	120							
3	140			140	400							
4		310	140	0		310			100			
5		120	400		0	300	100					
6				310	300	0		180		130		
7					100		0					
8						180		0		180		
9				100					0		100	
10						130		180		0		130
11									100		0	
12										130		0

Table E.3. From to chart showing PDF values for twelve-department multi-period case study (second period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		250									
2		0		330	100							
3	250			180	130							
4		330	180	0		330			100			
5		100	130		0	130	100					
6				330	130	0		200		130		
7					100		0					
8						200		0		200		
9				100					0		100	
10						130		200		0		120
11									100		0	
12										120		0

Table E.4. From to chart showing PDF values for twelve-department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		180									
2		0		350	410							
3	180			180	110							
4		350	180	0		350			340			
5		410	110		0	110	410					
6				350	110	0		220		130		
7					410		0					
8						220		0		220		
9				340					0		340	
10						130		220		0		50
11									340		0	
12										50		0

Table E.5. From to chart showing mean values for twelve-department multi-period case study (first period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		140									
2		0		300	100							
3	140			140	400							
4		300	140	0		300			50			
5		100	400		0	400	100					
6				300	400	0		200		100		
7					100		0					
8						200		0		200		
9				50					0		50	
10						100		200		0		100
11									50		0	
12										100		0

Table E.6. From to chart showing mean values for twelve-department multi-period case study (second period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		180									
2		0		330	100							
3	180			180	100							
4		330	180	0		330			100			
5		100	100		0	100	100					
6				330	100	0		200		130		
7					100		0					
8						200		0		200		
9				100					0		100	
10						130		200		0		120
11									100		0	
12										120		0

Table E.7. From to chart showing mean values for twelve-department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		160									
2		0		300	400							
3	160			160	100							
4		300	160	0		300			300			
5		400	100		0	100	400					
6				300	100	0		200		100		
7					400		0					
8						200		0		200		
9				300					0		300	
10						100		200		0		50
11									300		0	
12										50		0

Table E.8. From to chart showing PDF values for twelve-department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		570									
2		0		990	630							
3	570			570	540							
4		990	570	0		990			540			
5		630	540		0	540	630					
6				990	540	0		600		390		
7					630		0					
8						600		0		600		
9				540					0		540	
10						390		600		0		300
11									540		0	
12										300		0

Table E.9. From to chart showing mean values for twelve-department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		480									
2		0		960	600							
3	480			480	600							
4		960	480	0		960			450			
5		600	600		0							
6				960		0		600		360		
7							0					
8						600		0		600		
9				450					0		450	
10						360		600		0		270
11									450		0	
12										270		0

Table E.10. From to chart showing variance values for twelve-department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0		4800									
2		0		7500	4800							
3	4800			4800	14700							
4		7500	4800	0		7500			2700			
5		4800	14700		0		4800					
6				7500		0		4800		2700		
7					4800		0					
8						4800		0		4800		
9				2700					0		2700	
10						2700		4800		0		4800
11									2700		0	
12										4800		0

Appendix F: Twenty- department case study (multi-period)

Table F.1. Area requirements for multi-period case study

department	Area (m^2)	Length (m)	Width (m)	department	Area (m^2)	Length (m)	Width (m)
1	100	10	10	11	200	10	20
2	200	10	20	12	200	10	20
3	200	10	20	13	400	20	20
4	200	10	20	14	100	10	10
5	200	10	20	15	400	20	20
6	400	20	20	16	100	10	10
7	100	10	10	17	200	10	20
8	400	20	20	18	100	10	10
9	100	10	10	19	200	10	20
10	600	20	30	20	100	10	10

Table F.2. From to chart showing PDF values for twenty-department multi-period case study (first period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		60																	
2		0		370	130								150							
3	60		0	60	160															
4		370	60	0		370			60											
5		130	160		0	160	130													
6				370	160	0		240		130			160							
7					130		0						70							
8						240		0		240										
9				60					0		108				60					
10						130		240		0		40								
11									108		0		108							
12										40		0		40						
13		150				160	70				108		0		70		108	150		160
14												40		0		40				
15									60				70		0	40				
16														40	40	0				
17													108				0		108	
18													150					0		
19																	108		0	
20													160							0

Table F.3. From to chart showing PDF values for twenty-department multi-period case study (second period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		150																	
2		0		320	275								145							
3	150		0	150	145															
4		320	150	0		320			150											
5		275	145		0	145	275													
6				320	145	0		230		90			145							
7					275		0						120							
8						230		0		230										
9				150					0		110				150					
10						90		230		0		80								
11									110		0		110							
12										80		0		80						
13		145				145	120				110		0		120		110	145		145
14												80		0		80				
15									150				120		0	60				
16														80	60	0				
17													110				0		110	
18													145					0		
19																	110		0	
20													145							0

Table F.4. From to chart showing PDF values for twenty-department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		100																	
2		0		340	370								190							
3	100		0	100	140															
4		340	100	0		340			100											
5		370	140		0	140	370													
6				340	140	0		195		45			140							
7					370		0						200							
8						195		0		195										
9				100					0		130				100					
10						45		195		0		390								
11									130		0		130							
12										390		0		390						
13		190				140	200				130		0		200		130	190		140
14												390		0		390				
15									100				200		0	100				
16														390	100	0				
17													130				0		130	
18													190					0		
19																	130		0	
20													140							0

Table F.5. From to chart showing mean values for twenty-department multi-period case study (first period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		50																	
2		0		300	100								150							
3	50		0	50	150															
4		300	50	0		300			50											
5		100	150		0	150	100													
6				300	150	0		200		100			150							
7					100		0						50							
8						200		0		200										
9				50					0		250				50					
10						100		200		0		50								
11									250		0		250							
12										50		0		50						
13		150				150	50				250		0		50		250	150		150
14												50		0		50				
15									50				50		0	25				
16														50	25	0				
17													250				0		250	
18													150					0		
19																	250		0	
20													150							0

Table F.6. From to chart showing mean values for twenty-department multi-period case study (second period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		75																	
2		0		260	275								150							
3	75		0	75	150															
4		260	75	0		260			75											
5		275	150		0	150	275													
6				260	150	0		200		60			150							
7					275		0						100							
8						200		0		200										
9				75					0		100				75					
10						60		200		0		80								
11									100		0		100							
12										80		0		80						
13		150				150	100				100		0		100		100	150		150
14												80		0		80				
15									75				100		0	50				
16														80	50	0				
17													100				0		100	
18													150					0		
19																	100		0	
20													150							0

Table F.7. From to chart showing mean values for twenty-department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		85																	
2		0		250	225								150							
3	85		0	85	150															
4		250	85	0		250			85											
5		225	150		0	150	225													
6				250	150	0		200		50			150							
7					225		0						150							
8						200		0		200										
9				85					0		100				85					
10						50		200		0		320								
11									100		0		100							
12										320		0		320						
13		150				150	150				100		0		150		100	150		150
14												320		0		320				
15									85				150		0	75				
16														320	75	0				
17													100				0		100	
18													150					0		
19																	100		0	
20													150							0

Table F.8. From to chart showing mean values for twenty-department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		70																	
2		0		270	200								150							
3	70		0	70	150															
4		270	70	0		270			70											
5		200	150		0	150	200													
6				270	150	0		200		70			150							
7					200		0						100							
8						200		0		200										
9				70					0		150				70					
10						70		200		0		150								
11									150		0		150							
12										150		0		150						
13		150				150	100				150		0		100		150	150		150
14												150		0		150				
15									70				100		0	50				
16														150	50	0				
17													150				0		150	
18													150					0		
19																	150		0	
20													150							0

Table F.9. From to chart showing PDF values for twenty-department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		103																	
2		0		310	258								162							
3	103		0	103	148															
4		310	103	0		310			103											
5		258	148		0	148	258													
6				310	148	0		222		88			148							
7					258		0						130							
8						222		0		222										
9				103					0		116				103					
10						88		222		0		170								
11									116		0		116							
12										170		0		170						
13		162				148	130				116		0		130		116	162		148
14												170		0		170				
15									103				130		0	67				
16														170	67	0				
17													116				0		116	
18													162					0		
19																	116		0	
20													148							0

Table F.10. From to chart showing variances values for twenty-department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0		900																	
2		0		2500	3600								1600							
3	900		0	900	1600															
4		2500	900	0		2500			900											
5		3600	1600		0	1600	3600													
6				2500	1600	0		1600		900			1600							
7					3600		0						369							
8						1600		0		1600										
9				900					0		900				900					
10						900		1600		0		1600								
11									900		0		900							
12										1600		0		1600						
13		1600				1600	369				900		0		369		900	1600		1600
14												1600		0		1600				
15									900				369		0	225				
16														1600	225	0				
17													900				0		900	
18													1600					0		
19																	900		0	
20													1600							0

Appendix G: Thirty- department case study (multi-period)

Table G.1. Area requirements for thirty-department case study (multi-period)

department	Area (m^2)	Length (m)	Width (m)	department	Area (m^2)	Length (m)	Width (m)
1	100	10	10	16	200	10	20
2	200	10	20	17	200	10	20
3	200	10	20	18	200	10	20
4	200	10	20	19	400	20	20
5	200	10	20	20	900	30	30
6	200	10	20	21	400	20	20
7	200	10	20	22	100	10	10
8	200	10	20	23	100	10	10
9	100	10	10	24	100	10	10
10	200	10	20	25	200	10	20
11	200	10	20	26	100	10	10
12	200	10	20	27	100	10	10
13	200	10	20	28	100	10	10
14	100	10	10	29	100	10	10
15	200	10	20	30	100	10	10

Table G.2.From to chart showing PDF values for thirty- department multi-period case study (first period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		60																											60
2		0		350	110								175																	
3	60		0	60	186																									
4		350	60	0		350			60																					
5		110	186		0	186	110																							
6				350	186	0		250		100			186																	
7					110		0						50																	55
8						250		0		250																				
9				60					0		130				60															
10						100		250		0		30																		
11									130		0		130																	
12										30		0		30																
13		175				186	50				130		0		50		130	175		186										
14												30		0		30							100							
15									60				50		0	30														
16														30	30	0		260												
17													130				0		130											
18													175			260		0		260										
19																	130		0		130									
20													186					260		0		260								
21																			130		0									
22																				260		0								
23														100									0		100					
24																								0		205				
25																							100		0		140	50		
26																								205		0		205		
27																									140		0		140	
28																									50	205		0		205
29																											140		0	
30	60						55																					205		0

Table G.3. From to chart showing PDF values for thirty- department multi-period case study (second period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		50																											600
2		0		500	250								50																	
3	50		0	50	150																									
4		500	50	0		500			50																					
5		250	150		0	150	250																							
6				500	150	0		300		200			150																	
7					250		0						50																	50
8						300		0		300																				
9				50					0		100				50															
10						200		300		0		50																		
11									100		0		100																	
12										50		0		50																
13		50				150	50				100		0		50		100	50		150										
14												50		0		50							700							
15									50				50		0	25														
16														50	25	0		500												
17													100				0		100											
18													50			500		0		500										
19																	100		0		100									
20													150					500		0		500								
21																			100		0									
22																				500		0								
23														700									0		700					
24																								0		200				
25																							700		0		450	100		
26																								200		0		200		
27																									450		0		450	
28																									100	200		0		200
29																											450		0	
30	600						50																					200		0

Table G.4. From to chart showing PDF values for thirty- department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		50																											510
2		0		580	370								190																	
3	50		0	50	150																									
4		580	50	0		580			50																					
5		370	150		0	150	370																							
6				580	150	0		320		260			150																	
7					370		0						80																	100
8						320		0		320																				
9				50					0		190				50															
10						260		320		0		80																		
11									190		0		190																	
12										80		0		80																
13		190				150	80				190		0		80		190	190		150										
14												80		0		80							100							
15									50				80		0	40														
16														80	40	0		650												
17													190				0		190											
18													190			650		0		650										
19																	190		0		190									
20													150					650		0		650								
21																			190		0									
22																				650		0								
23														100									0		100					
24																								0		230				
25																							100		0		850	50		
26																								230		0		230		
27																									850		0		850	
28																									50	230		0		230
29																											850		0	
30	510						100																					230		0

Table G.5. From to chart showing mean values for thirty- department multi-period case study (first period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		55																											400
2		0		300	100								153																	
3	55		0	55	150																									
4		300	55	0		300			55																					
5		100	150		0	150	100																							
6				300	150	0		200		100			150																	
7					100		0						50																	50
8						200		0		200																				
9				55					0		100				55															
10						100		200		0		25																		
11									100		0		100																	
12										25		0		25																
13		153				150	50				100		0		50		100	153		150										
14												25		0		25							100							
15									55				50		0	25														
16														25	25	0		200												
17													100				0		100											
18													153			200		0		200										
19																	100		0		100									
20													150					200		0		200								
21																			100		0									
22																				200		0								
23														100									0		100					
24																								0		400				
25																							100		0		150	50		
26																								400		0		400		
27																									150		0		150	
28																									50	400		0		400
29																											150		0	
30	400						50																					400		0

Table G.6. From to chart showing mean values for thirty- department multi-period case study (second period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		58																											475
2		0		500	250								200																	
3	58		0	58	150																									
4		500	58	0		500			58																					
5		250	150		0	150	250																							
6				500	150	0		300		200			150																	
7					250		0						50																	50
8						300		0		300																				
9				58					0		100				58															
10						200		300		0		40																		
11									100		0		100																	
12										40		0		40																
13		200				150	50				100		0		50		100	200		150										
14												40		0		40							700							
15									58				50		0	25														
16														40	25	0		480												
17													100				0		100											
18													200			480		0		480										
19																	100		0		100									
20													150					480		0		480								
21																			100		0									
22																				480		0								
23														700									0		700					
24																								0		200				
25																							700		0		440	100		
26																								200		0		200		
27																									440		0		440	
28																									100	200		0		200
29																											440		0	
30	475						50																					200		0

Table G.7. From to chart showing mean values for thirty- department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		62																											1000
2		0		560	370								220																	
3	62		0	62	150																									
4		560	62	0		560			62																					
5		370	150		0	150	370																							
6				560	150	0		300		260			150																	
7					370		0						80																	100
8						300		0		300																				
9				62					0		130				62															
10						260		300		0		50																		
11									130		0		130																	
12										50		0		50																
13		220				150	80				130		0		80		130	220		150										
14												50		0		50							100							
15									62				80		0	40														
16														50	40	0		510												
17													130				0		130											
18													220			510		0		510										
19																	130		0		130									
20													150					510		0		510								
21																			130		0									
22																				510		0								
23														100									0		100					
24																								0		225				
25																							100		0		610	50		
26																								225		0		225		
27																									610		0		610	
28																									50	225		0		225
29																											610		0	
30	1000						100																					225		0

Table G.8. From to chart showing PDF values for thirty- department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		53																											390
2		0		477	243								138																	
3	53		0	138	162																									
4		477	138	0		477			53																					
5		243	162		0	162	243																							
6				477	162	0		290		187			162																	
7					243		0						60																	68
8						290		0		290																				
9				53					0		140				53															
10						187		290		0		53																		
11									140		0		140																	
12										53		0		53																
13		138				162	60				140		0		60		140	138		162										
14												53		0		53							300							
15									53				60		0	32														
16														53	32	0		470												
17													140				0		140											
18													138			470		0		470										
19																	140		0		140									
20													162					470		0		470								
21																			140		0									
22																				470		0								
23														300									0		300					
24																								0		212				
25																							300		0		480	67		
26																								212		0		212		
27																									480		0		480	
28																									67	212		0		212
29																											480		0	
30	390						68																					212		0

Table G.9. From to chart showing mean values for thirty- department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		50																											625
2		0		454	240								190																	
3	50		0	50	150																									
4		454	50	0		454			50																					
5		240	150		0	150	240																							
6				454	150	0		267		187			150																	
7					240		0						60																	67
8						267		0		267																				
9				50					0		110				50															
10						187		267		0		40																		
11									110		0		110																	
12										40		0		40																
13		190				150	60				110		0		60		110	190		150										
14												40		0		40							300							
15									50				60		0	30														
16														40	30	0		397												
17													110				0		110											
18													190			397		0		397										
19																	110		0		110									
20													150					397		0		397								
21																			110		0									
22																				397		0								
23														300									0		300					
24																								0		275				
25																							300		0		400	67		
26																								275		0		275		
27																									400		0		400	
28																									67	275		0		275
29																											400		0	
30	625						67																					275		0

Table G.9. From to chart showing variance values for thirty- department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		179																											75208
2		0		7400	1156								4033																	
3	179		0	179	1067																									
4		7400	179	0		7400			179																					
5		1156	1067		0	1067	1156																							
6				7400	1067	0		4900		2500			1067																	
7					1156		0						100																	256
8						4900		0		4900																				
9				179					0		1633				179															
10						2500		4900		0		300																		
11									1633		0		1633																	
12										300		0		300																
13		4033				1067	100				1633		0		100		1633	4033		1067										
14												300		0		300							2900							
15									179				100		0	64														
16														300	64	0		10006												
17													1633				0		1633											
18													4033			10006		0		10006										
19																	1633		0		1633									
20													1067					10006		0		10006								
21																			1633		0									
22																				10006		0								
23														2900									0		2900					
24																								0		5208				
25																							2900		0		10417	196		
26																								5208		0		5208		
27																									10417		0		10417	
28																									196	5208		0		5208
29																											10417		0	
30	75208						256																							0

Appendix H: Thirty- department case study (robust layout against stable layout)

Table H.1. Area requirements for thirty-department case study (multi-period)

department	Area (m^2)	Length (m)	Width (m)	department	Area (m^2)	Length (m)	Width (m)
1	100	10	10	16	200	10	20
2	200	10	20	17	200	10	20
3	200	10	20	18	200	10	20
4	200	10	20	19	400	20	20
5	200	10	20	20	900	30	30
6	200	10	20	21	400	20	20
7	200	10	20	22	100	10	10
8	200	10	20	23	100	10	10
9	100	10	10	24	100	10	10
10	200	10	20	25	200	10	20
11	200	10	20	26	100	10	10
12	200	10	20	27	100	10	10
13	200	10	20	28	100	10	10
14	100	10	10	29	100	10	10
15	200	10	20	30	100	10	10

Table H.2. From to chart showing PDF values for thirty- department multi-period case study (first period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		500																											8000
2		0		3000	1000								2000																	
3	500		0	500	1500																									
4		3000	500	0		3000			500																					
5		1000	1500		0	1500	1000																							
6				3000	1500	0		2000		1000			1500																	
7					1000		0						500																	500
8						2000		0		2000																				
9				500					0		1500				500															
10						1000		2000		0		500																		
11									1500		0		1500																	
12										500		0		500																
13		2000				1500	500				1500		0		500		1500	2000		1500										
14												500		0		500							1000							
15									500				500		0	300														
16														500	300	0		5000												
17													1500				0		1500											
18													2000			5000		0		5000										
19																	1500		0		1500									
20													1500					5000		0		5000								
21																			1500		0									
22																				5000		0								
23														1000									0		1000					
24																								0		1800				
25																							1000		0		3500	500		
26																								1800		0		1800		
27																									3500		0		3500	
28																									500	1800		0		1800
29																											3500		0	
30	8000						500																					1800		0

Table H.3. From to chart showing PDF values for thirty- department multi-period case study (second period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		550																											4000
2		0		3000	1000								1530																	
3	550		0	550	1500																									
4		3000	550	0		3000			550																					
5		1000	1500		0	1500	1000																							
6				3000	1500	0		2000		1000			1500																	
7					1000		0						500																	500
8						2000		0		2000																				
9				550					0		1000				550															
10						1000		2000		0		250																		
11									1000		0		1000																	
12										250		0		250																
13		1530				1500	500				1000		0		500		1000	1530		1500										
14												250		0		250							1000							
15									550				500		0	250														
16														250	250	0		2000												
17													1000				0		1000											
18													1530			2000		0		2000										
19																	1000		0		1000									
20													1500					2000		0		2000								
21																			1000		0									
22																				2000		0								
23														1000									0		1000					
24																								0		2000				
25																							1000		0		1500	500		
26																								2000		0		2000		
27																									1500		0		1500	
28																									500	2000		0		2000
29																											1500		0	
30	4000						500																					2000		0

Table H.4. From to chart showing PDF values for thirty- department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		500																											2600
2		0		3500	2500								1500																	
3	500		0	500	1500																									
4		3500	500	0		3500			500																					
5		2500	1500		0	1500	2500																							
6				3500	1500	0		2500		1000			1500																	
7					2500		0						500																	500
8						2500		0		2500																				
9				500					0		1800				500															
10						1000		2500		0		450																		
11									1800		0		1800																	
12										450		0		450																
13		1500				1500	500				1800		0		500		1800	1500		1500										
14												450		0		450							7000							
15									500				500		0	250														
16														450	250	0		8600												
17													1800				0		1800											
18													1500			8600		0		8600										
19																	1800		0		1800									
20													1500					8600		0		8600								
21																			1800		0									
22																				8600		0								
23														7000									0		7000					
24																								0		2000				
25																							7000		0		8400	1000		
26																								2000		0		2000		
27																									8400		0		8400	
28																									1000	2000		0		2000
29																											8400		0	
30	2600						500																					2000		0

Table H.5. From to chart showing PDF values for thirty- department multi-period case study (fourth period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		580																											4750
2		0		5000	2500								2000																	
3	580		0	580	1500																									
4		5000	580	0		5000			580																					
5		2500	1500		0	1500	2500																							
6				5000	1500	0		3000		2000			1500																	
7					2500		0						500																	500
8						3000		0		3000																				
9				580					0		1000				580															
10						2000		3000		0		450																		
11									1000		0		1000																	
12										450		0		450																
13		2000				1500	500				1000		0		500		1000	2000		1500										
14												450		0		450							7000							
15									580				500		0	250														
16														450	250	0		1000												
17													1000				0		1000											
18													2000			1000		0		1000										
19																	1000		0		1000									
20													1500					1000		0		1000								
21																			1000		0									
22																				1000		0								
23														7000									0		7000					
24																								0		2000				
25																							7000		0		6400	1000		
26																								2000		0		2000		
27																									6400		0		6400	
28																									1000	2000		0		2000
29																											6400		0	
30	4750						500																					2000		0

Table H.6. From to chart showing PDF values for thirty- department multi-period case study (fifth period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		1100																											300
2		0		2000	4000								1500																	
3	1100		0	1100	1500																									
4		2000	1100	0		2000			1100																					
5		4000	1500		0	1500	4000																							
6				2000	1500	0		1500		500			1500																	
7					4000		0						800																	1000
8						1500		0		1500																				
9				1100					0		1300				1100															
10						500		1500		0		500																		
11									1300		0		1300																	
12										500		0		500																
13		1500				1500	800				1300		0		800		1300	1500		1500										
14												500		0		500							1000							
15									1100				800		0	400														
16														500	400	0		5000												
17													1300				0		1300											
18													1500			5000		0		5000										
19																	1300		0		1300									
20													1500					5000		0		5000								
21																			1300		0									
22																				5000		0								
23														1000									0		1000					
24																								0		3100				
25																							1000		0		2500	500		
26																								3100		0		3100		
27																									2500		0		2500	
28																									500	3100		0		3100
29																											2500		0	
30	300						1000																					3100		0

Table H.7. From to chart showing PDF values for thirty- department multi-period case study (sixth period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		520																											10000
2		0		5600	3700								2200																	
3	520		0	520	1500																									
4		5600	520	0		5600			520																					
5		3700	1500		0	1500	3700																							
6				5600	1500	0		3000		2600			1500																	
7					3700		0						800																	1000
8						3000		0		3000																				
9				520					0		1300				520															
10						2600		3000		0		500																		
11									1300		0		1300																	
12										500		0		500																
13		2200				1500	800				1300		0		800		1300	2200		1500										
14												500		0		500							1000							
15									520				800		0	400														
16														500	400	0		5100												
17													1300				0		1300											
18													2200			5100		0		5100										
19																	1300		0		1300									
20													1500					5100		0		5100								
21																			1300		0									
22																				5100		0								
23														1000									0		1000					
24																								0		2250				
25																							1000		0		6100	500		
26																								2250		0		2250		
27																									6100		0		6100	
28																									500	2250		0		2250
29																											6100		0	
30	10000						1000																					2250		0

Table H.8. From to chart showing mean values for thirty- department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		625																											4942
2		0		3683	2450								1488																	
3	625		0	625	1500																									
4		3683	625	0		3683			625																					
5		2450	1500		0	1500	2450																							
6				3683	1500	0		2333		1350			1500																	
7					2450		0						600																	667
8						2333		0		2333																				
9				625					0		1317				625															
10						1350		2333		0		442																		
11									1317		0		1317																	
12										442		0		442																
13		1488				1500	600				1317		0		600		1317	1488		1500										
14												442		0		442							3000							
15									625				600		0	308														
16														442	308	0		3700												
17													1317				0		1317											
18													1488			3700		0		3700										
19																	1317		0		1317									
20													1500					3700		0		3700								
21																			1317		0									
22																				3700		0								
23														3000									0		3000					
24																								0		2191				
25																							3000		0		4733	667		
26																								2191		0		2191		
27																									4733		0		4733	
28																									667	2191		0		2191
29																											4733		0	
30	4942						667																					2191		0

Table H.9. From to chart showing variance values for thirty- department multi-period case study (all periods)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		791																											11428
2		0		5308	1635								3492																	
3	791		0	791	1513																									
4		5308	791	0		5308			791																					
5		1635	1513		0	1513	1635																							
6				5308	1513	0		3800		1508			1513																	
7					1635		0						100																	186
8						3800		0		3800																				
9				791					0		1697				791															
10						1508		3800		0		231																		
11									1697		0		1697																	
12										231		0		231																
13		3492				1513	100				1697		0		100		1697	3492		1513										
14												231		0		231							7291							
15									791				100		0	64														
16														231	64	0		4683												
17													1697				0		1697											
18													3492			4683		0		4683										
19																	1697		0		1697									
20													1513					4683		0		4683								
21																			1697		0									
22																				4683		0								
23														7291									0		7291					
24																								0		5270				
25																							7291		0		24791	232		
26																								5270		0		5270		
27																									24791		0		24791	
28																									232	5270		0		5270
29																											24791		0	
30	11428						186																					5270		0

Table H.10. From to chart showing variance values for thirty- department multi-period case study (first period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		1599																											20001
2		0		12675	300								75																	
3	1599		0	1599	7200																									
4		12675	1599	0		12675			1599																					
5		300	7200		0	7200	300																							
6				12675	7200	0		10800		1875			7200																	
7					300		0						300																	108
8						10800		0		10800																				
9				1599					0		5001				1599															
10						1875		10800		0		399																		
11									5001		0		5001																	
12										399		0		399																
13		75				7200	300				5001		0		300		5001	75		7200										
14												399		0		399							300							
15									1599				300		0	192														
16														399	192	0		900												
17													5001				0		5001											
18													75			900		0		900										
19																	5001		0		5001									
20													7200					900		0		900								
21																			5001		0									
22																				900		0								
23														300									0		300					
24																								0		6051				
25																							300		0		62499	108		
26																								6051		0		6051		
27																									62499		0		62499	
28																									108	6051		0		6051
29																											62499		0	
30	20001						108																					6051		0

Table H.11. From to chart showing variance values for thirty- department multi-period case study (second period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		537																											122499
2		0		8700	300								3444																	
3	537		0	537	4050																									
4		8700	537	0		8700			537																					
5		300	4050		0	4050	300																							
6				8700	4050	0		7500		1200			4050																	
7					300		0						300																	108
8						7500		0		7500																				
9				537					0		3600				537															
10						1200		7500		0		225																		
11									3600		0		3600																	
12										225		0		225																
13		3444				4050	300				3600		0		300		3600	3444		4050										
14												225		0		225							300							
15									537				300		0	192														
16														225	192	0		5001												
17													3600				0		3600											
18													3444			5001		0		5001										
19																	3600		0		3600									
20													4050					5001		0		5001								
21																			3600		0									
22																				5001		0								
23														300									0		300					
24																								0		9999				
25																							300		0		4050	108		
26																								9999		0		9999		
27																									4050		0		4050	
28																									108	9999		0		9999
29																											4050		0	
30	122499						108																					9999		0

Table H.12. From to chart showing variance values for thirty- department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		99																											20001
2		0		8175	11100								16899																	
3	99		0	99	2499																									
4		8175	99	0		8175			99																					
5		11100	2499		0	2499	11100																							
6				8175	2499	0		7500		675			2499																	
7					11100		0						300																	300
8						7500		0		7500																				
9				99					0		8451				99															
10						675		7500		0		312																		
11									8451		0		8451																	
12										312		0		312																
13		16899				2499	300				8451		0		300		8451	16899		2499										
14												312		0		312							69375							
15									99				300		0	192														
16														312	192	0		12801												
17													8451				0		8451											
18													16899			12801		0		12801										
19																	8451		0		8451									
20													2499					12801		0		12801								
21																			8451		0									
22																				12801		0								
23														69375									0		69375					
24																								0		16899				
25																							69375		0		28800	1875		
26																								16899		0		16899		
27																									28800		0		28800	
28																									1875	16899		0		16899
29																											28800		0	
30	20001						300																					16899		0

Table H.13. From to chart showing variance values for thirty- department multi-period case study (third period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		2304																											37812
2		0		18300	5724								25599																	
3	2304		0	2304	5001																									
4		18300	2304	0		18300			2304																					
5		5724	5001		0	5001	5724																							
6				18300	5001	0		10800		7500			5001																	
7					5724		0						300																	432
8						10800		0		10800																				
9				2304					0		3600				2304															
10						7500		10800		0		1224																		
11									3600		0		3600																	
12										1224		0		1224																
13		25599				5001	300				3600		0		300		3600	25599		5001										
14												1224		0		1224							60675							
15									2304				300		0	192														
16														1224	192	0		6399												
17													3600				0		3600											
18													25599			6399		0		6399										
19																	3600		0		3600									
20													5001					6399		0		6399								
21																			3600		0									
22																				6399		0								
23														60675									0		60675					
24																								0		9999				
25																							60675		0		291600	1875		
26																								9999		0		9999		
27																									3E+05		0		291600	
28																									1875	9999		0		9999
29																											291600		0	
30	37812						432																					9999		0

Table H.14. From to chart showing variance values for thirty- department multi-period case study (fifth period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		7398																											399
2		0		8700	6000								2448																	
3	7398		0	7398	6048																									
4		8700	7398	0		8700			7398																					
5		6000	6048		0	6048	6000																							
6				8700	6048	0		7500		1200			6048																	
7					6000		0						300																	1200
8						7500		0		7500																				
9				7398					0		1800				7398															
10						1200		7500		0		399																		
11									1800		0		1800																	
12										399		0		399																
13		2448				6048	300				1800		0		300		1800	2448		6048										
14												399		0		399							300							
15									7398				300		0	192														
16														399	192	0		19998												
17													1800				0		1800											
18													2448			19998		0		19998										
19																	1800		0		1800									
20													6048					19998		0		19998								
21																			1800		0									
22																				19998		0								
23														300									0		300					
24																								0		44100				
25																							300		0		11250	108		
26																								44100		0		44100		
27																									11250		0		11250	
28																									108	44100		0		44100
29																											11250		0	
30	399						1200																							0

Table H.15. From to chart showing variance values for thirty- department multi-period case study (sixth period)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	0		2304																											5001
2		0		39000	6000								14400																	
3	2304		0	2304	2448																									
4		39000	2304	0		39000			2304																					
5		6000	2448		0	2448	6000																							
6				39000	2448	0		24300		14700			2448																	
7					6000		0						300																	1200
8						24300		0		24300																				
9				2304					0		8100				2304															
10						14700		24300		0		1599																		
11									8100		0		8100																	
12										1599		0		1599																
13		14400				2448	300				8100		0		300		8100	14400		2448										
14												1599		0		1599							300							
15									2304				300		0	192														
16														1599	192	0		3921												
17													8100				0		8100											
18													14400			3921		0		3921										
19																	8100		0		8100									
20													2448					3921		0		3921								
21																			8100		0									
22																				3921		0								
23														300									0		300					
24																								0		7812				
25																							300		0		48051	108		
26																								7812		0		7812		
27																									48051		0		48051	
28																									108	7812		0		7812
29																										48051			0	
30	5001						1200																							0

Appendix I: Input data and computation results for Rosenblatt and Kropp's (1992) problem

Table I.1. Rosenblatt and Kropp (1992)'s from to charts with probability P=0.3 and P=0.1

		1	2	3	4	5	6			1	2	3	4	5	6
	1		63	605	551	116	136		1		175	804	904	56	176
	2	63		635	941	50	191		2	63		734	936	54	177
P=0.3	3	104	71		569	136	55	P=.01	3	168	85		918	138	134
	4	65	193	622		77	90		4	51	94	962		173	39
	5	162	174	607	591		179		5	97	104	730	634		144
	6	156	13	667	611	175			6	95	115	983	597	24	

Table I.2. Rosenblatt and Kropp (1992)'s from to chart with probability P=.05and P=.015

		1	2	3	4	5	6			1	2	3	4	5	6
	1		90	77	553	769	139		1		112	15	199	665	649
	2	168		114	653	525	185		2	153		116	173	912	671
P=.05	3	32	35		664	898	87	P=0.15	3	10	28		182	855	542
	4	27	166	42		960	179		4	29	69	15		552	751
	5	185	56	44	926		104		5	198	71	42	24		758
	6	72	128	173	634	687			6	62	109	170	90	973	

Table I.3. Rosenblatt and Kropp (1992)'s from to chart with probability P=0.4

		1	2	3	4	5	6
	1		663	23	128	119	50
	2	820		5	98	141	66
P=0.4	3	822	650		137	78	91
	4	826	570	149		93	151
	5	915	515	53	35		177
	6	614	729	178	10	99	

Table I.4. Rosenblatt and Kropp (1992)'s $\overline{F} = \sum_{s=1}^{S} P_s \; F_s =$

	1	2	3	4	5	6
1	c	322.9	277.2	364.4	226.2	182.7
2	384.55		289	473.7	239.9	211.3
3	379.9	295.75		377.8	259	151.95
4	360.7	313.95	346.75		208.4	212.9
5	463.25	282.05	284.8	304.6		257.8
6	314.8	329.75	403.75	292.2	274.8	

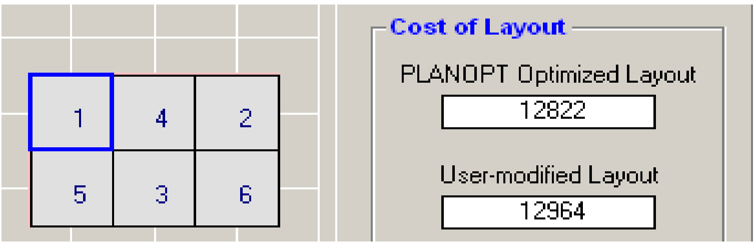


Fig.I.1. Material handling cost of using Layout 2 in state 1.

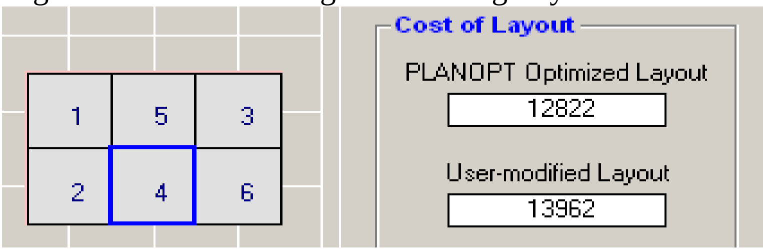


Fig.I.2. Material handling cost of using Layout 3 in state1.

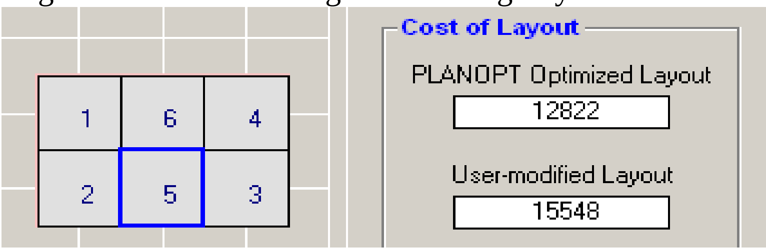


Fig.I.3. Material handling cost of using Layout 4 in state 1.

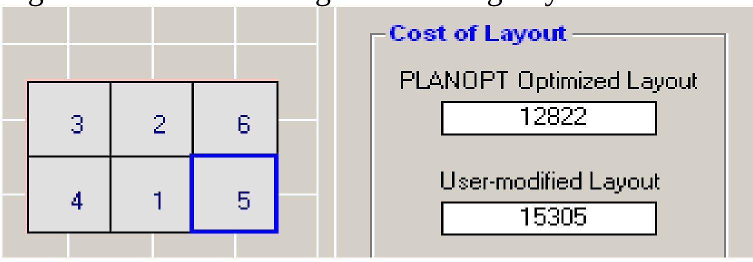


Fig.I.4. Material handling cost of using Layout 5 in state 1.

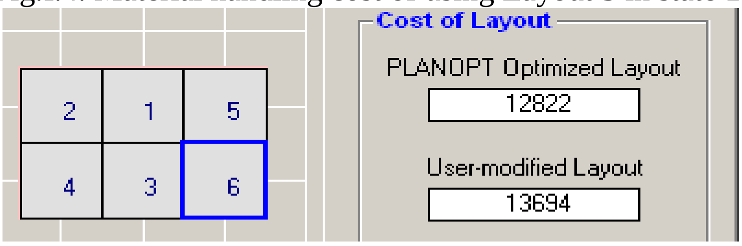


Fig.I.5. Material handling cost of using Layout $\overline{F}$ in state 1.

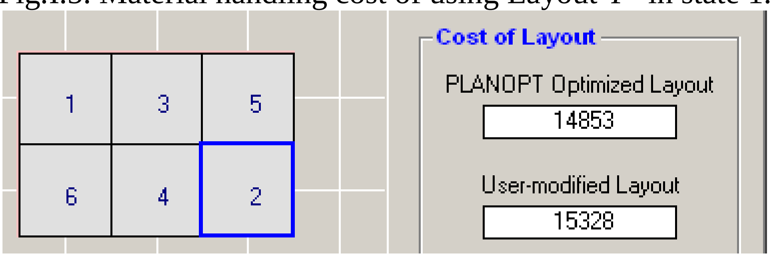


Fig.I.6. Material handling cost of using Layout 1 in state 2.

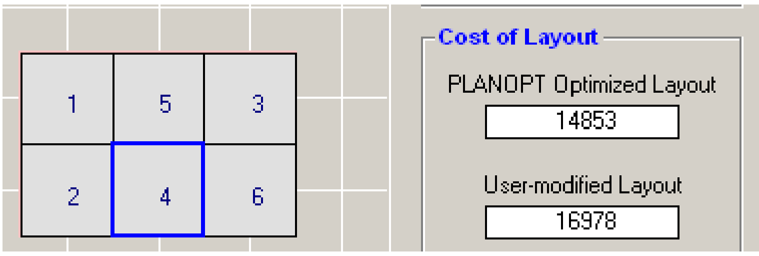


Fig.I.7. Material handling cost of using Layout 3 in state 2.

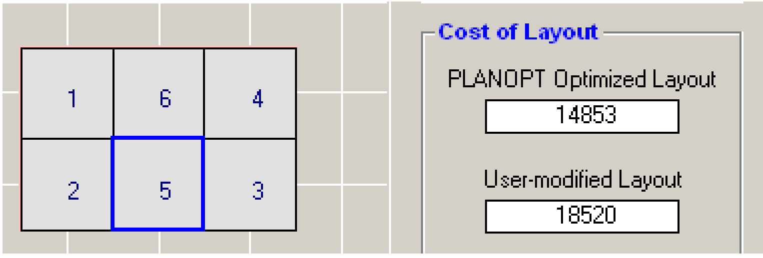


Fig.I.8. Material handling cost of using Layout 4 in state 2.

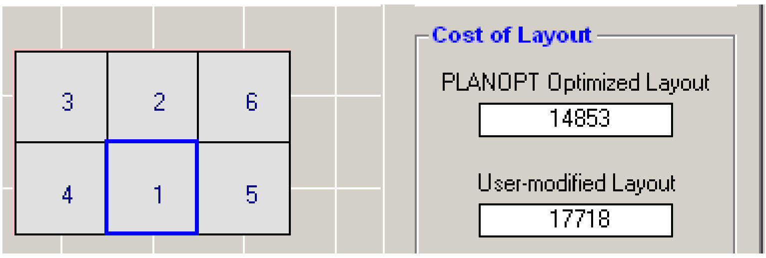


Fig.I.9. Material handling cost of using Layout 5 in state 2.

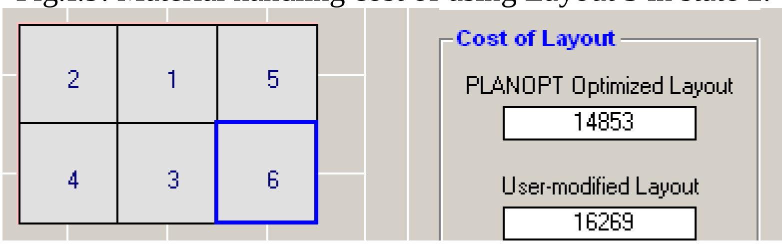


Fig.I.10. Material handling cost of using Layout $\overline{F}$ in state 2

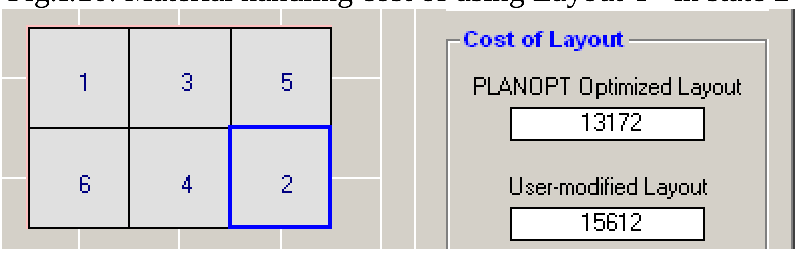


Fig.I.11. Material handling cost of using Layout 1 in state 3.

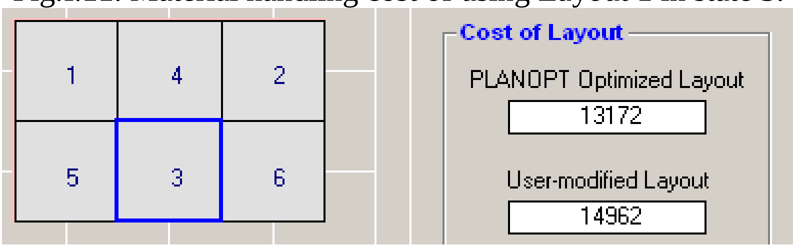


Fig.I.12. Material handling cost of using Layout 2 in state 3.

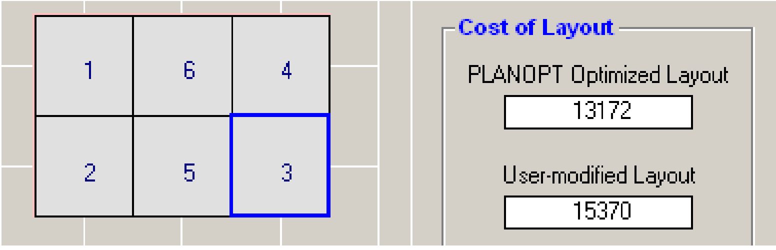


Fig.I.13. Material handling cost of using Layout 4 in state 3.

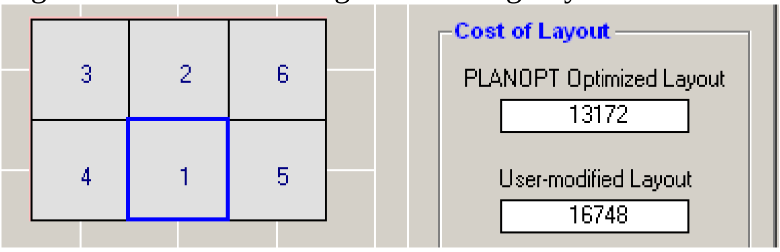


Fig.I.14. Material handling cost of using Layout 5 in state 3.

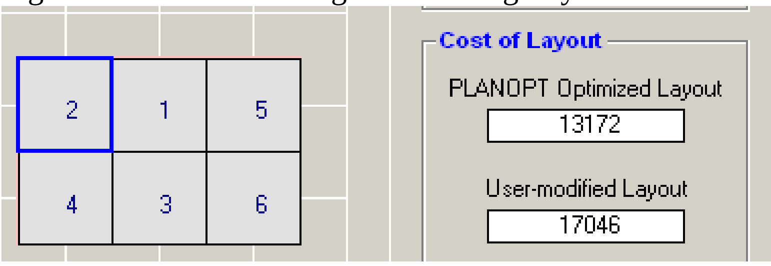


Fig.I.15. Material handling cost of using Layout $\overline{F}$ in state 3.

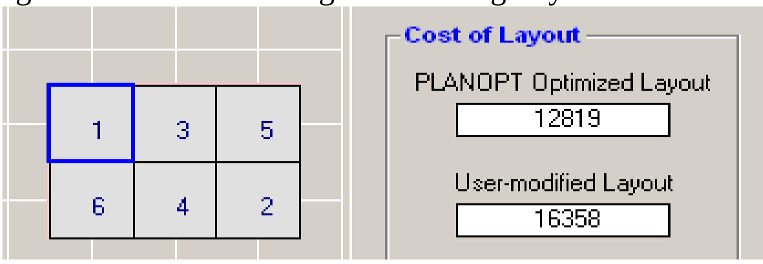


Fig.I.16. Material handling cost of using Layout 1 in state 4.

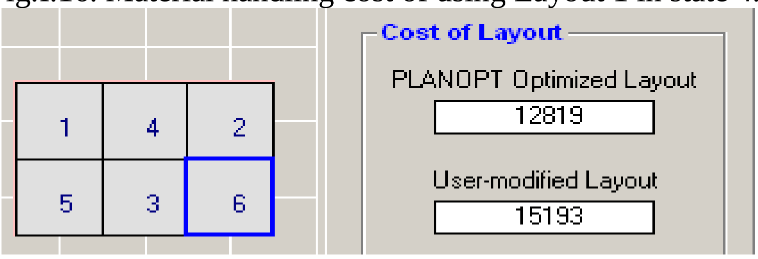


Fig.I.17. Material handling cost of using Layout 2 in state 4.

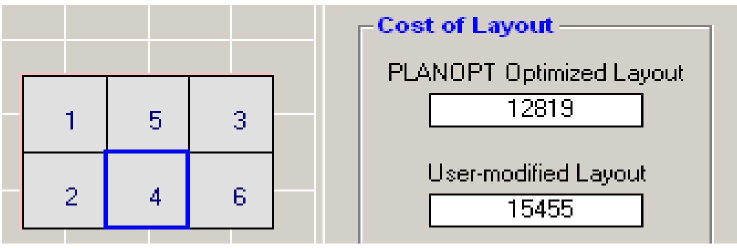


Fig.J.18. Material handling cost of using Layout 3 in state 4.