DESIGN OF DYNAMIC FACILITY LAYOUTS UNDER PRODUCTION AND MATERIAL HANDLING CAPACITY CONSTRAINTS

A Dissertation by

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DEDICATION

To my son, wife, and parents
for their unconditional love and support

Satisfaction lies in the effort, not in attainment,
full effort is full victory.

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ABSTRACT

For a manufacturing facility to be competitive in today's market driven conditions, it is inevitable that it meet the market's demand with optimal resources within the required time. Resources and its utilization can be limited by logistic constraints, such as facility layout and material handling, and production constraints, such as machine capacity and type of machines. Research until now has focused on addressing demand requirements under static and dynamic conditions. However, facility layout approaches have assumed infinite capacities for the production system in determining the layout. In addition, facility layout research does not consider material handling capacity consideration in determining feasibility and adaptability of layout. This study conducts research on addressing dynamic facility layout designs in which the demand varies from one time period to the next while taking into consideration finite capacity constraints for both the logistics (facility layout and material handling system) and production systems (machine capacities-operational limitations).

The research used a genetic algorithm and CRAFT program to develop the facility layout for each time period. Simulation studies are conducted for the developed layout to determine if demand can be met for the given time period in Chapter 2. The research also develops functions that can be used to evaluate the costs of changes in the parameters, such as increased production capacity, increased material handling capacity, or a combination of both parameters, to meet the demand. The research also evaluates alternative sequence as a parameter considered to design a dynamic facility layout in Chapter 3. The research develops and proposes a forward pass and backward pass approach to design dynamic facility layouts in Chapter 4. The aim of this research is to minimize the cost of meeting demand over a given time period under dynamic conditions.

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LIST OF ABBREVIATIONS / NOMENCLATURE

AGV	Automated guided vehicle
CRAFT	Computerized Relative Allocation of Facilities Technique
DLP	Dynamic layout problem
DFLP	Dynamic facility layout problem
FBC	From between chart
FLP	Facility layout problem
FMS	Flexible manufacturing systems
GA	Genetic algorithm
LCS	Logistic constrained state
MHU	Material handling unit
PCS	Production constrained state
QAP	Quadratic assignment problem
RA	Rearrangement
SA	Simulated annealing
SFLP	Static facility layout problem
TS	Transition state
TV	Threshold value

CHAPTER 1

INTRODUCTION

The objective of a manufacturing facility is to fulfill customer's demands within specified times. Today's businesses are driven by market conditions and a manufacturing facility is no exception to that. For a manufacturing facility to be competitive, it is inevitable that it meets the market's demand within the required time. Besides meeting demand, it also has to be profitable. For profitability, it is important that the facility minimizes the cost associated with production, while not compromising the quality of the products demanded. Thus a manufacturing facility has to deliver a quality product in the required quantity at the right time while keeping production cost low.

Production costs can broadly be classified into two types: the *supply chain cost* and the *facility and planning cost*.

Supply chain cost: Supply chain cost can further be classified into raw material cost which consists of procurement cost of the material, and other overheads involved in procurement like warehouse cost, trucking cost, etc.

Facility and planning cost: Facility and planning cost involve costs such as labor cost, production cost, scrap cost, material handling cost, downtime/maintenance cost, facility layout cost, etc.

These categories can be generalized and classified into following major systems: production system, supply chain system, material handling system, and facility layout.

1.1 Literature Review

Material handling is a non-value added cost and the cost associated with it can be as high as 20 to 50 percent of the total operating cost (Tompkins, 2003). Engineers constantly focus on reducing non-value added cost. Material handling thus provides quite a bit of opportunity for cost cutting. A significant body of work has been done to reduce cost associated with material handling systems. Manufacturing facilities have implemented some of these research findings towards the objective of overall production cost reduction. Material handling cost depends on product demand and product mix which changes with changing demand.

Quite a bit of academic work has been done in the area of facility layout as well to ensure that the most optimal facility can be designed to meet demand. Most of the research has focused on redesigning of an existing layout or designing a new layout at the beginning of the time period. Research has focused on static layout problems which mean that product demand and product mix are static and do not change with time and the flow of material from one machine to the other can be defined by a from-to chart. The research thus failed to consider dynamicity of demand and other conditions. As the product mix and demand changes, it may render the facility layout to be inefficient as the material handling requirements change; this might necessitate a change in the layout (Afentakis, Millen and Solomon, 1990). Efforts were later made to address Dynamic Facility Layouts Problems (DFLP) which focuses on the changing product mix and demand. Krishnan, Cheraghi, and Nayak (2008) classified approaches to solving DFLP and also developed models to solve a DFLP. They also introduced the concept of Dynamic From Between charts to analyze the need for redesign when flow requirements between stations change. Several other researchers have made an attempt to solve DFLP.

Material handling system and facility layout system work hand-in-hand. As requirements of one change, requirements for the other might change. All research so far in the areas of material handling system and facility layout system has made an assumption that infinite resources are available in both systems. Another limitation as mentioned earlier is that research often assumed static conditions. Thus when a facility layout generated with those limitations is used with limited resources available of the other systems, the interaction between the systems may not result in the same output as might be suggested by theoretical work, which assume infinite capacity or constancy in the other system. In other words, the results due to interaction of all the systems working together may often lead to worse results than the predicted results.

The focus of this research is to address both the limitations. The research focuses on studying the effect of constrained material handling system and production system capacities in conjunction with facility layout under dynamic conditions. Each manufacturing facility in reality has finite capacities of material handling and production. The market conditions drive demand changes constantly from one time period to the other. This research focuses on taking these practical limitations and conditions into account to develop a dynamic facility layout with limited capacities of material handling and production system for a manufacturing facility. The research also focuses on developing a method to estimate cost of meeting demand.

1.2 Research Objectives and Proposal Outline

The research is divided into four major areas, each described in a chapter.

Each manufacturing facility has a given facility layout. It also has fixed capacities for its production system and material handling system. Both the capacities are known. With the facility layout and the with the production and material handling capacities, the manufacturing facility tries to meet demand which changes from one time period to another.

Chapter 2 evaluates effects of capacity constraints and facility layouts under dynamic conditions on demand fulfillment. The objective of this research is to develop a methodology for determining the changes needed in a facility layout or capacities of production or material handling system under dynamic demand changes from period-to-period.

A facility layout is generated using Genetic Algorithm (GA) at the beginning of the first time period. The research focuses on determining if demand can be met with the GA suggested layout along with finite and known production system and material handling system capacities. This is done by building a simulation model in QUEST with the GA suggested layout and known production system and material handling system capacities. Simulation data is collected after steady state is achieved in the system. This is ensured by adding warm-up time in the beginning of the time period. The paper utilizes the concept of state of the system introduced by Dhuttargoan, Krishnan and Shah (2014). If the simulation output indicates that demand cannot be met, the chapter provides a method and algorithm to determine the state of the system. The chapter utilizes the concepts of production constrained state (PCS), logistics constrained state (LCS), and transition state (TS). The paper introduces the concept of masking where both the material handling system and production systems are short on capacity but the shortage of capacity in one system is hidden under the capacity shortage of the other system.

The research also develops a cost function for meeting demand which includes developing equations for material handling cost, rearrangement cost, material handling capacity addition cost, and production system addition cost. The research also develops an optimal solution for meeting demand using the proposed methodology. The solution is based on cost estimation of adding capacity or changing layout design and thus rearrangement changes for the machines.

Chapter 3 introduces the effect of production sequence along with facility layout, and production system and material handling system constraints on demand fulfillment. A part requires a combination of several steps to go from its initial raw material form to it final shape and form. Production sequence is a series of operations carried out on a part to convert it from raw material form to its final shape and form. With a known set of machines available within the facility, there is a possibility that a part can be manufactured utilizing any one of multiple feasible sequences. Thus alternative sequences might be available for manufacturing the same part within the same facility. Production system requirements are a direct function of production sequences that are selected. The distance that a part has to travel to transform from raw material to its final form is also a direct function of the production sequence that is used. The distance travelled is a direct input in determining the requirements of the material handling system. Thus material handling system requirements are also a direct function of the production sequence. Thus usage of a production system and material handling system depend on the production sequence that is used for production. Often when production capacity constraints are enforced, the selected production sequence may be rendered infeasible in terms of meeting production demands. Under this condition, it is theorized that to meet demand, rather than increasing the production and material handling capacity or changing facility layout, an alternate sequence could be selected which would prevent or reduce the costs involved in rearranging the facility and the costs associated with increasing the production and material handling capacities. In other words, the selection of a production sequence has a direct bearing on the ability of the production system to meet the expected demand for a given product mix in a given time period with a given facility layout and known constraints of production system and material handling system capacities.

Chapter 3 studies the impact of alternate production sequences that could lead to reduced facility layout rearrangement cost under dynamic conditions when production system and material handling system capacity constraints are enforced. It also attempts to find an optimal solution for a production facility by considering alternative sequences as compared to adding capacities for production or material handling systems and changing facility layout using the proposed methodology. It thus builds up on Chapter 2 by adding alternate production sequence as a parameter for solving the dynamic facility layout problem.

The research thus focuses on utilizing alternative part sequencing as an approach to meeting demand instead of changing facility layout or adding more capacity to the facility. The research also develops equations for cost of meeting demand with alternative sequencing. It also focuses on finding the most optimal solution within the capacity constraints for the facility to be most profitable.

Most manufacturing industries, add machines, remove machines, introduce new products, and stop production of existing products due to part obsolescence. In a dynamic facility layout problem which is also capacity-constrained, rearrangement of some machines can be expensive. Hence in dynamic facility layout problems it is advisable to provide space for future expansion or addition of machines in future time periods. Thus, as product demands change and new products are introduced, production capacity requirements change and new machines must be introduced into the system to meet demand. To ensure that the designed facility layout satisfies future demands, a proper analysis of future needs have to be incorporated into the layout.

There are two possible approaches to increasing production capacity. It can either add a machine of comparable capacity or it can discontinue the usage of that machine and add a machine with larger capacity. If the facility decides to add a machine to supplement the existing machine, there is a decision to be made with respect to facility layout in terms of where should the new supplemental machine be located. Ideally, the machine should be located close to the existing bottleneck machine so that either of the two machines can be used to pick up the production rate. Alternatively, the machine can be placed at a different location away from the existing bottleneck machine. This location might be more demanding on the material handling system. In this research, a method using forward pass and a backward pass is developed to ensure optimal design of the facility layout. The values obtained in the forward pass can be used as the upper bound for material handling costs in the backward pass.

Chapter 4 introduces a modified heuristic to develop facility layout arrangements. This modified heuristic uses the forward pass approach similar to one proposed by Urban (1993) which uses a pair-wise steepest descent method. In this research, the facility layout is generated using CRAFT. According to Armour and Buffa (1963), pair-wise exchange method is similar to CRAFT. Urban's methodology was further enhanced by Balakrishnan, Conway, and Cheng (2000) by adding backward pass. Chapter 4 builds on that research as the research so far in this area has not taken capacity constraints and alternative production sequence into consideration. This research develops a methodology to develop an optimal layout using forward pass and backward pass approaches using modified heuristics with capacity constraints and alternative production sequences. Thus it builds up on the research in Chapters 2 and 3 as Chapters 2 and 3 used GA to develop a layout based on demand only from a given time period. Using the proposed methodology, we find best layout by taking demand from multiple time periods simultaneously. Using this methodology, we find the best solution for the facility such that the cost of meeting demand is least. The selection of the best layout is done using the cost functions developed as a part of the research. The selection criteria for selecting the best solution is based on minimization of the cost associated with material handling and rearrangement. The proposed method develops multiple solutions for each time period and compares with the current best solution. If a solution is better than the current best solution, then it is selected as the new best solution. The proposed methodology and cost functions which are developed for supporting the methodology are detailed in Chapter 4.

In the next chapter, the capacity constrained dynamic facility layout methodology is detailed.

1.3 References

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CHAPTER 2

DYNAMIC FACILITY PLANNING UNDER PRODUCTION AND MATERIAL HANDLING CAPACITY CONSTRAINTS

2.1 Abstract

For a manufacturing facility to be competitive in today's market driven conditions, it is inevitable that it meet the market's demand with optimal resources within required time. Resources and its utilization can be limited by logistic constraints, such as facility layout and material handling, and production constraints, such as machine capacity and type of machines. Research until now has focused on addressing demand requirements under static and dynamic conditions. However, facility layout approaches have assumed infinite capacities for the production system in determining the layout. In addition, facility layout research do not consider material handling capacity consideration in determining feasibility and adaptability of layout. This study conducts research on addressing dynamic facility layout designs in which the demand varies from one time period to the next while taking into consideration finite capacity constraints for both the logistics (facility layout and material handling system) and production systems (machine capacities-operational limitations).

The research uses a genetic algorithm to develop the facility layout for each time period. Simulation studies are conducted for the developed layout to determine if demand can be met for the given time period. The research develops functions that can be used to evaluate the costs of changes in the parameters, such as increased production capacity, increased material handling capacity, or a combination of both parameters, to meet the demand. The aim of this research is to minimize the cost of meeting demand over a given time period under dynamic conditions.

2.2 Introduction

As more and more factories reduce the labor content from their product cost, facility layout and material handling costs represent the next frontier in product cost reduction. Facility layout is concerned with the location and arrangement of departments, cells or machines on the shop floor. Material handling is concerned with equipment and logistics associated with transportation of products from one machine to another within the facility.

According to Tompkins (2003) the material handling cost, a non-value added cost, assumes 20 to 50 percent of the total operating cost of the product. Over $250 billion is being spent annually in the United States itself on facilities for planning and rearranging (Tompkins, 2003). Changes in product demand and product mix causes material handling cost to fluctuate and often increase. Changes in product mix can be the result of new products or the discontinuation of existing products. Changes in the machines used or process plans can also cause the existing facility layout to be inefficient and can increase material handling cost, which in turn necessitates a change in the layout (Afentakis, Millen, and Solomon, 1990). Thus a good facility layout results in optimal material handling cost. As material handling cost is a non-value adding cost, it is imperative that engineers focus their efforts on reducing this cost. This can be achieved either by optimizing the existing material handling system or it can be achieved by developing optimized layouts, which in turn would help reducing the material handling cost.

2.3 Facility Layout Problem (FLP)

Most of the initial research in facility layout was focused on generating new layouts. Depending on the parameters and input requirements along with time periods under consideration, the research can be classified into static facility layout problem (SFLP) or dynamic facility layout problem (DFLP).

2.3.1 Static Facility Layout Problem

In these static layout researches, the layout is generated for a single time period and the flow between machines never changes. Thus in this type of research, the product demands and product mix are considered to be static and do not have any changes throughout the time period under analysis. Traditionally, “from-to” charts, which represent the flow between machines, are used as inputs to generate these layouts. Meller and Gau (1996) performed a comprehensive literature review on static layout research. Static layout problems can be further classified as:

1) detailed layout and
2) block layout

In the case of the block layout problem, the department shapes, sizes and their relative locations are specified. The detailed layout problem in addition to shape, size, and location can also handle constraints such as aisle structures, department locations and input/output points.

2.3.2 Dynamic Facility Layout Problem

Most facility layout issues are not concerned with designing a new facility layout. A majority of facility layout issues deal with the redesign of existing facility layouts. Fluctuations in product demand, product mix changes, changes in production processes and other factors cause changes (often increase) in material handling costs. Introduction of new products/machines or discontinuation of existing products/machines can also lead to changes in material handling requirements. Any change in the product mix, production process or any other factor that influences material handling requirements render the current facility layout inefficient and can increase the material handling cost, which necessitates a change in the layout (Afentakis, Millen and Solomon, 1990). As a facility matures, often with changes in the product mix and machine obsolescence, the facility efficiency deteriorates, and the cost of material handling as a function of product design cost increases. Thus for factories to be competitive, analysis and redesign of facilities have to be undertaken periodically depending on the changes that occur and the factories must be designed to be flexible, modular and easily reconfigurable. Continuous assessment of product demand, flow between departments, and evaluation of the layout to determine the time at which a redesign should be performed is necessary for maintaining a good facility layout for multiple periods (Benjaffar and Sheikhzadeh, 2000). To do a performance assessment for multiple time periods, there is a need for dynamic facility layout algorithms that are flexible enough to accommodate any future possible changes. The redesign of an existing layout is expensive but can be justified when there is a sufficient reduction in material handling cost.

There have been several attempts to address DFLP. The problem of dynamic facility layouts was first addressed by Rosenblatt (1986) who developed a procedure to determine optimal layout for multiple periods, which takes into consideration both material handling cost and rearrangement cost. Krishnan, Cheraghi, and Nayak (2006) classified approaches to solving dynamic facility layout problems into four major categories: Robust layouts that address multiple production scenarios (uncertainties) for a single period, robust layouts for multiple time periods, redesigned layouts for various time horizons based on changes in production requirements, and multiple layouts for various time horizon that are robust to address multiple production scenarios (uncertainties) for each time period.

In development of robust layouts for handling uncertainty in a single time period, the evaluation of a layout for a single period is performed by considering multiple possible production scenarios (Rosenblatt and Lee, 1987; Rosenblatt and Kropp, 1992). The best layout is one that can address all possible scenarios by minimizing the maximum possible loss. In the second category of dynamic layout research in which robust layouts for multiple time periods are developed, it is assumed that the production data for multiple-periods are known in the initial stages of layout design. The solution involves the development of a single robust layout that minimizes cost over the periods under consideration (Kouvelis and Kiran, 1991). Krishnan, Cheraghi, and Nayak (2008) developed three models, of which, the first one dealt with minimizing the maximum loss for a single period when multiple production scenarios were present.

Redesigning layouts for each time period based on changes in production requirements is preferred when there are considerable changes in product mix and demand; and when the material handling costs are high compared to rearrangement costs. The material handling requirements change from one period to the next and hence multiple layouts are generated and evaluated to meet the demand with reduced cost. A significant reduction in production cost can be achieved when a redesign of the layout can be accomplished with minimum rearrangement costs. Redesigning layouts becomes feasible when material handling cost is high and the transition or rearrangement cost is low. One of the models developed by Krishnan, Cheraghi, and Nayak (2008) was for a multi-period multi-scenario model in which layouts are generated to minimize maximum loss due to material handling costs for multiple periods while taking into consideration the transition cost. In yet another model, Krishnan, Cheraghi, and Nayak (2008) focused on minimizing the total expected loss. They developed a model in which the associated probability of occurrence of each scenario is taken into account and the model generated a compromise layout that minimizes the total expected loss from all scenarios rather than reducing the maximum losses of specific scenarios.

Heuristics such as Genetic Algorithms (GA), Simulated Annealing (SA) etc., have been developed and optimization techniques have also been used to address DFLP problems. Conway and Venkataramanan (1994) developed a GA based methodology to generate feasible layouts for

DLPs. Balakrishnan and Cheng, (2000) proposed improvements in the application of GA procedures to solve DFLP. Baykasoglu and Gindy (2001) used a SA approach to solve the DLP. A steepest descent pair-wise exchange method was used by Urban (1993) to develop dynamic layouts for DLPs. Solutions to DLP problems using GA approaches for a multi-floor facility were developed by Kochhar and Heragu (1999). This algorithm is an extension of the Multiple-Floor Heuristically Operated Placement Evolution (MULTI-HOPE) algorithm for a single period to the DLP problem. The pair-wise exchange heuristic developed by Urban (1993) was modified by Balakrishnan, Cheng and Conway (2000) to include a backward pass pair-wise exchange to further refine the solutions to DLP. They also proposed a dynamic programming approach for the backward pass to solve the DLP. Krishnan, Cheraghi and Nayak (2006) introduced the concept of Dynamic From-Between charts to analyze the need for redesign when flow requirements between stations change.

Finally, in the fourth type, multiple layouts for various time horizon that are robust to address multiple production scenarios (uncertainties) for each time period are developed to minimize costs. Yang and Peters (1998) proposed an optimization approach over multiple-periods along with multiple possible scenarios for each period, which provides an optimal layout for each period from the possible set of scenarios and evaluates the efficiency of the layout for a future period by minimizing the sum of RA and material handling costs. Krishnan, Jithavech and Liao (2009) developed a model for reducing risk when the product demand is uncertain. The models developed addressed both single period and multi-period problems.

In a DFLP, the decision to redesign is influenced by the material flow changes, cost of rearrangement, etc. The disadvantages of the existing layout are addressed during redesign with respect to the new requirements. One assumption that previous researchers have made in dynamic facility layout is that there is unlimited capacity with respect to both material handling and production resources. When assuming infinite capacity for both material handling and production capacity, it is possible that the new layout may not be able to deliver the expected throughput under finite capacity constraints. The objective functions in previous research have focused on cost savings from the high throughput. Thus, when capacity limitations are considered, it is possible that because of the capacity limitations the facility layout redesign may not be cost effective. This paper thus focuses on the dynamic redesign of layouts under capacity limitations of both material handling and production systems. The concept of state systems proposed by (Dhuttargaon, Krishnan, and Shah, 2014) is used to determine whether the manufacturing system is in a Production Constrained State (PCS), Transition State (TS) or Logistics Constrained State (LCS). Based on the state of the manufacturing system, the research proposes methodologies for effective utilization of the production resources.

2.4 Research Objective

The objective of this research is to develop a methodology for designing layouts under dynamic conditions of product demands which changes from period-to-period, while taking into consideration production and material handling capacity constraints for each time period. It is assumed that the product demands are known at the beginning of each time period under consideration. It is also assumed that the process sequence for each product is fixed and known. The research focuses on the development of layouts that are feasible with respect to capacity for both the material handling system and the production system while minimizing costs. To meet demand, the facility may have to be redesigned and/or material handling and production capacities may have to be added. The process of redesign takes into consideration the cost of meeting demand, the cost of production and material handling equipment that is added and the rearrangement costs of the facility. The research also develops a cost function that takes into account the material handling cost for the layout, the cost of rearrangement, the cost of adding production capacity and the cost of adding material handling capacity. The developed cost function helps to calculate the cost of meeting demand with existing capacity and with the added capacity or facility layout changes.

2.5 Cost Analysis for Capacity Constrained Dynamic Facility Layout Design

The objective of a manufacturing facility is to be profitable and satisfy customer needs within required time frame. For this, it has to be able to meet demand with least cost. The cost of making a product can be classified into operating cost, material handling cost, rearrangement cost, and cost of adding material handling capacity and/or production capacity. For the purposes of this research, the product sequences do not change over different time periods in the planning horizon. As the product sequences are same, the cost of operation is only a function of the demand during the given time period. To highlight the impact of the material handling cost, rearrangement cost, and the cost of adding more capacity, the operating cost is not taken into account in the total cost of meeting demand. Thus the total cost of meeting the demand in a given time period is a function of the facility rearrangement cost, material handling cost, cost of adding production capacity and cost of adding material handling capacity.

Notations:

p = total number of products, ranges from p = A, …, P,

R_{pt} = Rate of part creation for product p during time period t,

g_{ijt} = Dynamic flow between departments i and j during time period t

f_{tp} = flow of product p during time period t,

N = total number of departments (Locations) during time period t,

X_{ijtp}

$$= \begin{cases} 1, & if\ there\ is\ flow\ between\ departments\ i\ and\ j\ for\ product\ p\ during\ time\ period\ t, \\ 0, & Otherwise \end{cases}$$

M_t = Material handling cost during time period t,

U_{MHi} = Percentage utilization of each Material Handling Unit (MHU) (i = 1 to n),

U_{MH} = Average percentage utilization during a given time period,

U_{MCi} = Percentage utilization of each machine (i = 1 to n),

D_{ijt} = Rectilinear distance between departments *i* and *j* for layout in time period t,

C = Fixed material handling cost/unit distance,

F_t = Fixed cost of transition to current time period t

V_t = Variable cost associated with the movement of departments (machine locations) from time period t-1 to t

$d_{n(t-1,t)}$ = Rectilinear distance between locations of machine 'n' in time period t-1 and t

Y = Cost per unit distance incurred in moving machine n (n=1 to N)

A_t = Cost of increasing production capacity in given time period t

n_t= Number of machines that are required to be added in time period t

a_n = Cost of each machine of type 'n'

B_t = Cost of adding material handling capacity

m_t= Number of MHUs that are required to be added in time period *t*

b_m = Cost of adding each MHU

C_{Dt} = Total cost of production in a given time period t

C_{DT} = Total production cost over the planning horizon which consists of total time periods

Q_{pt}= Demand for product p in time period t

R_{pt}= Rate at which product p has to be made available at source during time period t

t^*= Time in seconds in a given time period

2.5.1 Material Handling Cost

With any production facility there is always cost associated with material handling of the products. This is a non-value added cost. Efficient facility layouts strive to minimize this cost. Cost of material handling is a function of distance between the machines that the products have to travel based on the processing sequence for a product. In other words the material handling cost for a given time period t depends on the dynamic flow (g_{ijt}) between departments, the distance (D_{ijt}) between departments and the cost of carrying a product per unit distance (C). Dynamic Flow of products depends on whether or not a given product has to travel from machine A to machine B. This is a function of the processing sequence for a given product. Flow of product from one machine to another is given by demand quantities for that product during the time period. For known sequence of operations and for a given product, the dynamic flow (g_{ijt}) between departments i and j for any time period 't' can be calculated as shown in equation (2.1)

$$g_{ijt} = \sum_{p=A}^{P} f_{tp} * X_{ijtp}, i=1,\ldots,N-1; j=i+1,\ldots,N \tag{2.1}$$

Material Handling cost during time period 't', $M_t$can be calculated as shown in equation (2.2).

$$M_t = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijt} * D_{ijt} * C \tag{2.2}$$

2.5.2 Rearrangement Cost

Rearrangement cost consists of fixed cost and variable cost. Fixed cost consists of expenses incurred in dismantling and reinstalling the machines. It can be calculated using equation (2.3).

$$F_t = F_{t-1,t} \tag{2.3}$$

The variable cost depends on the cost of lost production during the rearrangement period and also depends on the cost of moving the machines from their current location to the new location. If we consider changing our layout only during down time, it may be assumed that there is no cost associated with lost production. Thus the variable cost would reduce just to the cost of moving the machines from one location to another. The variable cost (V_t) for transition from time period 't-1' to 't' can thus be defined as a function of the cost associated with the movement of departments, which depends on the distance $d_{n(t-1,t)}$ each department has to be moved and the cost Y per unit distance of the move. It can be calculated per equation (2.4).

$$V_t = \sum_{i=1}^{N} \sum_{j=1}^{N} d_{n(t-1,t)} * Y_n \tag{2.4}$$

2.5.3 Cost of Adding Production and Material Handling Capacities

If production and material handling demand cannot be met with the current capacities, it might indicate that the system is constrained by production capacity or material handling capacity or both. If the given facility is constrained by production capacity, we can add more production capacity by adding new machines at the location where capacity is a constraint. Normally the cost of adding production capacity depends on the type of machine that needs to be added. Thus, cost of increasing production capacity in given time period t depends only on the number of machines that would need to be added and is given by equation (2.5).

$$A_t = n_t * a_n \tag{2.5}$$

Similarly, if additional material handling capacity is needed, they can be added and the cost of adding material handling capacity can be calculated per equation (2.6).

$$B_t = m_t * b_m \tag{2.6}$$

Thus, the total cost of production in a given time period can be given as a sum of rearrangement cost, material handling cost, cost of adding production and material handling capacities. It can be calculated per equation (2.7).

$$\begin{aligned} C_{Dt} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijt} * D_{ijt} * C + F_t + \sum_{i=1}^{N} \sum_{j=1}^{N} d_{n(t-1,t)} * Y_n \\ \pm (n_t * a_n) \pm (m_t * b_m) \end{aligned} \tag{2.7}$$

However, when the layout is determined using the GA, the additional capacity necessary for meeting the material handling and production requirement has not been determined. This can be analyzed only after the simulation has been used to determine capacity limitations. Hence, while running the GA the cost function (C_{Dtg}) does not take into consideration, the additional capacity needed in production and material handling.

$$C_{Dtg} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijt} * D_{ijt} * C + F_t + \sum_{i=1}^{N} \sum_{j=1}^{N} d_{n(t-1,t)} * Y_n \tag{2.8}$$

The plus or minus sign in the fourth term is used to account for an increase in overall cost (if production capacity needs to be added) and reduction of cost (if the production capacity can be reduced) respectively. A similar approach is used for the material handling cost calculation in the fifth term.

The planning horizon consists of ‘T’ time periods. Equation 2.9 below shows the total production cost over the planning horizon which is the sum of production costs incurred in each time period.

$$C_{DT} = \sum_{t=1}^{T} C_{Dt} \tag{2.9}$$

2.6 General Methodology for Redesign

The product quantities in each time period are assumed to be known and fixed. There is only one process sequence that can be used to manufacture each product. The processing times for each product on each machine are also known and deterministic. The steps of the algorithm are detailed below.

Step 1: The procedure starts with the previous layout (for period t-1) as one of the inputs. The demand data for the current time period (t) is also used as an input. Product demand data and processing sequences of each product for time period ‘t’ are used to identify the new layout using a GA procedure. Details of the GA procedure are outlined in the GA procedure section.

Step 2: Using the new layout obtained from the GA procedure a simulation model that reflects the new product demand data is developed.

Step 3: Based on the data obtained from the simulation model, a feasibility analysis is carried out to evaluate if the new layout along with the production capacity constraints can be used to meet the product demands for the time period under consideration. If product demand can be met, cost analysis is carried out to determine if changing the layout is more economical, compared to adding more capacity using the layout from the previous time period. Details of cost analysis are outlined in the procedure for cost analysis section. If demand is not met, go to step 4.

Step 4: If demand cannot be met, identify the current state of the manufacturing system state. Procedures for identification of the manufacturing system’s current state are described later. If the system is in a Logistics Constrained State, material handling input parameters are iteratively changed until the new product requirement can be met. If the system is in a production constrained state, more capacity is added at the bottleneck stations. If the system is in a transition state, both material handling and production capacities may have to be modified to meet the demands of the time period. After adding additional capacity, the simulation model is modified and used to verify if the demand for the time period can be met. This is done iteratively until the right combination of capacities to be used with the layout is identified for the time period.

Flowchart showing general methodology for redesigning is shown in Figure 2.1.

2.6.1 GA Procedure for Developing the Layout for the New Time Period

As shown in previous literatures, facility layout problems are np-hard and it is easier to solve using heuristics. The GA algorithm used for this approach has been developed by Krishnan, Jithavech and Liao (2009). The parameters of the procedure have been modified with slight changes in the objective function and in fitness function. The procedure is briefly outlined here for the sake of completion.

Similar to most genetic algorithms applied to facility layout problems, a one-dimensional array chromosome is used to represent the order of departments to be placed in a layout. The chromosomes were represented by numerical representation (e.g., 02, 08, 04, 11,…etc.) of a string placement scheme for the layout generation. An s-shaped placement scheme in which departments are placed in successive rows from left-to-right and then from right-to-left is used for locating department. The width and height of the facility were specified for placement of the departments. For example, the placement of departments for the string 120803050910040701021106 is shown in Figure 2.2.

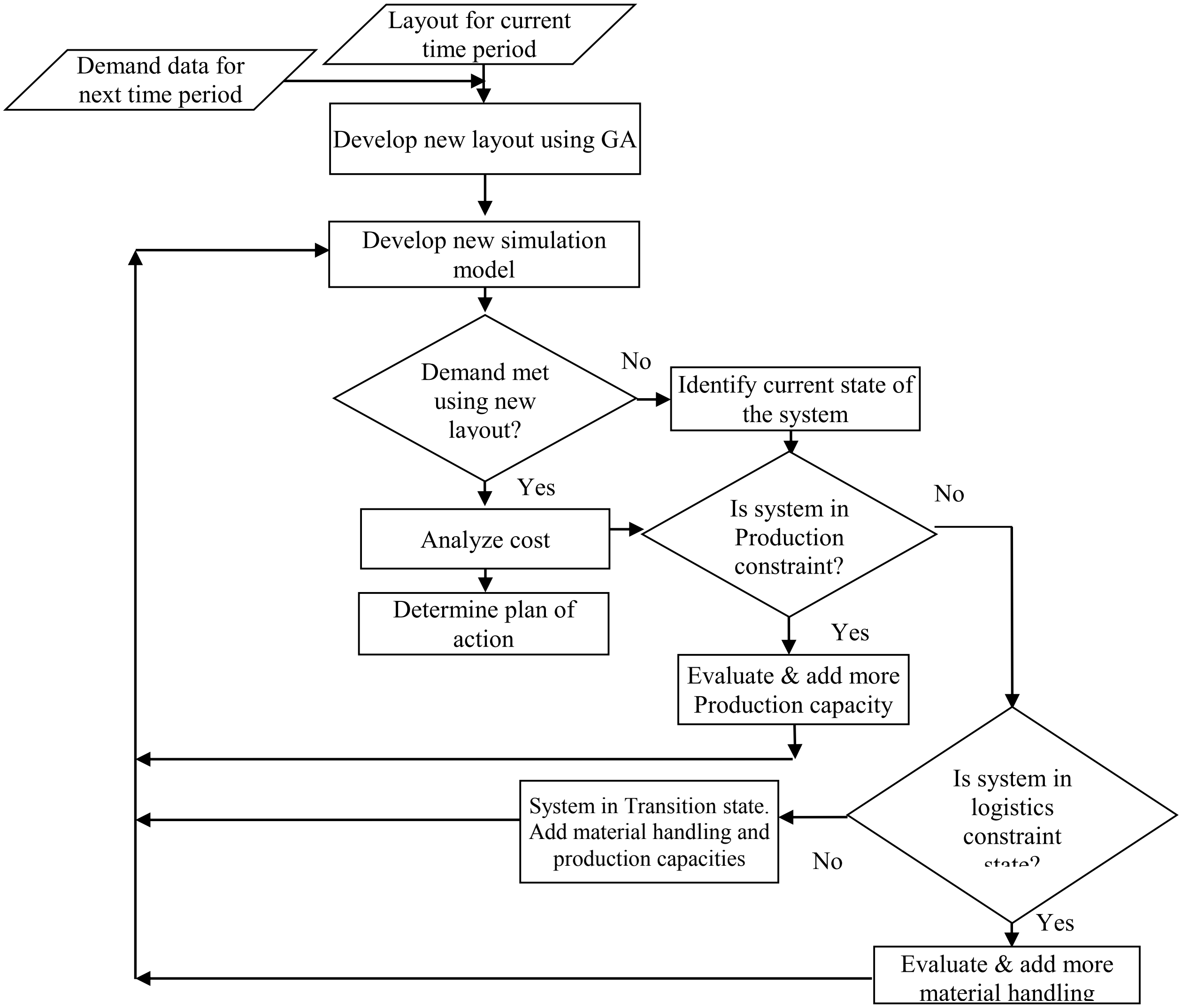

Figure 2.1. Redesign methodology flowchart.

01	2	11	06
07	04	10	09
12	08	03	05

Figure 2.2. Department placement scheme.

The GA cost function is provided in equation (2.8). This cost function attempts to minimize the material handling cost for the projected demand. The fitness function is given in equation (2.10) (Krishnan, Jithavech and Liao, 2009).

$$Fitness\,Value = v(i) = K(C_{Dtg})^{\alpha-1} e^{-\left(\left(-\frac{Zi-Z^*}{Z^*}\right)\beta\right)} \tag{2.10}$$

where α = 0.4 and β is a dynamic factor that is continuously modified as time increases. For each time period, after experimentation, the following ranges of values are used for β (Krishnan, Jithavech and Liao, 2009):

$$\beta = \begin{cases} 0\,.002Z^*, \text{ when } 0<n<I/5 \\ 0.004Z^*, \text{ when } I/5 \le n<2I/5 \\ 0.006Z^*, \text{ when } 2I/5 \le n<3I/5 \\ 0.008Z^*, \text{ when } 3I/5 \le n<4I/5 \\ 0.01Z^*, \text{ when } 4I/5 \le t \le I \end{cases}$$

where i is the current generation, Z^* is the cost of the best solution in any population, I is the total number of iterations and n is the current iteration. The value of β used in the fitness function is dependent on time as well as minimum cost. This fitness function was designed such that as the cost function value increased, the corresponding fitness value decreased. The probability of accepting a bad solution also decreased as the time increased.

The steps used in generating the layout using the GA procedure are given below:

Step 1: Determine population size (Y) and number of iterations (I).

Step 2: Generate a random layout (string/chromosome), and set $y_{gst} = 1$. Conduct a string feasibility check. The condition for infeasibility exists when a department is represented twice in a string. In a case where the string is not feasible, eliminate the second occurrence of the same department, and replace it with a department that is not represented in the string (corrective action). Evaluate the fitness of this string. Set $y_{gst} = y_{gst} + 1$.

Step 3: If $y_{gst} + 1 < Y$, then go to Step 2; otherwise, set $g_{st} = 1$. Save the ten best-fit strings according to fitness values, and use the ten best-fit solutions for crossover and mutation.

Step 4: Perform the roulette wheel selection method for crossover in the selection of the parents based on fitness values obtained. After the crossover and mutation operations, check the new strings obtained for feasibility; if required, and perform corrective action. Add strings into a new generation $g_{st} + 1$. Set $y_{gst}+1 = y_{gst}+1 + 1$.

Step 5: If $y_{gst}+1 + 1 < Y$, then go to Step 4; otherwise, set $g_{st} = g_{st} + 1$. Retain the ten best-fit strings based on fitness value. Perform elitism operation by keeping the ten best-fit solutions from the combined set of layouts generated in the two runs. Continue the process until n = I is satisfied.

2.6.2 Simulation Procedure

Step 1: Using the layout generated by the GA procedure, develop a simulation model. Besides the layout, other inputs required for the simulation model are production capacity, material handling capacity, and rate of part generation at the source for the given period. For purposes of this research, at the beginning of the simulation for a given time period, the production capacity and material handling capacities were kept the same as they were in the previous time period. The rates at which parts enter the system is determined using the "Rate of Part Generation" procedure detailed in section 2.6.2.1.

Step 2: Run simulation for a total time period which includes warm up time and time associated with the given time period. Warm-up time is introduced to ensure that the model achieves steady state prior to data collection.

Step 3: Analyze results obtained from simulation to see if the throughput is equal or greater to the demand data for the time period. If demand is met, we can conclude that the combination of input parameters (layout, production capacity and material handling capacity) can be used for the given time period and we can run simulation for the next time period. If demand is not met, go to step 4.

Step 4: Determine state of the system and constraints of the system. The system can be in logistics constrained state, production constrained state, or transition state. Constraint determination can be carried out using Constraint Determination Procedure.

2.6.2.1 Part Generation Procedure

The rate of part generation uses demand data as input. This rate governs the frequency with which new parts are generated at the source for being processed through the system before it goes to the sink. Rate of part generation is important to ensure that the right mix of product types are generated at the source at the right time. For example, if six pieces of product 'A' and ten pieces of product 'B' were to be produced at the source per hour, the rate of generation for product 'A' would be every ten minutes while the rate of generation for product 'B' would be every six minutes. This would ensure that a right quantity of product mix is generated at the right time. If all products in required quantities were made available at the beginning of the simulation, Quest would stack all six pieces of product 'A', then stack ten pieces of product 'B' above that and so on. As the material handling system picks up parts on a first-in-first-out (FIFO) basis from the source, this would result in all six pieces of product 'A' being picked up by material handling system and taken toward the first machine before any instance of product 'B' would be picked up by the material handling system. This would not represent a practical condition. To ensure that this does not happen, part generation was driven by a file based process. A file based process allowed us to create an input file with all the times at which the parts were to be produced and the sequence in which the parts were to be produced. This input file was then used as a logic to generate parts at the source. By doing so, it can be ensured that the first instance of product 'A' is created at six minutes on the simulation clock, first instance of product 'B' is created at ten minutes on the simulation clock, followed by two instances of product 'A' created at twelve and eighteen minutes respectively before second instance of product 'B' is created at twenty minutes on the simulation clock. To eliminate idle time for the material handling system and production systems till the first part is created, an instance of each part was created at the source at start of the simulation before the file based generation kicked in. Steps involved in calculating production rates and generating a file based input are shown below:

Step 1: Obtain Q_{pt} demand data for all products (P) for a given time period

Step 2: Calculate R_{pt} - rate at which an instance of a part type has to be made available at the source. This can be done by equation (2.11).

$$\forall P \left(for\ a\ given\ t \right):\ R_{pt} = Q_{pt} / t^{*} \tag{2.11}$$

Step 3: Create a table with R_{pt} values for product p=A. Append the table with R_{pt} values for product B, product C and so on till all products are included in the table.

Step 4: Sort R_{pt} data in ascending order with respect to time.

Step 5: Calculate difference in time between each instance of part production by subtracting value in Row 2 from Row 1; Row 3 from Row 2; and so on. This gives the relative time of part production with respect to previous time of part production.

Step 6: With lot size of one, save this data as .dat file to be used for file based production schedule in QUEST.

2.6.3 Procedure for Determining the Current State of Manufacturing System

From the results of simulation, if the system does not meet expected demands, the current state of the manufacturing system must be identified before enhancements to the system are considered. Failure to meet demand at the end of a time period indicates that one of the parameters selected for the simulation model is not adequate. This research is limited to the following parameters: a) Layout generated by GA; b) Material Handling capacity; and c) Production capacity. Thus failure to meet demand indicates that either the layout as generated using the GA procedure is not acceptable for the time period under consideration, or the material handling or production capacities or combination of both material handling capacities and production capacities are not sufficient enough. If the layout is good, the system can be in a logistics constrained state or a production constrained state or in a transition state (which is a combination of the logistics constrained state and production constrained state). Capacities can be evaluated based on percent utilizations as obtained from results of simulation.

Simulation model was designed to minimize the blocking of one material handling unit by the other, either during loading or travel, and hence the percent utilization is representative of actual usage of each material handling unit. Material handling unit's travel can be classified into:

1. Loaded travel
2. Empty travel.

As blocking is minimized, and MHU scheduling is based on closest-free- material-handling-unit and the path selection is based on minimum path distance, the average utilization of all material handling units is representative of actual utilization of each material handling unit and hence it is used to determine the need for additional material handling units.

Utilization of production machines is a function of the product processing time and the associated production sequences. So even though the machine times are deterministic, using average utilization of all the machines is not representative of utilization of each of the machines as each product requires specified times on each machine which may be different for each product. Thus to determine if the system is constrained by production capacity, the utilization of each of the machines is considered/studied.

Figure 2.3 shows a flowchart detailing procedure for determination of manufacturing system state.

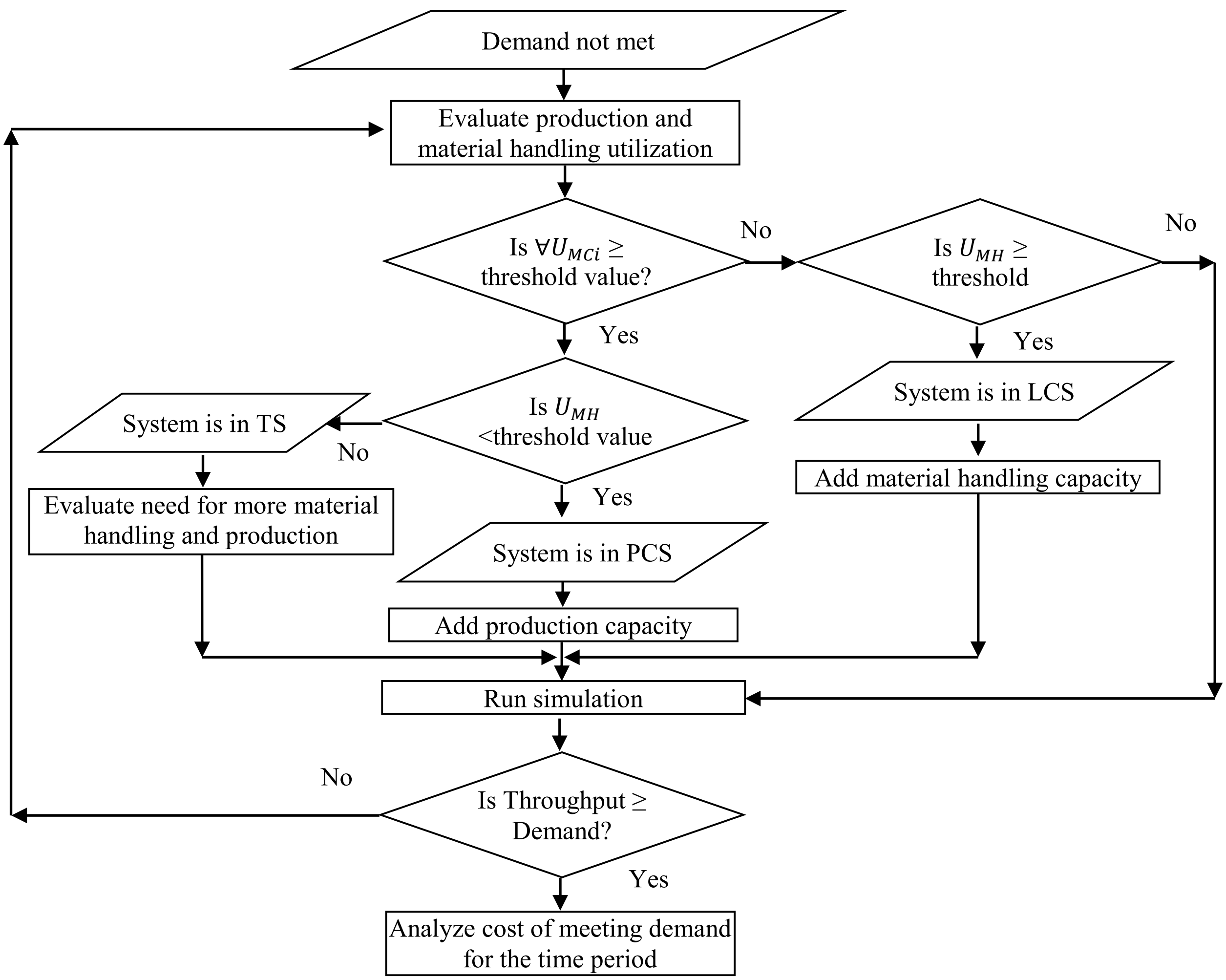

Figure 2.3. Flowchart showing procedure for determination of manufacturing system state.

Following steps outline the procedure for determination of the current state of the system:

Step 1: Obtain and use data from initial simulation model for a given time period.

Step 2: Let U_{MCi} be percent utilization of each machine (i=1 to n) and let U_{MHi} be percentage utilization of each MHU (i = 1 to n). Calculate average percentage utilization U_{MH} for all material handling units using equation (2.12).

$$U_{MH} = \left(\sum_{i=1}^{n} U_{MHi} \right) / n \tag{2.12}$$

Step 3: Check if $\forall U_{MCi} \geq$ threshold percentage, system can be in Production System constraint state or Transient zone. To determine which state is the system is in, go to Step 4; else go to step 6.

Step 4: Check if $U_{MH} <$ threshold percent. If yes, we conclude that the system is in Production Constrained State and go to step 5, else go to step 8.

Step 5: Add production capacity at machine where $U_{MCi} \geq$. Threshold, then go to step 9.

Step 6: Check if $U_{MH} \geq$ Threshold, if yes system is in Logistic constrained state, else go to step 9.

Step 7: Add material handling capacity and go to step 9.

Step 8: Evaluate need for more Material Handling capacity and Production capacity and go to step 9.

Step 9: Run simulation again.

Step 10: Check if throughput > demand, if yes, go to step 11, else go to step 1.

Step 11: Analyze cost of meeting demand.

2.6.4 Sample Case Study to Illustrate Cost Calculations (4-machines, 2-products, 3-time periods)

Consider a facility that has 4 machines and makes 2 products. Product demands for the facility in time periods are known and the product sequence is given in Table 2.1. The layouts GA suggested layouts for different time periods are shown in Table 2.2.

TABLE 2.1

SEQUENCE AND DEMAND DATA

Product	**Sequence**	**Demand**		
		t=1	**t=2**	**t=3**
A	1-2-4	3	4	5
B	1-3-4	7	6	5

TABLE 2.2

LAYOUTS FOR EACH TIME PERIOD

Layout							
t=1			**t=2**			**t=3**	
1	2		1	2		1	3
4	3		3	4		2	4

2.6.4.1 Cost Calculations for Time Period t = 1

The cost associated with meeting demand in time period t=1 is calculated as shown.

The f_{tp} values for all three time periods are shown in Table 2.3 below:

TABLE 2.3

f_{tp} VALUES FOR EACH PRODUCT IN EACH TIME PERIOD

		$\boldsymbol{f_{tA}}$	$\boldsymbol{f_{tB}}$
Time Period (t)	1	3	7
	2	4	6
	3	5	5

Product 1 (p=A) follows sequence 1-2-4. Thus $X_{121A} = X_{122A} = X_{123A} = 1$. Similarly, $X_{241A} = X_{242A} = X_{243A} = 1$. For product 2 (p=B) which follows sequence 1-3-4, $X_{131B} = X_{132B} = X_{133B} = 1$, and $X_{341B} = X_{32B} = X_{343B} = 1$. All other combinations for X_{ijtp} will be equal to 0 as products do not flow between other pairs of machines during any time period. Substituting all values in Equation 1, we get the values for g_{ijt} as shown is Table 2.4.

TABLE 2.4

g_{ijt}VALUES FOR EACH PRODUCT DURING EACH TIME PERIOD

$g_{121} = 3(1) + 7(0) = 3$	$g_{131} = 3(0) + 7(1) = 7$
$g_{122} = 4(1) + 6(0) = 4$	$g_{132} = 4(0) + 6(1) = 6$
$g_{123} = 5(1) + 5(0) = 5$	$g_{133} = 5(0) + 5(1) = 5$
$g_{241} = 3(1) + 7(0) = 3$	$g_{241} = 3(0) + 7(1) = 7$
$g_{242} = 4(1) + 6(0) = 4$	$g_{242} = 4(0) + 6(1) = 6$
$g_{243} = 5(1) + 5(0) = 5$	$g_{243} = 5(0) + 5(1) = 5$

For this case study, it is assumed that the distance between adjacent machines is (D_{ijt}) is 10 feet and the cost C of moving each product is \$1/foot. Thus the material handling cost for time period t=1 can be calculated using equation (2.2).

$$M_1 = \left(g_{121} * 10 * 1\right) + \left(g_{241} * 10 * 1\right) + \left(g_{131} * 10 * 1\right) + \left(g_{341} * 10 * 1\right) = 200$$

No rearrangement was necessary during time period 1 and the production capacities and material handling capacities were adequate to meet the demand.

Total production cost in time period 1 is \$200.

$$C_{D1} = 200 + 0 + 0 \pm 0 \pm 0 = 200$$

2.6.4.2 Cost Calculations for Time Period t = 2

The cost associated with meeting demand in time period t=2 is calculated as shown:

For time period t=2, the material handling cost calculated as follows and results in a total of \$200.

$$M_2 = \left(g_{122} * 10 * 1\right) + \left(g_{242} * 10 * 1\right) + \left(g_{132} * 10 * 1\right) + \left(g_{342} * 10 * 1\right) = 200$$

Going from time period t=1 to 2, we have to change the layout of the facility. The fixed cost of rearrangement during this time period is $100. Layout for t=2 when compared to layout from t=1 shows that the locations for machine 3 and 4 were swapped. As the rectilinear distance between adjacent machines was considered to be 10 feet, we can calculate the variable cost for this move. If the cost to move the machines is $10/foot, then the total variable cost for rearrangement is given as equation (2.4)

$$V_2 = (D_{234} * Y) + (D_{243} * Y)$$

$$V_2 = (D_{234} * Y) + (D_{243} * Y) = (10 * 10) + (10 * 10) = 200$$

If the production capacity is not adequate and an additional machine is required at machine 2 but no additional MHUs are required, the cost of acquiring each machine is $500.

Thus total cost of production in time period t = 2 can be calculated as shown:

$$C_{D2} = 200 + 100 + 200 + 500 \pm 0 = 1000$$

2.6.4.3 Cost Calculations for Time Period t = 3

The cost associated with meeting demand in time period t=3 is calculated as shown:

For time period t=3, the material handling cost calculated as follows results in a total of $200.

$$M_3 = (5 * 10 * 1) + (5 * 10 * 1) + (5 * 10 * 1) + (5 * 10 * 1) = 200$$

Going from time period 2 to 3, there is a need to change the layout of the facility. The fixed cost of rearrangement during this time period is $100. Layout for t=3 when compared to layout from t=2 shows that the locations for machine 2 and 3 were swapped. As the rectilinear distance between adjacent machines was considered to be 10 feet, we can calculate the variable cost for this move. If the cost to move the machines is \$10/feet, the total variable cost for rearrangement is given as:

$$V_3 = (d_{2(2,3)} * Y) + (d_{3(2,3)} * Y)$$

$$V_3 = (d_{2(2,3)} * Y) + (d_{3(2,3)} * Y) = \left(2*10*10\right) + \left(2*10*10\right) = 400$$

If based on capacity calculations, the production capacity for machine 1 has to be increased (compared to time period t=2) and an additional MHUs is required. The cost of acquiring each machine is \$500 and each MHU is \$250. Thus total cost of production in time period t = 3 can be calculated as:

$$C_{D3} = 200 + 100 + 400 + 500 + 250 = 1450$$

Thus the total production cost over all three time periods is given by

$$C_{DT} = 200 + 1000 + 1450 = \$2650$$

2.7 Case Study (9-department, 5-product, 4-time periods)

To demonstrate the effectiveness of this methodology a larger case study with 9 departments and 4 time periods is used. The projected demands and sequences of manufacturing for each product in each time period is given in Table 2.5.

TABLE 2.5

PRODUCT DEMANDS AND SEQUENCE DATA

Product	**Projected Demands**				**Sequence**
	t=1	**t=2**	**t=3**	**t=4**	
Product 1	340	400	240	400	1-3-5-7-9
Product 2	560	460	450	300	1-2-7-4-6
Product 3	600	560	400	700	4-5-6
Product 4	200	350	280	660	3-5-7-8-6
Product 5	200	260	950	600	1-8

Following considerations were made and parameters were selected for the multi-period nine department case study:

- Rectilinear distance between machines is 50 feet
- All MHU have equal speed (120 feet/minute) and capacity (1 part)
- MHU paths are unidirectional i.e. MHUs can travel only in one direction
- Each department is equipped with an input and an output buffer with infinite capacity
- Process sequence for each product is known and is fixed for all time periods
- Product demands are deterministic and known for each time period
- Material handling cost during each time period is $3/feet
- Cost of moving machines 1, 3, 5, 7, 9 is $50/foot and machines 2, 4, 6, 8 is $45/foot
- Cost of buying new machine is $10,000
- Cost of buying new MHU is $5,000
- Fixed cost of rearrangement for each time period is $1,000

In order to ensure that the system has reached steady state, the simulation used a warm up period of two weeks. The simulation software starts collecting data once the time clock reaches 4800 minutes and collects data for next 9600 minutes i.e. each time period is 4 weeks.

2.7.1 Nine Department Case Study: Time Period 1

Based on the product demand for time period t=1, a from between chart is constructed. The from between chart is as shown in the Table 2.6.

Simulation results indicate that with the layout obtained using GA and with the existing production capacity and material handling capacity, the demand for the time period can be met.

The dynamic flow values (g_{ijt}) for time period t =1 are shown in the Table 2.6. The rest of the values are zero.

The layout for time period t = 2 obtained for GA is shown in Figure 2.4. The material handling cost associated with these dynamic flow values for time period t = 1 as calculated using Equation 2.2 is $1,131,000.

TABLE 2.6

DYNAMIC FROM BETWEEN CHART (TIME PERIOD 1)

	1	2	3	4	5	6	7	8	9
1		560	340					200	
2							560		
3					540				
4					600	560	560		
5						600	540		
6								200	
7								200	340
8									
9									

1	3	5
2	7	4
8	9	6

Figure 2.4. GA generated layout (time period 1).

As the demand can be met during this time period, no fixed or variable rearrangement costs are incurred in time period t = 1. As seen earlier, existing production capacity and material handling capacity for the layout in time period t = 1 is sufficient to meet the demand and hence there is no need for additional machines or MHUs. Thus the total cost for meeting demand in time period t = 1 calculated using Equation 2.7 is $1,131,000.

2.7.2 Nine Department Case Study: Time Period 2

Based on the product demand for time period t=2, a from-between chart can be constructed. The from-between chart is as shown in the Table 2.7. The layout for time period t = 2 obtained for GA is shown in the Figure 2.5.

Simulation data results shown in Table 2.8 shows that with the layout obtained using GA and with the existing production capacity and material handling capacity, we can meet demand for the time period.

TABLE 2.7

DYNAMIC FROM BETWEEN CHART (TIME PERIOD 2)

	1	2	3	4	5	6	7	8	9
1		460	400					260	
2							460		
3					750				
4					560	460	460		
5						560	750		
6								350	
7								350	400
8									
9									

9	2	1
7	5	3
4	6	8

Figure 2.5. GA generated layout (time period 2).

TABLE 2.8

SIMULATION RESULTS (TIME PERIOD 2)

Name	**Demand**	**Throughput**
Part1	400	401

TABLE 2.8 (continued)

Name	Demand	Throughput
Part2	460	460
Part3	560	561
Part4	350	351
Part5	260	261

The dynamic flow values (g_{ijt}) for time period t = 2 are shown in the Table 2.8. The material handling cost associated with these dynamic flow values for time period t = 2 as calculated using Equation 2.2 is $1,230,000. GA suggests that rearrangement is required for this period. Fixed rearrangement cost for each period is assumed to be $1,000. The facility layout for this time period when compared with the previous time period indicates that machines need to be moved to get the layout in time period t = 2. Table 2.9 summarizes the machines that need to move, the rectilinear distance the machines need to be moved and cost associated with each move at the rate of $50/foot for machines 1, 3, 5, 7, and 9; and $45/foot for machines 2, 4, 6, and 8. Equation (2.4) is used to calculate total variable cost of rearrangement.

TABLE 2.9

REARRANGEMENT DISTANCE AND COST (TIME PERIOD 2)

Machine Moves	Distance of move (Feet)	Cost of move
D_{215}	100	$5,000
D_{223}	100	$4,500
D_{234}	100	$5,000
D_{248}	150	$6,750
D_{257}	100	$5,000
D_{269}	100	$5,000
D_{272}	50	$2,500
D_{286}	100	$4,500
D_{291}	150	$7,500
Total		$35,000

Existing production capacity and material handling capacity for the layout in time period t = 2 is sufficient to meet the demand and hence there is no need for additional machines or MHUs. Thus the total cost for meeting demand in time period t = 2 calculated using equation (2.7) is $1,266,000.

2.7.3 Nine Department Case Study: Time Period 3

Based on the product demand for time period t = 3, a from-between chart can be constructed. The from-between chart is as shown in Table 2.10. The layout for time period t = 3 is shown in the Figure 2.6.

Simulation data suggests that for the layout suggested by GA and with the existing production and material handling capacities, demand for this period cannot be met as can be seen in simulation result in Table 2.11.

TABLE 2.10

DYNAMIC FROM BETWEEN CHART (TIME PERIOD T = 3)

	1	2	3	4	5	6	7	8	9
1		450	240					950	
2							450		
3					520				
4					400	450	450		
5						400	520		
6								280	
7								280	240
8									
9									

3	5	6
2	7	4
1	8	9

Figure 2.6. GA generated layout (time period t = 3).

The dynamic flow values (g_{ijt}) for time period t = 3 are shown in the Table 2.11. The material handling cost associated with these dynamic flow values for time period t = 3 as calculated using equation (2.2) is $1,060,500.

TABLE 2.11

SIMULATION RESULTS (TIME PERIOD T = 3)

Name	**Demand**	**Throughput**
Product1	240	239
Product2	450	453
Product3	400	400
Product4	280	145
Product5	950	495

GA suggests that rearrangement is required for this period. Fixed rearrangement cost for each period is assumed to be $1,000. The facility layout for this time period when compared with the previous time period indicates that machines need to be moved to get the layout in time period t = 3. Table 2.12 below summarizes the machines that need to move, the rectilinear distance the machines need to be moved and cost associated with each move at the rate of $50/foot for machines 1, 3, 5, 7, and 9; and $45/foot for machines 2, 4, 6, and 8. Equation 2.4 is used to calculate total variable cost of rearrangement.

TABLE 2.12

REARRANGEMENT DISTANCE AND COST

Machine Moves	**Distance of move (Feet)**	**Cost of move**
D_{314}	200	$10,000
D_{327}	100	$5,000
D_{339}	150	$7,500
D_{343}	150	$6,750
D_{352}	50	$2,500

TABLE 2.12 (continued)

Machine Moves	Distance of move (Feet)	Cost of move
D_{375}	50	$2,500
D_{386}	50	$2,250
D_{398}	200	$10,000
Total		$52,750

Thus the total cost of rearrangement going from time period t = 2 to t = 3 is $53,750 including the $1,000 of fixed re-arrangement cost.

However throughput for this time period shows that the demand cannot be met. Further analysis of utilization of the machine times shown below in Table 2.13 indicates that machines 8 is utilized 100% and hence is a bottleneck.

TABLE 2.13

PERCENT UTILIZATIONS FOR MACHINES (TIME PERIOD T = 3)

Name	Utilization (%)
Machine1	90.062
Machine2	54.355
Machine3	65
Machine4	46.703
Machine5	50.324
Machine6	46.835
Machine7	53.255
Machine8	100
Machine9	45

2.7.4 Nine Department Case Study: Time Period 3 (Increased Production Capacity)

To address the production system constraint, machine capacities for machine 8 was increased by adding an additional machine at location 8. For purpose of simulation, this was done by cutting the machine time for machine 8 into half which would be representative of adding additional machine at that location.

At a cost of $10,000/machine, the cost of adding production system capacity can be calculated to be $10,000 using Equation 2.5. With increase in production capacity machine is not a bottleneck any more, and simulations results shown in Table 2.14 indicate that demand can be met after adding production capacity.

The results indicate that demand can only be met after production system capacity was added. The cost of meeting demand during this time period as calculated by equation (2.7) as shown below is $1,124,250.

TABLE 2.14

SIMULATION RESULTS WITH INCREASED PRODUCTION CAPACITY

Name	Demand	Throughput
Product1	240	240
Product2	450	453
Product3	400	400
Product4	280	281
Product5	950	950

2.7.5 Nine Department Case Study: Time Period 4

Based on the product demand for time period t = 4, a from-between chart can be constructed. The from-between chart is as shown in the Table 2.15.

TABLE 2.15.

DYNAMIC FROM-BETWEEN CHART (TIME PERIOD T = 4)

	1	2	3	4	5	6	7	8	9
1		300	400					600	
2							300		
3					1060				
4					700	300	300		
5						700	1060		

TABLE 2.15 (continued)

	1	2	3	4	5	6	7	8	9
6								660	
7								660	400
8									
9									

The layout for time period t = 4 is shown in the Figure 2.7. Simulation data suggests that for the layout suggested by GA and with the existing production and material handling capacities as in time period t = 3, demand for this period cannot be met as can be seen in simulation result in Table 2.16.

9	7	8
4	5	6
2	3	1

Figure 2.7. GA generated (time period t = 4)

TABLE 2.16

SIMULATION RESULTS (TIME PERIOD T = 4)

Name	**Demand**	**Throughput**
Product1	400	302
Product2	300	296
Product3	700	690
Product4	660	498
Product5	600	591

The dynamic flow values (g_{ijt}) for time period t = 4 are shown in the Table 2.16.

The material handling cost associated with these dynamic flow values for time period t = 4 as calculated using equation (2.2) is $1,554,000.

GA suggests that rearrangement is required for this period. Fixed rearrangement cost for each period is assumed to be $1,000. The facility layout for this time period when compared with the previous time period indicates that machines need to be moved to get the layout in time period t = 4. Table 2.17 below summarizes the machines that need to move, the rectilinear distance the machines need to be moved and cost associated with each move at the rate of $50/foot for machines 1, 3, 5, 7, and 9; and $45/foot for machines 2, 4, 6, and 8. Equation (2.4) is used to calculate total variable cost of rearrangement. Thus the total cost of rearrangement going from time period t = 3 to t = 4 is $44,250 including the $1,000 of fixed re-arrangement cost.

TABLE 2.17

REARRANGEMENT DISTANCE AND COST

Machine Moves	**Distance of move (Feet)**	**Cost of move**
D_{419}	100	$5,000
D_{421}	50	$2,250
D_{438}	150	$7,500
D_{442}	100	$4,500
D_{457}	50	$2,500
D_{464}	50	$2,250
D_{475}	50	$2,500
D_{486}	150	$6,750
D_{493}	200	$10,000
Total		$43,250

However throughput for this time period shows that the demand cannot be met. Further analysis of utilization of the machine times shown below in Table 2.18 indicates that Machine 3 is utilized 100% and hence it is a bottleneck. Additional capacity is required for Machine 3. There are already two units of machines 8.

TABLE 2.18

PERCENT UTILIZATIONS FOR MACHINES (TIME PERIOD T = 4)

Name	Utilization (%)
Machine1	69.981
Machine2	35.348
Machine3	100
Machine4	53.836
Machine5	81.429
Machine6	69.516
Machine7	59.904
Machine8	85.053
Machine9	56.737

2.7.5.1 Nine Department Case Study: Time Period 4 (Increased Production Capacity)

To address the production system constraint, machine capacity for machine 3 was increased by adding an additional machine at location 3. For purpose of simulation, this was done by cutting the machine time for machine 3 into half which would be representative of adding additional machine at that location. At a cost of $10,000/machine, the cost of adding production system capacity can be calculated to be $10,000 using equation (2.5).

With increase in production capacity the machines are not bottlenecks any more, however simulation results run with increased production capacity shown in Table 2.19 shows that demand for the time period is still not met.

TABLE 2.19

SIMULATION RESULTS WITH INCREASED PRODUCTION CAPACITY

Name	Demand	Throughput
Product1	400	365
Product2	300	274
Product3	700	638
Product4	660	603
Product5	600	548

This warrants analysis of the material handling system and its utilization. The analysis of the material handling system shown in Table 2.20 reveals that utilizations of MHUs is approximately 100% making them bottlenecks as well. Utilization of MHUs before increasing the production capacity also shown in Table 2.21 was almost 100%. Thus the material handling capacity constraint was masked by the production system capacity constraint. But increasing the production system capacity unmasks the material handling capacity constraint.

TABLE 2.20

MATERIAL HANDLING UNIT UTILIZATION: ORIGINAL CAPACITY VS. INCREASED PRODUCTION CAPACITY

Name	**Utilization (%)**	
	Original Production Capacity	**Increased Production Capacity**
MHU1	99.781	99.769
MHU2	99.799	99.816

2.7.5.2 Nine Department Case Study: Time Period 4 (Increased Production Capacity and Material Handling Capacity)

Material handling capacity constraint was handled by adding one more MHU at the cost of $5000 each. The cost of adding material handling capacity can thus be calculated using Equation (2.6) and is $5,000. Simulation was run again after adding both production system and material handling capacity. Running simulation again after adding capacities and analyzing results indicates that the demand can be met due to these increased capacities with layout as suggested by GA procedure. Through put results of simulation are shown in Table 2.21.

Analysis of utilization MHUs shown in Table 2.22 indicates while the utilization is still pretty high, that none of them are utilized to the maximum capacity of 100%. Analysis of utilization of the machines indicates that none of them are utilized 100%, however the utilization for machine 5 and 8 is still pretty high. The utilizations are shown in Table 2.23.

TABLE 2.21

SIMULATION RESULT AFTER INCREASED PRODUCTION SYSTEM AND MATERIAL HANDLING CAPACITIES

Name	Demand	Throughput
Product1	400	400
Product2	300	300
Product3	700	700
Product4	660	661
Product5	600	600

TABLE 2.22

UTILIZATION OF MATERIAL HANDLING UNITS AFTER INCREASED PRODUCTION SYSTEM AND MATERIAL HANDLING CAPACITIES

Name	Utilization (%)
MHU1	98.758
MHU1	98.701
MHU1	98.88

TABLE 2.23

UTILIZATION OF MACHINES AFTER INCREASED PRODUCTION SYSTEM AND MATERIAL HANDLING CAPACITIES

Name	Utilization (%)
Machine1	71.094
Machine2	35.937
Machine3	66.25
Machine4	54.687
Machine5	96.211
Machine6	77.815
Machine7	74.361
Machine8	98.463
Machine9	75.002

Thus both production capacity and material handling capacity were constrained and logistics constraint can be masked under production system constraint. Similarly if the material handling capacity data obtained from simulation results was analyzed before production system capacity, the production system capacity constraint could have been masked by the material handling capacity constraint. Masking is thus a phenomenon where a constraint is hidden and is not visible in analysis until another constraint is addressed. This is possible when a manufacturing facility is limited by more than one constraint.

The results indicate that demand can only be met if both the material handling and production system capacities were added. The cost of meeting demand during this time period as calculated by equation (2.7) as shown below is $1,613,250.

2.8 Conclusion and Future Work

In this chapter, we developed a methodology for the design of facility layouts under dynamic conditions of product demands which changes from period-to-period, while taking into consideration production and material handling capacity constraints for each time period. The methodology uses a three-step procedure in which the layout for the next period is developed first. This is followed by an analysis using simulation to determine if the layout with the current production and material handling capacity can meet the needs of the time period under consideration. If the production demands cannot be met, an analysis for identifying the types of enhancements needed in the production and material handling system is determined. The three steps are repeated until the production demand is met. The main objective in the analysis is to minimize the cost of production. This is achieved by using a cost function that takes into account the material handling cost for the layout, the cost of rearrangement, the cost of adding production capacity and the cost of adding material handling capacity. The developed cost function helps to calculate the cost of meeting demand with existing capacity and with the added capacity or facility layout changes.

In this chapter, the material handling and production system constraints are satisfied by adding capacity as and when necessary. However, another method for meeting capacity requirements is by using alternate production sequences. These can be cost effective as it is often cheaper to use existing capacity rather than adding new production equipment or material handling units. This development of a methodology for determining more cost effective methods using alternate production sequences will be addressed in a follow-up paper. In the development of layouts for multiple time-periods, the solutions are dependent on the layouts generated for the initial time -periods that are generated. Hence, the sequence of facility generation also plays a part in the best layouts that are generated. In a follow-up research, the development of layouts for multiple time periods, when addition of machines and material handling units occur are investigated using heuristics. Hence, the impact of initial layouts and sequence of generation will be investigated in future research as well.

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CHAPTER 3

AMELIORATION OF CAPACITY CONSTRAINTS IN MANUFACTURING SYSTEMS USING ALTERNATE PRODUCTION SEQUENCE

3.1 Abstract

Today's market is in a constant flux of demand changes. Due to this the product demand and the product mix continuously change from one time period to another. For a company to be profitable and competitive, it has to ensure that all of its resources are optimally utilized. These resources include facility layout, material handling, and production system. Research till now has focused on solving the dynamic facility layout problem by addressing the layout problem while ignoring the limitations and characteristics of the material handling and production system and assume that these resources are infinite. However, a good facility layout can often lead to poor implementation because of the finite nature of production and material handling resources.

As the demand and product mix change, a facility layout that was efficient can soon become inefficient or the cost of production and material handling increase. To keep these cost in check for being profitable, companies have to constantly evaluate the resources they have on hand and add more capacity if necessary. This research evaluates usage of alternate part sequence as a means to eliminate or reduce production system constraints. It focuses on reducing machine usage when the selected process sequence leads to production capacity constraints. Thus it looks at the option of using alternate production sequence in lieu of adding more production capacity. It also develops a cost function to evaluate the cost of optimal solution.

3.2 Introduction

Today's competitive manufacturing sector demands new technologies. One of the ways to improve the competitiveness of manufacturing systems is to incorporate efficient facility layouts in the organization. A logically designed facility layout will be able to accommodate new products to the system, operate at low cost, by delivering the products at right time and respond to demand variations in the system. Thus facility design plays an important role in an enterprise for the smooth flow of work, material and information flow throughout the system. A facility layout problem can be addressed as positioning and arrangement of machines on a shop floor. The facility layout problem can be defined as the determination and allocation of available space for departments, machines etc., and the aisle space between workstations. Many researchers focused on the material handling cost between departments, since material handling cost can contribute 20-50% of the manufacturing cost of a product. By designing efficient layouts 10-30% of these expenses can be reduced (Tompkins and White, 1984).

Material handling cost is the cost associated with moving the material from one machine to other machines or from one location to another. By changing the location of machines/workstations in the facility, the distance traveled by the material handling equipment can be reduced and eventually the cost associated with material handling will reduce. Facility layout problems can be classified broadly into -

- Static Facility Layout Problems (SFLP)
- Dynamic Facility Layout Problems (DFLP)

Static facility layout problems: Static facility layout problem models are used when the product demands are static and do not change from period to period. Dynamic facility layout problem models are used when the demand is dynamic and changes from one period to the next. Techniques that are used to model static facility layout problems are quadratic assignment problem and mixed integer programming (MIP), which has been used as an optimization approach for facility problems. Researchers have used heuristic approaches such as genetic algorithms (GA), simulated annealing and tabu search for solving these problems. Gau and Meller (1999) used an iterative approach in which both GA and MIP were considered, but the computation time was large. Azadivar and Wang (2000) developed a new approach in which a GA package, simulation package, an automatic simulation model generator and a graphical user interface was used. This approach failed to preserve the feasibility of the solution.

A static facility layout model cannot be used when there are fluctuations in product demand and product mix. Moreover, when introducing new products or removing existing products from the system the material handling requirements and cost will increase abruptly. These possibilities make static layout approaches inefficient and necessitate change in the layout (Afentakis, Millen and Solomon, 1990). Maintaining a good facility layout requires continuous assessment of product demands, the flow between departments, and evaluation of the layout to determine the time at which a redesign should be performed. All these lead to the need for dynamic facility layout algorithms which are flexible enough to accommodate any possible changes in future product mix (Benjaffar and Sheikzadeh, 2000). The redesigned layout is accepted only if there is a reduction in cost while comparing the new layout with the previous one.

Dynamic facility layout problems: There are few research works that addressed the dynamic layout problem (DLP). Rosenblatt (1986) proposed a procedure for constructing a multi-period optimal layout by considering material handling cost and rearrangement cost. Dynamic facility layout can be solved by two approaches; the first approach is to develop a robust layout for a multi period scenario. The production data must be provided while constructing multi-period robust layout. Kochhar & Heragu (1999) proposed a methodology to develop an agile manufacturing layout which satisfies all variability for a production requirement. Kouvelis and Kiran (1991) addressed the primary approach for developing a layout that minimizes the material handling cost for a particular time period. In this approach, multiple demand scenarios are utilized for determining the optimal robust layout for a particular period under consideration (Rosenblatt and Lee, 1987, Rosenblatt and Kropp, 1992). Kouvelis and Kiran (1991) proposed a dynamic programming approach which gives an optimal solution for a multi-period scenario. Braglia, Zanoni and Zavanella (2003) proposed an "agility index" which determines the need for an agile layout compared to single robust layout.

The second approach assumes that the layout will be subjected to changes from time to time as it considers for a wide variety of product mix and demand. In this approach material handling costs are reduced while comparing the first approach. Situations where a wide variation is experienced, it is sensible to modify the layout for optimizing the material handling cost. Heuristic approaches have been used for DLP's for constructing the layout in a multi-period scenario. Conway and Venkatramanan, (1994), and Balakrishnan and Cheng, (2000) proposed genetic algorithms for solving the DLP. Enea, Galante, and Panascia (2005) used fuzzy flow patterns between departments and used genetic search approach to deal with uncertain production demand scenarios for a single period problem. The approach considers a wide variety of fuzzy demand scenarios to develop a robust layout in order to maximize the system efficiency over a time period under consideration. Finite capacity constraints are used to ensure that production capacity is not exceeded during the period. However, the system does not consider adding additional production capacity or material handling capacity based on the needs of the current time period. The final flows are assumed to be deterministic.

Optimization approaches over multiple periods have been proposed by Yang and Peters (1998), where both the rearrangement and material handling cost are reduced. Baykasoglu and Gindy (2001) used simulated annealing approach to solve DLP problems. Urban (1993) proposed a descent pair-wise exchange to reduce material handling cost in DFL scenario. In this procedure, the solution for any period is not changed until the analysis on a subsequent period is done. This approach was further modified by Balakrishnan, Cheng, and Conway (2000). In the modified procedure, the forward pass method in Urban's procedure, is followed by a backward pass pair-wise exchange for each period in order to generate multiple solutions. The alternative approach uses the same forward pass method in Urban's procedure including dynamic programming approach to solve DLP.

For achieving competitive manufacturing performances, parameters such as facility layout, material handling system, process routing & production plan should be considered. In the presence of production and capacity constraints, earlier research has focused on identifying and improving facility layouts and by addition of material handling and production capacity. However, an alternate approach to mitigating production and material handling capacity constraints is to use alternate sequences for production, which will allow for use of non-bottleneck machines more effectively and for easing the usage of bottleneck machines.

3.3 Literature Review

Designing and locating workstations efficiently in a facility can be treated as a facility layout problem. The objective function in many of the facilities planning problems is to minimize the material handling cost. The facility layout problem can be noticed in wide variety of environments such as designing of circuit boards, hospitals and schools, designing of turbines and warehouses, etc. and in any manufacturing facility. Throughput, cycle time and work-in-process levels can be greatly minimized with the reduction of movement of materials within the facility. In addition, damage to products and overall congestion can be reduced by minimizing material movement. This results in minimized material handling cost which is treated as the ultimate objective. Large amount of costs are involved in the modification of the current layout. The layout should be well designed in order to eliminate future rearrangement costs. As mentioned earlier the academic work has focused either on static facility layout problem or dynamic facility layout problem.

3.3.1 Static Facility Layout

As stated earlier, static layouts are used for single time period with an assumption that the demand does not change and the flow between machines is constant. A comprehensive review on static layout research was done by Meller and Gau (1996). Kochhar and Heragu (1999) stated that static layouts can be modelled with the assumption that the product demand and the product mix are constant. Static layout problems can further be classified into detailed layout or block layout. Block layout problem deals with specification of department shape, size and relative locations. Detailed layout problem addresses the aisle structure, department locations and input/output points in addition to shape, size and location of the departments.

3.3.2 Dynamic Facility Layout

The existing functional layouts are effective only if the product mix and volumes are pretty much constant throughout the planning horizon. However, when a product experiences this variability it will be very expensive to redesign and reconfigure a layout. The existing trend in the market reveals that majority of the products are subjected to shorter product life cycle with high amount of variability. Demand changes due to market conditions require that the models developed to address a FLP with multiple constraints produce a layout that is robust and agile to adapt to the changes. This cannot be achieved by static facility layouts because changes in the demand can quickly render a facility layout to be inefficient or can increase the material handling cost. These constraints make it necessary that the facility layout and the resources be constantly evaluated for any changes that might be necessary due to demand changes. Continuous assessment of product demand, flow between departments, and evaluation of the layout to determine the time at which a redesign should be performed is necessary for maintaining a good facility layout for multiple periods (Benjaffar and Sheikhzadeh, 2000).

Benjaafar, Heragu, and Irani (2002) detailed the different types of layouts and methods to design flexibility and re-configurability in these existing layouts. The dynamicity of the demand can be addressed either by designing a robust layout for multiple time periods or by designing a flexible layout which is easy to reconfigure from time period to time period with minimum cost. The decision to design a robust or flexible facility layout needs to be made by the facility based on the types of machines they have as it determines the cost of rearrangement. If the cost of rearrangement is low, a dynamic or flexible layout might be ideal; while if the cost of rearrangement is high, a robust layout design is preferable. Krishnan, Cheraghi, and Nayak (2006) classified approaches to solving dynamic facility layout problems into four major categories: Robust layouts that address multiple production scenarios (uncertainties) for a single period, robust layouts for multiple time periods, redesigned layouts for various time horizons based on changes in production requirements, and multiple layouts for various time horizon that are robust to address multiple production scenarios (uncertainties) for each time period.

Koren, Heisel, Jovane, Moriwaki, Pritschow, Ulsoy, and Brussel (1999) provide a comprehensive literature on dynamic aspects for the companies of 21st century. Meller and Gau (1996) provided a survey of emerging trends in facilities. Shore and Tompkins (1980) discuss incorporation of flexibility in facilities to address wide range of changes in production requirement. Enea, Galante, and Panascia (2005) used fuzzy theory approach to model the facility design to address uncertainties in existing environment for a single timer period. Konak Smith, and

Norman (2004) performed the layout optimization by considering production uncertainties and the flexibilities in routing.

3.3.3 Alternate Sequences

The manufacturing of a part requires it to be converted from its raw material form to its final shape and form. During the process of manufacture, the raw material flows from one machine to another for different operations to be carried out on it so that it gets it final fit, form, and function. The series of operations that need to be carried out on the part are identified as its process sequence. Process sequence is also known as process sequence or production sequence for the part.

For alternate sequences to be considered as an alternative to mitigate production capacities, a facility design has to ensure that the layout has similar capacity and capabilities machines strategically placed such that the production constraint is mitigated and the additional cost that might be incurred due to additional travel is minimized too. If alternate sequences are to be considered, it is critical to have a good layout which can either be based on process layout or cellular layout.

In a process layout, all machines which perform similar type of operations are grouped together as a department. In this layout, the products travel from one department to another depending upon their sequence of operation. For example, similar machines drilling, milling, grinding, lathes, etc. are grouped as a department. Greater convenience in performing an operation is achieved with high machine utilization rate in process layout. Furthermore, the inspection of parts can be decreased due to the higher expertise achieved by workers with the similar kind of operation. As the availability of similar type of machines is high, scheduling can be done with ease. With machine breakdowns, if similar alternate machines are available within the facility then the sequence of operations is not affected.

In a cellular layout, parts are formed as part families based on the similar machining processes. Each part family is allocated to a machine cell which consists of different type of machines together. Cellular layout is most advantageous when there is a medium volume and variety of parts. Machine failures often take place in a cellular manufacturing environment. The processing of various parts in a cell is delayed and due dates of the parts are affected due to the occurrence of machine failures. The various techniques such as grouping of machines into cells based on machine reliabilities, selection of alternative routes based on machine reliabilities and intercellular transfer of parts to another machine are the ways to reduce the delay of processing of parts during machine failure. High penalty is being laid for the suspension of production due to machine failures. Machine repair times may vary for each of the individual machines. The cost incurred in suspending the production for machine repairs might be more than the cost incurred in routing the parts to alternate machines. Also, the total time for manufacturing of parts with intercellular transfer might be less than that of without intercellular transfer during machine failures. Material handling costs are incurred due to the intercellular transfer of parts to the alternative machine in the other cell. Several methodologies have been developed in order to reduce the system costs and increase the reliability of machines.

Elleuch, Bacha, Masmoudi and Maalej (2008) proposed grouping of machines temporarily to form virtual cells which leads to the intercellular transfer of parts to a secondary machine during the breakdown of the primary machine. A cellular manufacturing system with two cells having three machines in the first cell and four machines in the second cell was considered for the analysis. Also the standby machines for the primary machines were considered. The waiting time of transfer to another cell was taken into account. The delay caused by the transfer preparation was distributed exponentially. An analytical method based on the property of Markov chain was used for modeling the availability of a cell. The system performance with and without the intercellular transfer during the breakdown was tested by simulation. The results obtained showed an improvement in cell availability with the use of intercellular transfer. The results were evaluated by considering cell productivity and machine utilization rate as performance criteria.

Jabalameli, Arkat and Sakri (2008) take into account the machine reliability and alternative process routes and developed a mathematical model which minimizes the intercellular movement costs and machine breakdown costs in addition to maximization of machine reliability. Simulated annealing, genetic algorithm and memetic algorithm were the three kinds of metaheuristics developed in order to solve the proposed mathematical model. The performance of branch and bound optimum algorithm was compared with that of the proposed algorithms by means of some numerical examples. The results obtained showed that branch and bound algorithm performs better with small size problems. It has been concluded that simulated annealing and memetic algorithm show better performance than genetic algorithm and branch-and-bound algorithm.

A bi-objective linear integer programming model which considers alternative process routes and machine reliability for the generalized cell formation problem was considered. The effects of costs and time due to unreliability of machines were considered. Minimization of total costs was considered as primary objective and minimization of the total time was taken as the secondary objective. ε-constraint method has been used to optimize the proposed model. With the use of a numerical example the performance of the model in analyzing several aspects such as total cost, total time and total movement cost has been compared with and without reliability consideration. The alternative processing routes considered had different number of machines in each alternate route for each individual part. Also the processing times vary for each individual route for each part. The results obtained showed that total movement costs increase while the total costs and total time decrease with machine reliability consideration. (Ameli, Arkat & Barzinpour, 2008).

Ameli and Arkat (2007) proposed a linear programming model by taking process sequence of parts and production volumes into account for the formation of machine cells. Furthermore, the proposed model has been considered with alternate process routes and machine reliability. A numerical example was used to compare the objective function of the model and formation of the cell configuration was done with and without reliability consideration. The number of machines and the total processing time of each alternative route for each individual part were different. The machine breakdown time was exponentially distributed and failure rate was known for reliability consideration case. The results show that there were increased intercellular movements and reduced overall costs when machine reliability was considered.

Das, Lashkari and Sengupta (2006) proposed a multi objective model to design a cellular manufacturing system which minimizes the system costs and maximizes the reliability of the system. The primary objective of the model was to optimize the machine variable costs, intercellular costs and machine non-utilization costs. The secondary objective was to select the best route with high reliability for the part type. A simulated annealing algorithm which combines the crossover and mutation operations of the genetic algorithm was developed in order to solve the proposed model. A numerical example having 24 part types and 14 machines was solved using the proposed model by considering several cases each having different values in the objective function. The cell configurations for each of the considered cases were obtained by use of simulated annealing technique.

Diallo, Pierreval and Quilliot (2001) presented an effective methodology for the configuration of cells when the part process plans were changed due to the machine breakdowns.

The reconsideration of process plans helps to overcome the disturbances caused due to the machine failures. Hence, alternate process routes should be considered during the cell configuration instead of a single process plan for each part. The methodology used in the cell configuration was based on the Markov chain model. Generalized optimization procedure has been used for the optimization of the model. A numerical example was solved in order to obtain the new cell configuration and process plans for each part by the use of the proposed methodology. The obtained cell configuration was compared with that of the configuration obtained without reliability consideration. The results obtained shows that the total number of parts transferred between cells was less in case of the configuration obtained by proposed methodology than the configuration without reliability consideration.

Jeon, Leep and Parasaei (1998) proposed a cell configuration procedure which consists of two phases. In phase 1, the possible number of alternative routes during machine failure was found by a new similarity coefficient and part families were formed by the use of p-median model. In phase 2, a mathematical model which takes into account the operational and scheduling aspects when a machine failure occurs was considered and their effects on machine utilization was observed. A numerical example has been solved using the proposed methodology and the cell configuration of the cellular manufacturing system has been obtained. The main aim of the proposed methodology was to form machine cells by minimizing the penalty cost for early or late finishing, cost of holding inventory, cost of operation and machine investment.

The number of alternative process routes during machine failure was found with the use of similarity coefficient for two parts by considering a numerical example. Part families were recognized by the application of p-median model with the use of similarity coefficients. Furthermore, a procedure for solving the same has been explained by considering C-program environment. (Jeon, Broering, Leep, Parsaei & Wong, 1998). Logendran and Talkington (1997) presented a comparison between cellular and functional layouts by taking machine breakdown and batch size into account. Two types of repair policies were considered in this study such as repair when breakdown occurs and preventive maintenance. Work in process and mean throughput time were the two performance measures used to compare the layouts. Hypothesis testing was used to determine the difference between two layouts by considering their performance measures. The configuration of cellular and functional layouts using 40 parts and 30 machines has been considered. The results obtained shows that in the absence of preventive maintenance, functional layout performs better than the cellular layout.

3.4 Research Objective

Cost of production within a manufacturing facility can broadly be classified into Supply chain cost, and facility and planning cost. Supply chain cost can further be classified into raw material cost which consists of procurement cost and other overheads involved in procuring the material like warehouse cost, trucking cost, etc. Facility and planning cost involve the following costs - labor, production cost, scrap cost, material handling cost, downtime/maintenance cost, facility layout cost, etc.

The objective of the manufacturing facility is to maximize profit by providing a quality product within the demanded time. One key to profitability and customer satisfaction is to meet customer demand in expected time. Profit can be maximized with utmost customer satisfaction if the facility is able to meet demand for each product within given time period. To achieve this, the facility has to operate within the capacity constraints it might have.

Constraints can be classified into capacity constraints and logistic constraints. Capacity constraints can further be classified into production capacity and material handling capacity constraint. Logistic constraints include constraints associated with supply chain, ware house space, and facility layout.

This research focuses on meeting the demands on the manufacturing system and increasing the profitability within the defined constraints by evaluating alternative sequences that can be used to manufacture a part. This research is limited to deterministic conditions and known demands. Hence demands for all time periods are known at the beginning of the first time period.

3.5 Methodology

Earlier research by Shah, Krishnan, and Dhuttargoan (2014) evaluated the impact of constraints on a facility layout under dynamic conditions. This paper enhances the research further by studying the impact of another parameter that could influence the production facilities capability to meet demand: part (or production) sequence.

Each part is manufactured by performing a specific sequence of steps and processes (operations). These steps and processes are required to take the part from its initial raw material form to its final shape and form. These operations are normally carried out in a specific sequence which is identified as process (or production) sequence. The process sequence is thus a series of operations that are needed to be carried out on a part starting from raw material to its final shape, fit, and form. For a part, there may be a single unique process sequence or it may have more than one sequence depending on the type and quantities of machines available in the facility.

As the process sequence provides details regarding steps required to convert the raw material its final form, it also provides details regarding the machines that will be required to make a given part. Besides the machines that are required, a process sequence also provides details regarding production times each part requires on the machine it needs to be processed on. So a process sequence provides details related to machines required and machine capacities required by a part to take it to its final fit and from. Process sequence thus can be used to determine the required production capacity. Thus production capacity limitations can be addressed by considering alternative process sequence or by adding new machines.

Thus, ability of a production facility to meet demand is a function of production capacity, material handling capacity, facility layout, and process sequence. The facility can successfully meet demand if all of the parameters are favorable to meeting demand, but it could fail to meet demand even if one parameter is not favorable. Thus failure to meet demand could be due to one of the following conditions or a combination of the following conditions:

3.5.1 Logistic and Production Capacity Constraints

As product demands change, the manufacturing system may fail to meet demand due to logistic or production capacity constraints. To meet demand, the facility may have to add production or material handling capacities or a combination of both. Production capacity restrictions can be alleviated by adding new machines with higher capacities (faster processing) replacing the existing lower capacity machines. Alternatively, adding machines with similar capacity as the bottle neck machine, thus doubling the capacity at that machine station could also help in improving production capacity. If the demand cannot be met due to material handling capacity constraints, the facility can add more material handling units. This can be done by adding more MH units with similar capacity or replacing the MH units with units that can handle more capacity. Material handling constraints can also be improved by changing speed of material handling. If a facility is in transition state, then there would be a need to add both production capacity and material handling capacity. Shah, Krishnan, and Dhuttargoan (2014) evaluated the impact of constraints on a facility layout under dynamic conditions.

3.5.2 Inefficiency of Facility Layout

Another possibility for failure to meet demand is inefficiency in facility layout. Under that situation, the facility has an alternative to re-evaluate the facility layout and re-arrange it. Changing facility layout involves fixed and variable cost. Going from one time period to another, the manufacturing facility can invest in changing the facility layout. A given layout may work fine for one product mix with given demands in a given time period, but may not work for the next product mix due to demand changes. Frequent facility design and changes can be expensive. Hence changing facility layouts may not be the most feasible long term option if demand cannot be met under dynamic conditions.

3.5.3 Demanding Part Sequence

Failure to meet demand can also be due to a demanding process sequence for a given product mix. Process sequence is a series of operations that each part as to go through starting from raw material to its final shape, fit, and form. While the combination of all operations is necessary for making that part, there is a possibility for operations to be re-sequenced. Re-sequencing of the operations involves re-routing the part through a different set of machines or through the same set of machines using different order than original.

Thus if demand cannot be met, an alternative solution is to evaluate process sequences. Based on the type of machines and the capabilities of the machines, it may be possible to make the same part using different set of machines or by following a different sequence of operations. For example if machines 1, 2 have similar capabilities and machines 3 and 4 have similar capabilities, and a part is normally made using machines 1 followed by 3, the primary sequence for that part would be 1-3, however since machine 1 and 2 are similar in capabilities, a possible alternate sequence would be 2-3. As machines 3 and 4 have similar capabilities, the part can also be produced on 1-4 or alternatively the part can be produced on machines 2-4. Thus the possible sequences for the part are 1-3, 2-3, 1-4, or 2-4. Based on capacity evaluation; if we find that machine 1 is over utilized, either capacity can be increased by adding another machine 1 or we can manufacture the same part using sequence 2-3 or 2-4 if enough capacities are available on the machines required in one of those two alternate sequences. Using an alternate process sequence can thus be considered as another way of eliminating production constrained state. However, when using an alternate process sequence, the cost of processing may increase. An algorithm showing general procedure for the research is shown in the Figure.3.1.

Identification of system state and details of methods associated with it are described by Shah, Krishnan, and Dhuttargoan (2014). They also described a method using GA to generate a new facility layout. However a limitation of that research was that the only solution that was considered was to add more machines at required locations as a solution to add more production capacity. The research did not evaluate the effectiveness of moving bottlenecks due to production capacity by considering alternate process sequence. This paper introduces the concept of using alternate sequence as a method to introduce more production capacity in case of a dynamic facility layout problem. It also introduces a method to determine optimal sequence from all possible sequences to make each part in the product mix. Thus the facility can use the alternate sequence in lieu of adding more machines to add production capacity if optimal sequence is resource intensive. As mentioned earlier, a given process sequence determines how a part is converted from its raw material from to its final fit and form. The process sequence thus provides details associated with machine usage.

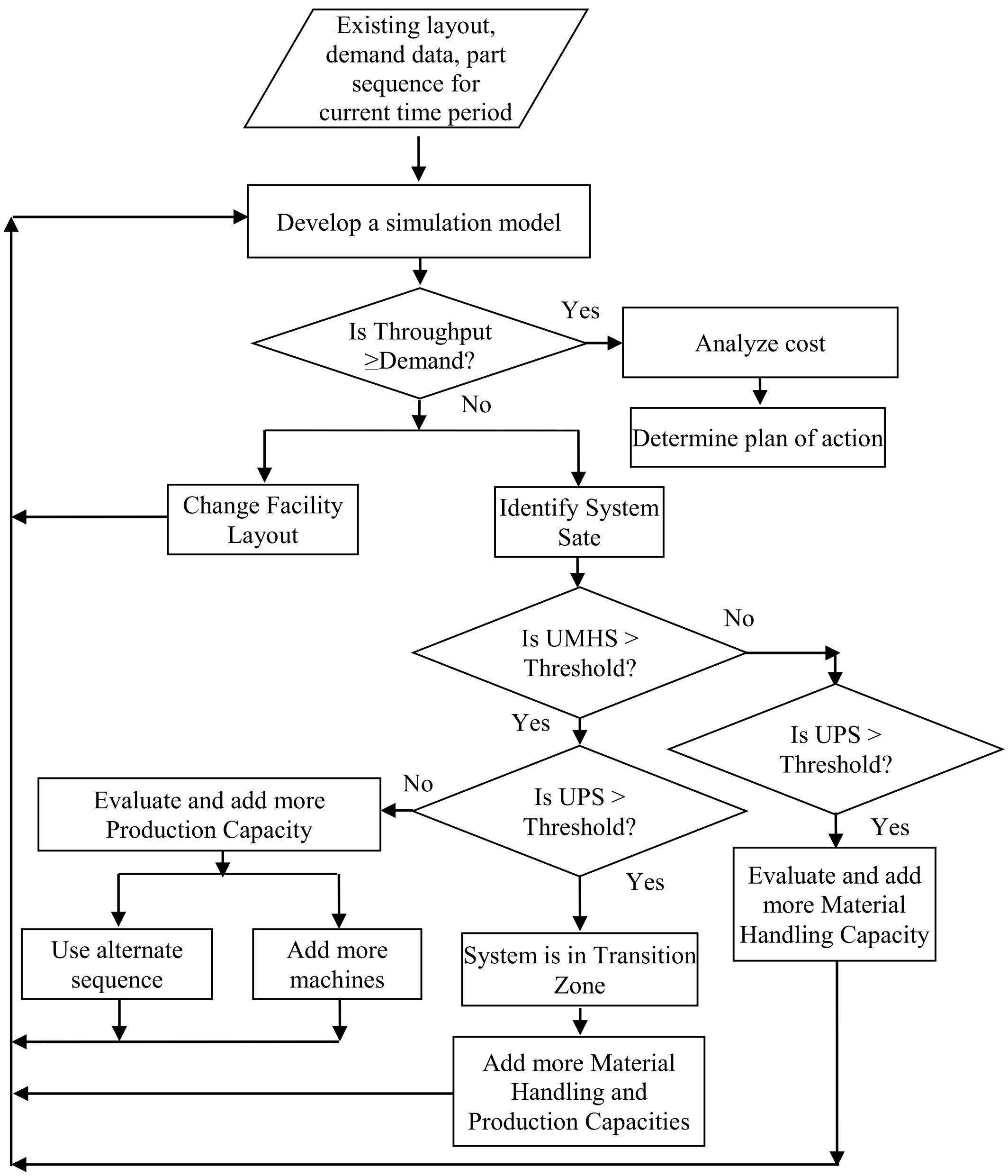

Figure 3.1. Redesign methodology flowchart

As process sequence provides details associated with machines and time required by a part on each machine, analyzing a process sequence provides details about utilization and available capacities available on the machines. In other words, it provides details regarding production system constraints based on sequence selection. If process sequence analysis is carried out, we can determine over utilization and underutilization of machines beforehand and can select appropriate sequence so that production system utilization would not be a limiting constraint. With process sequence analysis carried out early, the general methodology flowchart above can be modified as shown in Figure 3.2.

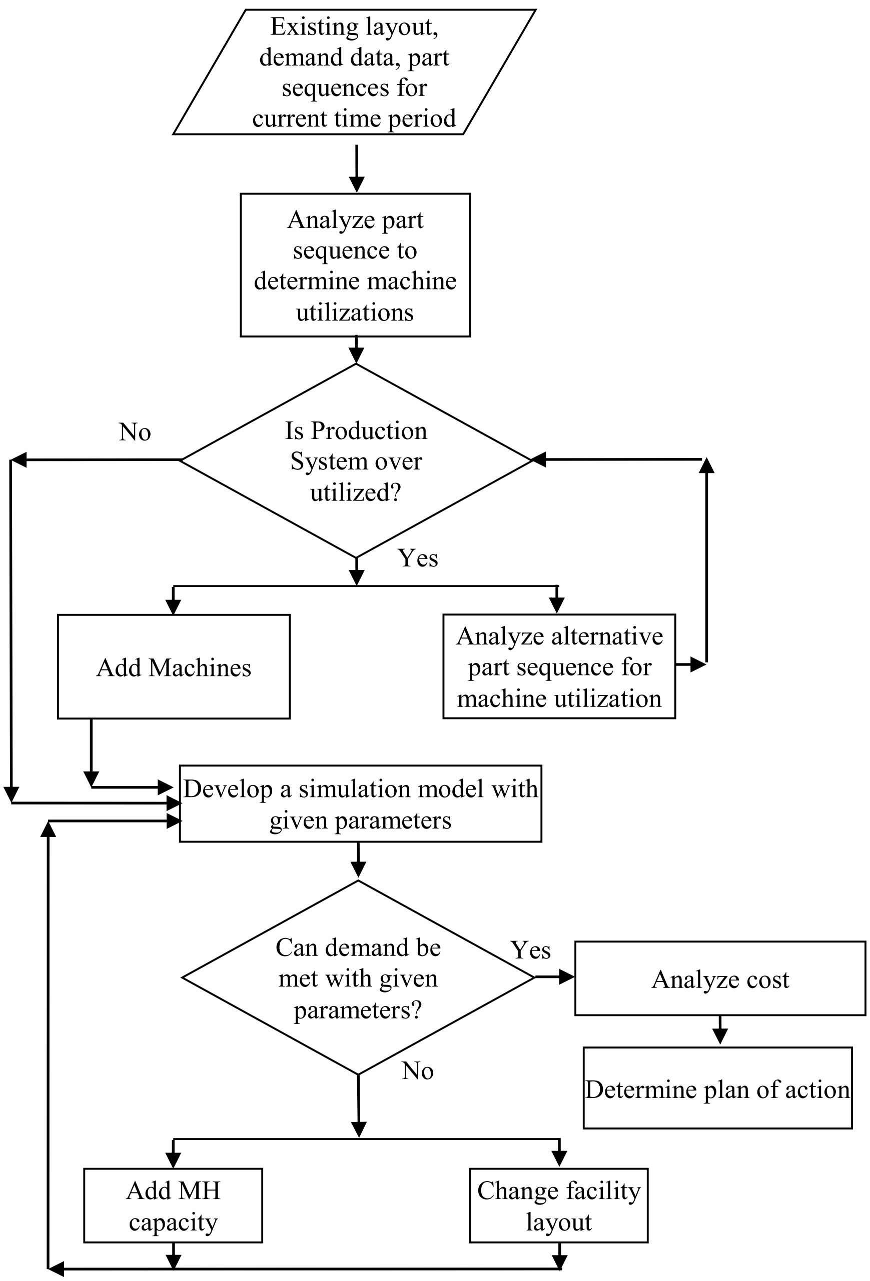

Figure 3.2. Modified redesign methodology flowchart

3.6 Cost Estimation

Cost of meeting demand is a function of the production sequence selection, facility layout changes and addition of production and material handling capacities as necessary based on the process sequence selection. Costs can be classified into production cost, facility layout Cost, and material handling Cost.

Notations

n = machine type; n = 1,…, N,

i = machine location; i = 1,…, N,

j = machine location; j = 1,…, N-1,

p = total number of products, ranges from p = A, …, P,

s = total number of sequences, ranges from s = 1, …, S,

t = time period under consideration

pst = total number of sequences for product p

ps = sequence number s for product p

t_{ntps} = Time product p takes on machine n selecting sequence ps during time period t

cx = specific combination with selected sequence for every product, x = 1, …, n,

c = total number of combinations possible with selected ps for every product

d_{pt} = demand for product p in time period t

T_{tps}= Total production time required for product p during time period t using sequence ps

UMC_{ncxt} = Average utilization of each machine type (n = 1 to N) for a selected sequence combination cx during time period t

TV = Threshold value

O_n = Operating cost of machine type n

C_{cxt} = Cost of production using sequence combination *cx* for time period *t*

C_{pt} = Production cost of meeting demand during time period t

C_{ptg} = Cost for GA function during time period t

C_{pT} = Total cost of meeting demand over all time periods

m = number of MHUs; *m* = 1,…, M,

UMH_{mcxt} = Percentage utilization of each material handling unit (m = 1 to M) for a selected sequence combination cx during time period *t*

UMH_{cxt} = Average percent utilization of all material handling units (*m* = 1 to M) for a selected sequence combination cx during time period *t*

$$X_{ijtps} = \begin{cases} 1, & \mathit{if\ there\ is\ flow\ between\ departments\ i\ and\ j\ for\ product\ p\ during\ time\ period\ t,} \\ 0, & \mathit{Otherwise} \end{cases}$$

g_{ijtps} = Dynamic flow between departments *i* and *j* during time period *t* for *ps*

D_{ijtps} = Distance between departments *i* and *j* during time period *t* for *ps*

C = Cost of carrying a part per unit distance

M_{tps} = Material handling cost during time period *t* using *ps*

F_t = Fixed cost of transition to current time period

V_t = Variable cost of transition to current time period

$D_{n(t-1,t)}$ = Distance each machine has to be moved going from time period *t-1* to *t* for *ps*

Y_n = Cost per unit distance of the moving machine from one location to another

A_t = Cost of adding production capacity in time period t

n_t = total number of machines of type ‘n’ that are required in time period t

a_n = cost of each machine of type ‘n’

B_t = Cost of adding material handling capacity in time period t

m_t = number of MHUs that are required to be added in time period t

b_m = cost of each MHU ‘m’

3.6.1 Production Cost

Process sequence provides information associated with the machines required and time required by the part on each machine to be converted from raw material to finished product. Optimal sequence is selected using the optimal sequence selection procedure. Each sequence combination *cx* has a specific combination of *ps*. The process sequence provides details associated with t_{ntps}. Average utilization of each machine associated with *cx* can be calculated as:

$$UMC_{ncxt} = \Big(\sum_{p=A}^{P} t_{ntps} * d_{pt} \Big) / n_t \tag{3.1}$$

Cost of production is calculated using the utilizations of the machines and the operating cost of each machine.

$$C_{cxt} = \sum_{n=1}^{N} \{ (UMC_{ncxt} * n_t) * O_n \} \tag{3.2}$$

3.6.2 Material Handling Cost

Material handling cost is a non-value added cost. However a manufacturing facility incurs by taking the part from one machine to the next so that it can be converted from raw material to finished product. As the selection of the machines depends on the process sequence selected, the material handling cost depends on the process sequence selected. Material handling cost depends on the distance between machines that the parts need to travel. Thus it also depends on the facility layout. If *gijtps* represents the dynamic flow between departments, and *Dijtps* is the distance between departments and the cost of carrying a part per unit distance is C, then we can calculate dynamic flow between machines i and j depends on whether or not a part flows from i to j depending on the sequence selected. Thus for a selected sequence, we can find dynamic flow between departments i and j using equation (3.3).

$$g_{ijtps} = \sum_{p=A}^{P} d_{pt} * X_{ijtps}, i=1,\ldots,N-1; j=i+1,\ldots,N \tag{3.3}$$

Material Handling cost during time period 't' *Mtps* can be calculated as shown in equation (3.4).

$$M_{tps} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijtps} * D_{ijtps} * C \tag{3.4}$$

3.6.3 Rearrangement Cost

Rearrangement cost consists of two different cost components: a variable cost component and a fixed cost component.

Equation (3.5) shows the calculation for Fixed Cost component:

$$F_t = F_{t-1,t} \tag{3.5}$$

The variable cost depends on the cost of the production time lost during the rearrangement period and also depends distance that the machines have to be moved from the current location to the new location. For the purpose of this research, we assume that the machines are moved from one location to another between time periods and thus there is no down time. Thus the rearrangement cost reduces to just the cost of moving the machines from one location to another. Variable cost going from time period *t-1* to *t* can thus be defined as a function of the cost associated with the movement of machines which depends on the distance *Dn(t-1,t)* each machine has to be moved and cost *Y* per unit distance of the move. It can be calculated as shown in equation (3.6).

$$V_t = \sum_{i=1}^{N} \sum_{j=1}^{N} D_{n(t-1,t)} * Y_n \tag{3.6}$$

3.6.4 Cost of Adding Production and Material Handling Capacities

If the demands cannot be met with the current capacities of production and material handling, it might indicate that the system is constrained by production capacity or material handling capacity or both. If the facility is constrained by production capacity, we can add more production capacity by adding new machines at the location where capacity is a constraint. The cost of adding production capacity depends on the type of machine that needs to be added. Thus, cost of increasing production capacity in given time period '*t*' depends only on the number of machines that will have to be added and can be calculated by equation (3.7).

$$A_t = (n_t - 1) * a_n \tag{3.7}$$

Similarly, if more material handling capacity is needed, material handling units can be added and the cost of adding material handling capacity can be calculated as shown in equation (3.8).

$$B_t = m_t * b_m \tag{3.8}$$

3.6.5 Total Cost

Total cost of production for a given time period is given by sum of all costs i.e. sum of production cost, cost of material handling, cost associated with facility rearrangement and cost associated with adding more material handling and production capacities. It is calculated by the equation (3.9).

$$\begin{aligned} C_{pt} = \sum_{n=1}^{N} \{(UMC_{ncxt} * n_t) * O_n\} + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijtps} * D_{ijtps} * C + F_t \; + \\ \sum_{i=1}^{N} \sum_{j=1}^{N} D_{n(t-1,t)} * Y_n \pm (n_t - 1) * a_n \pm (m_t * b_m) \end{aligned} \tag{3.9}$$

The plus or minus sign in the fourth term is used to account for an increase in overall cost (if production capacity needs to be added) and reduction of cost (if the production cost can be reduced) respectively. A similar approach is used for the material handling cost calculation in the fifth term.

However, when the layout is determined using the GA, the additional capacity necessary for meeting the material handling and production requirement has not been determined. This can be analyzed only after the simulation has been used to determine capacity limitations. Hence, while running the GA the cost function (C_{ptg}) does not take into consideration, the additional capacity needed in production and material handling.

$$\begin{aligned} C_{ptg} = \sum_{n=1}^{N} \{(UMC_{ncxt} * n_t) * O_n\} + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijtps} * D_{ijtps} * C + F_t \; + \\ \sum_{i=1}^{N} \sum_{j=1}^{N} D_{n(t-1,t)} * Y_n \end{aligned} \tag{3.10}$$

The planning horizon consists of 'T' time periods. Equation (3.11) shows the total production cost over the planning horizon which is the sum of production costs incurred in each time period.

$$C_{pT} = \sum_{t=1}^{T} C_{pt} \tag{3.11}$$

3.7 Procedures

Listed below are the different procedures used through the research.

3.7.1 Procedure for Process Sequence Analysis and Optimal Sequence Selection

Process sequence provides details associated with machines required and times required for a given part on each of the machines it needs to be processed on. Using these two parameters, and demand for each time period, production system capacity and constraints can be using the flowchart shown in Figure 3.3.

The objective function of a manufacturing facility is to minimize overall cost of meeting demand. The objective function is defined in equation (4.13).

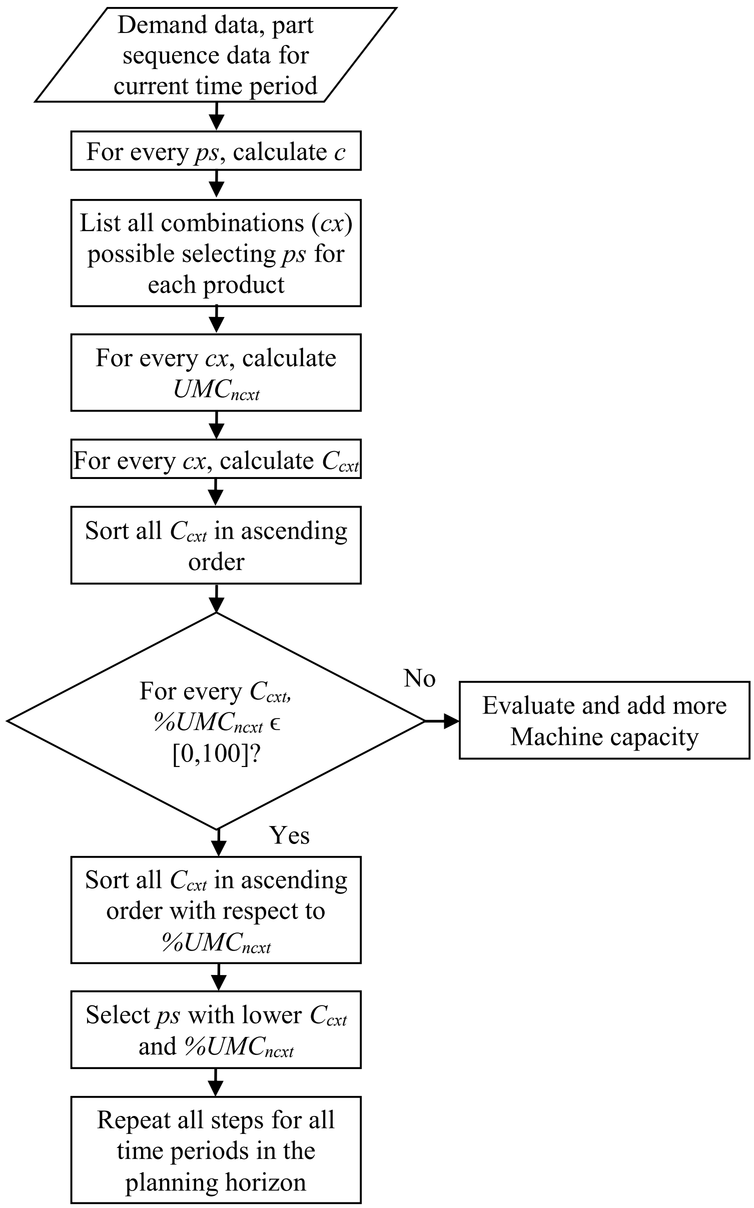

Figure 3.3. Flowchart for part sequence analysis and optimal sequence selection

Steps for the calculations are as shown:

Step 1: The procedure starts with the Process Sequence data (machine required, time required by each part on machine t_{npts}) and demand data for each product during given time period d_{pt}.

Step 2: For every product p, there are pst sequences. Based on the number of products and number of sequences by which each product can be manufactured, we can calculate total number of product sequence combinations possible as shown in equation (3.12)

$$c = \prod_{p=A}^{P} \left(\frac{pst!}{1!(pst-1)!} \right) \tag{3.12}$$

It can be simplified as

$$c = \frac{Ast!}{1!(Ast-1)!} * \frac{Bst!}{1!(Bst-1)!} * \ldots\ldots * \frac{Pst!}{1!(Pst-1)!}$$

For example if there are 2 products (p = A, B) and each can be made by 3 possible sequences x1, x2, x3 for A, and y1, y2, y3 for B and the total number of combinations possible to make A and B can be calculated as follows:

$$c = \frac{3!}{1!(3-1)!} * \frac{3!}{1!(3-1)!} = 9 \tag{3.13}$$

The combination can be listed as shown in Table 3.1.

TABLE 3.1

LIST OF POSSIBLE SEQUENCE COMBINATIONS

c1	**c2**	**c3**	**c4**	**c5**	**c6**	**c7**	**c8**	**c9**
x1y1	x1y2	x1y3	x2y1	x2y2	x2y3	x3y1	x3y2	x3y3

So if sequence combination c2 is selected, it means that product A is made using sequence x1 and B is made using sequence y2.

Step 3: For every sequence combination cx possible, calculate UMC_{ncxt} (with $nt = 1$ at beginning of each time period) using equation (3.1) for every machine type 'n' with Process Sequence data ps and demand data d_{pt} for that time period.

Step 4: For every sequence combination cx possible, calculate C_{cxt} using equation (3.2).

Step 5: Sort all C_{cxt} in ascending order.

Step 6: For every C_{cxt}, calculate $\%UMC_{ncxt}$ using equation (3.13)

$$\%UMC_{ncxt} = \left(\frac{UMC_{ncxt}}{TV} \right) * 100 \tag{3.13}$$

Step 7: For every C_{cxt} check if $0 \le \%UMC_{ncxt} \le 100$. For all values of $\%UMC_{ncxt}$ meeting this condition, sort C_{cxt} in ascending order with respect to $\%UMC_{ncxt}$. For example consider C_{cxt} and $\%UMC_{ncxt}$ values for a machine during a given time period shown in the Table 3.2.

TABLE 3.2

COST AND UTILIZATION FOR EACH SEQUENCE COMBINATION

Unsorted	C_{cxt}	$\%UMC_{ncxt}$
c1	50	70
c2	50	45
c3	80	65
c4	70	45

These sorted C_{cxt} values with respect to $\%UMC_{ncxt}$ are shown in Table 3.3.

TABLE 3.3

COST AND SORTED PERCENT UTILIZATION FOR EACH SEQUENCE COMBINATION

C_{cxt}	$\%UMC_{ncxt}$	**Sorted**
50	45	c2
50	70	c1
70	45	c4
80	65	c3

If the values $\%UMC_{ncxt}$>100, follow the procedure for evaluating the need for more machine capacity.

Step 8: Select *cx* with the lower value between C_{cxt} and $\%UMC_{ncxt}$ from the sorted list.

Step 9: Repeat steps 2 thru 8 for every time period until the end of the planning horizon.

3.7.2 Procedure for Determining Production Capacity Required

Instead of selecting alternative sequence to make the parts, in order to meet demand, the facility can add more production capacity by adding additional machines of similar capacity as existing machines. Each machine that is over utilized will need additional capacity. Flowchart in Figure 3.4 shows the procedure to determine production capacity requirement.

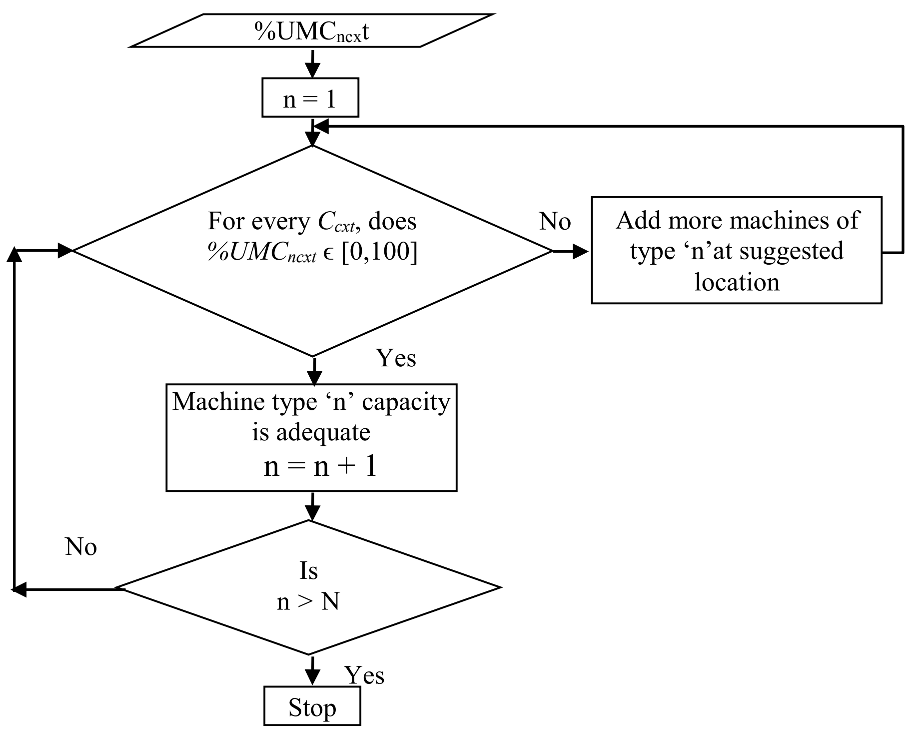

Figure 3.4. Flowchart for determining production capacity requirement.

Over utilization and subsequent evaluation for requirement of additional capacity can be done by following steps listed below:

Step 1: Use $\%UMC_{ncxt}$ calculated in the procedure for part sequence analysis and optimal sequence selection as the input.

Step 2: For n = 1; for every C_{cxt} check if $0 \leq \%\ UMC_{ncxt} \leq 100$, if so the machine capacity for machine type 'n' is adequate. If not, add 1 more machine of type 'n'.

Step 3: Set n = n + 1; if new n >N; stop else go to Step 2.

3.7.3 Procedure for Simulation

Step 1: Using the layout generated by the GA procedure as described by Shah, Krishnan, and Dhuttargoan (2014), the selected sequence for making the part using the procedure above, production capacity associated with the sequence, develop a simulation model. Besides those parameters, data associated with MH capacity, and rate of part generation at the source for given period are also used to build simulation model. For purpose of this research, at the beginning of simulation for a given time period, the MH capacities is kept same as in the previous time period. Rate of part generation is calculated using the Rate of Part Generation procedure as described by Shah, Krishnan, and Dhuttargoan (2014); repeated here for clarity.

Step 2: Run simulation for a total time period which includes warm up time and time associated with the given time period. Warm-up time is introduced to ensure that the model achieves steady state prior to data collection.

Step 3: Analyze results obtained from simulation to see if the throughput is equal or greater to the demand data for the time period. If demand is met, we can conclude that the combination of input parameters (layout, production capacity, and material handling capacity) can be used for the given time period and we can run simulation for the next time period. If demand is not met, go to step 4.

Step 4: As we have already checked the system for production capacity, the system cannot be in production constraint zone, so for the facility to be able to meet demand, we may be in logistic constraint zone or transient zone and hence we need to change layout or add more material handling capacities. Procedures for both were described by Shah, Krishnan, and Dhuttargoan (2014) and are repeated here for clarity.

3.7.4 Procedure for Part Generation

The rate of part generation uses demand data as input. This rate governs the frequency with which new parts are generated at the source for being processed through the system before it goes to the sink. Rate of part generation is important to ensure that the right mix of product types are generated at the source at the right time. For example, if six pieces of product ‘A’ and ten pieces of product ‘B’ were to be produced at the source per hour, the rate of generation for product ‘A’ would be every ten minutes while the rate of generation for product ‘B’ would be every six minutes. This would ensure that a right quantity of product mix is generated at the right time. If all products in required quantities were made available at the beginning of the simulation, Quest would stack all six pieces of product ‘A’, then stack ten pieces of product ‘B’ above that and so on. As the material handling system picks up parts on a first-in-first-out (FIFO) basis from the source, this would result in all six pieces of product ‘A’ being picked up by material handling system and taken toward the first machine before any instance of product ‘B’ would be picked up by the material handling system. This would not represent a practical condition. To ensure that this does not happen, part generation was driven by a file based process. A file based process allowed us to create an input file with all the times at which the parts were to be produced and the sequence in which the parts were to be produced. This input file was then used as the logic to generate parts at the source. By doing so, it can be ensured that the first instance of product ‘A’ is created at six minutes on the simulation clock, first instance of product 'B' is created at ten minutes on the simulation clock, followed by two instances of product 'A' created at twelve and eighteen minutes respectively before second instance of product 'B' is created at twenty minutes on the simulation clock. To eliminate idle time for the material handling system and production systems till the first part is created, an instance of each part was created at the source at start of the simulation before the file based generation kicked in. Steps involved in calculating production rates and generating a file based input are as shown:

<u>Step 1</u>: Obtain Q_{pt} demand data for all products (P) for a given time period

<u>Step 2</u>: Calculate R_{pt} - rate at which an instance of a part type has to be made available at the source. This can be done by equation (3.14).

$$\forall P\left(\text{for a given } t\right):\ R_{pt} = Q_{pt} / t^{*} \tag{3.14}$$

<u>Step 3</u>: Create a table with R_{pt} values for product p=A. Append the table with R_{pt} values for product B, product C and so on till all products are included in the table.

<u>Step 4</u>: Sort R_{pt} data in ascending order with respect to time.

<u>Step 5</u>: Calculate difference in time between each instance of part production by subtracting value in Row 2 from Row 1; Row 3 from Row 2; and so on. This gives the relative time of part production with respect to previous time of part production.

<u>Step 6</u>: With lot size of one, save this data as .dat file to be used for file based production schedule in Quest.

3.7.5 Procedure for Material Handling Capacity

<u>Step 1</u>: Obtain and use data from initial simulation model for a given time period.

Step 2: Let UMH_{mcxt} be percentage utilization of each material handling unit (m = 1 to M). Calculate average percentage utilization UMH_{cxt} for all material handling units using equation (3.15)

$$UMH_{cxt} = \left(\frac{\sum_{m=1}^{M} UMH_{mxct}}{M} \right) \tag{3.15}$$

Step 3: Check if $UMH_{cxt} \leq$ Threshold Value, if yes Material Handling system capacity is adequate, if not add MH units. For sake of simplicity, for the purpose of this research one material handling unit is added at a time before running simulation model again to check if demand can be met.

3.7.6 Procedure for Facility Layout Changes

As shown in previous literatures, facility layout problems are np-hard and it is easier to solve using heuristics. The GA algorithm used for this approach has been developed by Krishnan, Jithavech and Liao (2009). The parameters of the procedure have been modified with slight changes in the objective function and in fitness function. The procedure is briefly outlined here for the sake of completion.

Similar to most genetic algorithms applied to facility layout problems, a one-dimensional array chromosome is used to represent the order of departments to be placed in a layout. The chromosomes were represented by numerical representation (e.g., 02, 08, 04, 11,…etc.) of a string placement scheme for the layout generation. An s-shaped placement scheme in which, departments are placed in successive rows from left-to-right and then from right-to-left is used for locating department. The width and height of the facility were specified for placement of the departments.

For example, the placement of departments for the string 120803050910040701021106 is shown in Figure 3.5.

01	02	11	06
7	4	10	09
12	08	03	05

Figure 3.5. Department placement scheme.

The GA cost function is provided in equation (3.10). The cost function attempts to minimize the material handling cost for the projected demand. The fitness function is given in equation (3.16) (Krishnan, Jithavech and Liao, 2009).

$$Fitness\,Value = v(i) = K\left(C_{ptg}\right)^{\alpha-1} e^{-\left(\left(\frac{Z_i - Z^*}{Z^*}\right)\beta\right)} \tag{3.16}$$

where α = 0.4 and β is a dynamic factor that is continuously modified as time increases. For each time period, after experimentation, the following ranges of values are used for β (Krishnan, Jithavech and Liao, 2009):

$$\beta = \begin{cases} 0\,.002Z^*, \text{ when } 0<n<I/5 \\ 0.004Z^*, \text{ when } I/5 \le n<2I/5 \\ 0.006Z^*, \text{ when } 2I/5 \le n<3I/5 \\ 0.008Z^*, \text{ when } 3I/5 \le n<4I/5 \\ 0.01Z^*, \text{ when } 4I/5 \le t \le I \end{cases}$$

where i is the current generation, Z^* is the cost of the best solution in any population, I is the total number of iterations and n is the current iteration. The value of β used in the fitness function is dependent on time as well as minimum cost. This fitness function was designed such that as the cost function value increased, the corresponding fitness value decreased. The probability of accepting a bad solution also decreased as the time increased.

The steps used in generating the layout using the GA procedure are as given:

Step 1: Determine population size (Y) and number of iterations (I).

Step 2: Generate a random layout (string/chromosome), and set $y_{gst} = 1$. Conduct a string feasibility check. The condition for infeasibility exists when a department is represented twice in a string. In a case where the string is not feasible, eliminate the second occurrence of the same department, and replace it with a department that is not represented in the string (corrective action). Evaluate the fitness of this string. Set $y_{gst} = y_{gst} + 1$.

Step 3: If $y_{gst} + 1 < Y$, then go to Step 2; otherwise, set $g_{st} = 1$. Save the ten best-fit strings according to fitness values, and use the ten best-fit solutions for crossover and mutation.

Step 4: Perform the roulette wheel selection method for crossover in the selection of the parents based on fitness values obtained. After the crossover and mutation operations, check the new strings obtained for feasibility; if required, and perform corrective action. Add strings into a new generation $g_{st} + 1$. Set $y_{gst+1} = y_{gst+1} + 1$.

Step 5: If $y_{gst+1} + 1 < Y$, then go to Step 4; otherwise, set $g_{st} = g_{st} + 1$. Retain the ten best-fit strings based on fitness value. Perform elitism operation by keeping the ten best-fit solutions from the combined set of layouts generated in the two runs. Continue the process until n $= I$ is satisfied.

3.7.7 Example to Illustrate Usage of Formulation Above (4-machines, 2-products, 3-time periods)

Let us assume a facility with 4 machines makes 2 products. Product demands in every time periods are known and is shown in Table 3.4. Thus there are two sequences for each product. Thus $A_{st}=B_{st} = 2$. The sequences for each product are shown in Table 3.5.

TABLE 3.4

PRODUCT DEMAND

Product	Demand d_{pt}		
	t=1	t=2	t=3
A	5	10	10
B	10	10	15

TABLE 3.5

POSSIBLE PRODUCT SEQUENCES

Product	Sequence #1	Sequence #2
A	1-2-4	1-3-4
B	1-2-3	2-4

As only one sequence will be selected to make product A and only one will be selected to make B out of the sequences available, we can calculate total number of combinations possible using equation (3.12).

$$c = \frac{2!}{1!(2-1)!} * \frac{2!}{1!(2-1)!} = 4$$

Sequences combinations possible are as shown in the Table 3.6.

TABLE 3.6

POSSIBLE SEQUENCE COMBINATIONS

Sequence Combination cx	Sequence For A	Sequence For B
c1	1-2-4	1-2-3
c2	1-3-4	2-4
c3	1-2-4	2-4
c4	1-3-4	1-2-3

Times required for each product on each machine based on a selected sequence are given in Table 3.7. Production time (t_{ntps} * d_{pt}) and cost (C_{cxt}) for each sequence combination cx calculated using equations (3.1) and (3.2) are shown in the Table 3.8 (n_t = 1).

TABLE 3.7

TIME REQUIREMENTS

Time Period *t*	**Product *p***	**Sequence *ps***	**Demand d_{pt}**	**Time t_{ntps} (minutes)**			
				n=1	**n=2**	**n=3**	**n=4**
t=1	A	1-2-4	5	3	4	0	2
	A	1-3-4	5	3	0	4	2
	B	1-2-3	10	4	4	6	0
	B	2-4	10	0	5	0	4
t=2	A	1-2-4	10	3	4	0	2
	A	1-3-4	10	3	0	4	2
	B	1-2-3	10	4	4	6	0
	B	2-4	10	0	5	0	4
t=3	A	1-2-4	10	3	4	0	2
	A	1-3-4	10	3	0	4	2
	B	1-2-3	10	4	4	6	0
	B	2-4	10	0	5	0	4

TABLE 3.8

MACHINE UTILIZATION AND PRODUCTION COST FOR EACH SEQUENCE COMBINATION

Time Period *t*	**Sequence Combination *cx***	**Sequence For A**	**Sequence For B**	t_{ntps} * d_{pt}				C_{cxt}
				***n*=1**	***n*=2**	***n*=3**	***n*=4**	
t=1	c1	1-2-4	1-2-3	55	60	60	10	101.7
	c2	1-3-4	2-4	15	50	20	50	115.0
	c3	1-2-4	2-4	15	70	0	50	118.3
	c4	1-3-4	1-2-3	55	40	80	10	98.3
t=2	c1	1-2-4	1-2-3	70	80	60	20	133.3
	c2	1-3-4	2-4	30	50	40	60	143.3
	c3	1-2-4	2-4	30	90	0	60	150.0
	c4	1-3-4	1-2-3	70	40	100	20	126.7
t=3	c1	1-2-4	1-2-3	90	100	90	20	168.3
	c2	1-3-4	2-4	30	75	40	80	186.7
	c3	1-2-4	2-4	30	40	0	20	193.3
	c4	1-3-4	1-2-3	70	40	100	20	161.7

Sorted C_{cxt} along with $\%UMC_{ncxt}$ calculated per equation (3.13) for each time period are listed in Table 3.9.

TABLE 3.9

COST AND PERCENT UTILIZATION FOR EACH SEQUENCE COMBINATION

Time Period *t*	**Sequence Combination *cx***	**Sequence For A**	**Sequence For B**	$t_{ntps} * d_{pt}$				C_{cxt}
				***n*=1**	***n*=2**	***n*=3**	***n*=4**	
t=1	c4	1-3-4	1-2-3	91.7	75	133.3	16.7	98.3
	c1	1-2-4	1-2-3	91.7	100	100	16.7	101.7
	c2	1-3-4	2-4	25	83.3	33.3	83.3	115.0
	c3	1-2-4	2-4	25	116.7	0	83.3	118.3
t=2	c4	1-3-4	1-2-3	116.7	75	166.7	33.3	126.7
	c1	1-2-4	1-2-3	116.7	133.3	100	33.3	133.3
	c2	1-3-4	2-4	50	83.3	75	100	143.3
	c3	1-2-4	2-4	50	150	0	100	150.0
t=3	c4	1-3-4	1-2-3	116.7	75	166.7	33.3	161.7
	c1	1-2-4	1-2-3	150	166.7	150	33.3	168.3
	c2	1-3-4	2-4	50	125	75	133.3	186.7
	c3	1-2-4	2-4	50	75	0	33.3	193.3

Based on the cost and percent utilizations for each of the sequence combination for each time period, best sequence combination for each time period is selected. The best sequence combinations for each time periods are listed in Table 3.10.

TABLE 3.10

BEST SEQUENCE COMBINATION FOR EACH TIME PERIOD

Time Period *t*	**Sequence Combination *cx***	**Sequence For A**	**Sequence For B**	$t_{ntps} * d_{pt}$				C_{cxt}
				***n*=1**	***n*=2**	***n*=3**	***n*=4**	
t=1	c1	1-2-4	1-2-3	91.7	100	100	16.7	101.7
	c2	1-3-4	2-4	25	83.3	33.3	83.3	115.0
t=2	c2	1-3-4	2-4	50	83.3	75	100	143.3
t=3	c3	1-2-4	2-4	50	75	0	33.3	193.3

The threshold time for each time period is 60 minutes. As can be seen from the Table above, for time period t=1, sequence combination c1 and c2 have all $\%UMC_{ncxt}$ (using $n_t = 1$) less than or equal to 100, so either of them can be used to make the parts. However cost evaluation C_{cxt} shows that sequence combination c_1 is more cost effective than combination c2. Thus c1 should be used for making the parts in time period t=1. Similar evaluation of time periods t=2 and t=3 shows that only one sequence combination in each time period has $\%UMC_{ncxt}$ less than or equal to 100 and hence are the only sequence combinations that can be used to make the parts in those time periods. Thus for time period t=1, part A and B should be made using sequences 1-2-4 and 1-2-3 respectively. For t=2, part A and B should be made using sequences 1-3-4 and 2-4 respectively and for t=3 they should be made using sequences 1-2-4 and 2-4 respectively. Thus going from time period t=1 to t=2, keeping same layout and production and material handling capacities, we cannot meet demand if we continue to use the same sequences as were used in t=1. However changing sequences going from t=1 to t=2, we can meet demand. Similarly going from time period t=2 to t=3, we can meet demand only if we change sequence for both parts A and B if we want to keep the same facility layout and same capacities of production system and material handling system as in time period t=1. As all calculations shown above cover all time periods, we do not need to repeat any steps as mentioned by Step 8 in steps showing procedure for Process Sequence analysis and optimal sequence selection.

As an alternative to this sequence selection process where we can ensure that production capacity would not be a constraint, the manufacturing facility can opt to use the same sequence in all the time periods but it will then need to add more machines to meet the capacity requirements if the machine was a bottleneck and was over utilized.

Assuming that the manufacturing facility wanted to use sequence combination c4 as it is the most cost effective based on the C_{cxt} values shown in Table 3.9 above, the facility would need to determine production capacity required for that sequence combination selection.

Table 3.11 below shows $\%UMC_{ncxt}$ calculated with initial value of $n_t = 1$ for each of the time period. As can be seen for t=1, $\%UMC_{ncxt}$ for machine 3 is greater than 100, thus an additional instance of machine 3 will be required for time period t=1. Similarly looking at time periods t=2 and t=3, utilization for machine 1 and 3 is greater than 100, thus an additional instance of machine 1 and machine 3 would be required for time periods t=2 and t=3. Thus if the facility chooses to add an additional instance of machine 3 during time period t=1, it would need to add an additional instance of machine 1 during time period t=2 and with the added capacity, it should be able to meet demand in time period t=3.

TABLE 3.11

COST AND PERCENT UTILIZATION

Time Period *t*	**Sequence Combination *cx***	**Sequence For A**	**Sequence For B**	$t_{ntps} * d_{pt}$				C_{cxt}
				***n*=1**	***n*=2**	***n*=3**	***n*=4**	
t=1	c4	1-3-4	1-2-3	91.7	75	133.3	16.7	98.3
t=2	c4	1-3-4	1-2-3	116.7	75	166.7	33.3	126.7
t=3	c4	1-3-4	1-2-3	116.7	75	166.7	33.3	161.7

Thus the manufacturing facility could select alternative sequence during each time period or they can add an additional instance of machine 3 during time period t=1 and add an instance of machine 1 during time period 2. With either of the two solutions selected, we can make a simulation model with all the necessary parameters and the results obtained from the simulation model can be analyzed to see if demand is met or not. If the demand is not met, need for more MH unit is evaluated using procedure for more material handling capacity as described above or we can evaluate the need for new facility layout generation as described by Shah, Krishnan, Dhuttargoan (2014).

If demand is met, cost of meeting demand is calculated as shown in the procedure for cost estimation.

3.8 Case Study (7-departments, 5-products, 3-time periods)

To evaluate if a given sequence, facility layout, and production and material handling capacities are adequate, let us consider a seven department case study with five parts. In this case study the analysis was done using simulation for a given time period. Summarized product information along with demand quantities and possible sequences for each part is shown in Table 3.12. The table also shows demand for each of the part in each time period and the revenue each part generates.

TABLE 3.12

REVENUE, DEMAND, AND SEQUENCE DATA

Part	**Revenue**	**Projected Demands**			**Sequence**		
		t=1	**t=2**	**t=3**	**p1**	**p2**	**p3**
A	30	360	200	200	1-2-3-5-7	2-3-4-6	5-4-1-2
B	40	460	600	800	2-4-6-1	1-2-4-5-	7-5-3-4
C	30	260	1000	1000	5-1-6-3	7-1-3-6-2	3-1-5-7
D	15	320	400	400	1-2-3-4	6-5-2-1	2-5-6-3
E	10	540	800	1100	6-1-4-5-2	6-7-2-1	6-1-4-7-2

Table 3.13 shows the operating cost associated with the operating the machines in the time periods.

TABLE 3.13

OPERATING COST FOR EACH MACHINE

Machine	**Operating Cost**
1	30
2	40

TABLE 3.13 (continued)

Machine	Operating Cost
3	40
4	55
5	70
6	80
7	100

Time each part takes on any given machine based on the sequence selected to make that part is given in Table 3.14.

TABLE 3.14

MACHINE TIME PER PART BY SEQUENCE

Part	Sequence	MC#1	MC#2	MC#3	MC#4	MC#5	MC#6	MC#7
A	1-2-3-5-7	7	3	1		2		8
	2-3-4-6		1	8	3		4	
	5-4-1-2	7	5		4	10		
B	2-4-6-1	6	3		3		1	
	1-2-4-5	1	3		3	6		
	7-5-3-4			2	2	2		3
C	5-1-6-3	10		4		9	2	
	7-1-3-6-2	8	7	2			8	1
	3-1-5-7	3		5		3		3
D	1-2-3-4	4	8	9	4			
	6-5-2-1	3	7			2	4	
	2-5-6-3		4	7		7	3	
E	6-1-4-5-2	2	5		10	8	1	
	6-7-2-1	4	3				3	4
	6-1-4-7-2	6	4		6		5	7

Following assumptions were made for the multi-period seven department case study

- Total number of departments (machines) in the case study is seven.
- Rectilinear distance between machines is 50 feet
- All material handling units have equal speed (120 ft/minute) and capacity (1 part)
- Material handling units have unidirectional paths

- Each department was equipped with an input and an output buffer with infinite capacities to free up material handling units
- 3 process sequences are available for each product and one of them can be used during each time period; same set of process sequences are available to select one from in all time periods
- Product demands are deterministic and known before beginning of each time period
- Three time periods were analyzed
- Material handling cost during each time period is $0.10/foot
- Cost of moving machines 1, 3, 5, 7, 9 is $50/foot and machines 2, 4, 6, 8 is $45/foot
- Cost of buying new machine 1, 3, 4, 5, 7, 9 is $10,000; machine 2, 4, 6, 8 is $12,000
- Cost of buying new material handling unit is $50,000
- Fixed cost of rearrangement for each time period is $1,000

In order to ensure that the machines were loaded, simulation experiment was run with two week warm up time during which no simulation results were collected. The simulation software starts collecting data once the time clock reaches 4800 minutes and collects data for next 9600 minutes i.e. each time period is 4 weeks.

To evaluate if the model is in production system dominant zone or material handling system dominant zone, it was necessary that the source makes right mix of products available at the right time. This was achieved by file based input specific to each time period.

There are three sequences for each product. Thus Ast=Bst=Cst=Dst=Est=3. As only one sequence will be selected to make each product out of three available sequences, we can calculate total number of combinations possible using equation (3.12).

$$c = \frac{3!}{1!(3-1)!} * \frac{3!}{1!(3-1)!} * \frac{3!}{1!(3-1)!} * \frac{3!}{1!(3-1)!} * \frac{3!}{1!(3-1)!} = 243$$

Each of the sequence utilizes machines to a different extent, thus it is important to select a sequence for each part and thus a sequence combination for all parts such that demand can be met and it is most profitable. In other words, it is necessary to find out a combination which is optimal. Table 3.14 provides details of time taken by each part on a given machine based on sequence selected for that part.

To find the optimal sequence for each of the part, we need to find the machine utilizations for each machine for every sequence possible for every part using equation (3.1).

Using this utilization for each machine we can calculate the cost of production using each specific sequence combination using equation (3.2).

As the number of combinations is large we resorted to using MATLAB to find the most optimal sequence combination. Objective function for MATLAB was to minimize production cost.

3.8.1 Seven Department Case Study: Time Period 1

Result from MATLAB for time period 1 indicate that the most optimal Process Sequence combination uses A2, B1, C3, D2, E2 i.e. out of three sequences available for each part, a combination that included second sequence for parts A, D and E; first sequence for part B, third sequence for part C. Table 3.15 below lists the sequence selected for each of the parts during the time period.

The utilizations ($\%UMC_{ncxt}$) for each machine with an initial value of n_t = 1 calculated using equation (3.1) is shown in the Table 3.16. The cost of production C_{cxt} using that sequence combination calculated using equation (3.2) is $25,062.60.

TABLE 3.15

SEQUENCE SELECTED FOR EACH PART

Part	Sequence id	Sequence
A	A2	2-3-4-6
B	B1	2-4-6-1
C	C3	3-1-5-7
D	D2	6-5-2-1
E	E2	6-7-2-1

TABLE 3.16

UTILIZATION AND PRODUCTION COST FOR EACH MACHINE

Part	t_{ntps}*d_{pt} (minutes)						
	n=1	n=2	n=3	n=4	n=5	n=6	n=7
A	0	360	2880	1080	0	1440	0
B	2760	1380	0	1380	0	460	0
C	780	0	1300	0	780	0	780
D	960	2240	0	0	640	1280	0
E	2160	1620	0	0	0	1620	2160
$\%UMC_{ncxt}$	69	58	44	26	15	50	31

As $\%UMC_{ncxt}$ for each of the machine calculated using equation (3.13) is less than 100, this sequence combination can be selected to meet demand for this given time period.

As we used MATLAB to find the most optimal sequence combination based on operating cost per part for each of the machine within all possible sequences for the part, it gave us a sequence combination that has least C_{cxt} and $\%UMC_{ncxt}$ from all combinations of sequences possible. As the sequence is able to meet demand, we can select this sequence combination going forward.

Using sequences A2, B1, C3, D2, E2, and with known demand data for time period t= 1, a from between chart can be constructed. The from between chart is shown in Table 3.17.

TABLE 3.17

FROM BETWEEN CHART (TIME PERIOD 1)

	Source	1	2	3	4	5	6	7	Sink
Source			820	260			860		
1			860	260		260	460		1320
2				360	460	320		540	
3					360				
4							820		
5							320	260	
6								540	360
7									260
Sink									

The layout for time period t = 1 generated by GA is shown in the Figure 3.6.

Source	2	5
6	4	7
Sink	1	3

Figure 3.6. Layout generated by GA (time period t = 1).

Simulation data results obtained are shown in Table 3.18. The data shows that with the layout obtained using GA and with the existing production capacity and material handling capacity, we can meet demand for the time period. Thus for this time period we do not need to add any production or material handling capacities.

TABLE 3.18

THROUGHPUT DATA (TIME PERIOD 1)

Part	Demand	Throughput Parts
A	360	360
B	460	460
C	260	260
D	320	320
E	540	540

The material handling cost associated with these dynamic flow values for time period t = 1 as calculated by equation (3.4) is $78,200.

As demand can be met during this time period, no fixed or variable rearrangement costs are incurred in time period t = 1. As seen earlier, existing production capacity and material handling capacity for the layout in time period t = 1 is sufficient to meet the demand and hence there is no need for additional machines or material handling units. Thus the total cost of meeting demand in the time period t = 1 calculated using equation (3.10) is 103,262.60.

3.8.2 Seven Department Case Study: Time Period 2

Going from time period t = 1 to t = 2, as the number of sequences for each product is unchanged from previous time period, we have three sequences for each parts. The total number of sequence combinations possible for time period t = 2 are 243. MATLAB results indicate that out of all the possible sequence combinations, the sequence combination found in time period t = 1 is most optimal in terms of manufacturing cost. Analysis of $\%UMC_{ncx}$ using equation (3.13) shows that the utilization of machine 1 for time period 2 is 115% which means that the production capacity is a constraint. To eliminate this constraint, the choices are to add more production capacity at machine 1 or to consider alternate sequencing.

Based on the modified flow chart suggested in Figure 3.2, if we evaluate the usage of alternate sequences, we can eliminate the production constraint limitation. Using that methodology, and using MATLAB to find the most optimal sequence combination for this time period, we found that out of 243 sequence combinations possible for this time period, sequence combination that uses A2, B3, C3, D2, E2 i.e. out of three sequences available for each part is the most optimal combination. Thus a combination that included second sequence for parts A, D, and

E, third sequence for parts B, and C was used for further analysis. Table 3.19 below lists the sequences selected for each of the parts during the time period.

The utilizations (UMC_{ncxt}) for each machine with an initial value of n_t = 1 calculated using equation (3.1) is shown in Table 3.20. The cost of production C_{cxt} using that sequence combination calculated using equation (3.2) is \$39,714.00.

TABLE 3.19

SEQUENCE SELECTED FOR EACH PART (TIME PERIOD 2)

Part	Sequence id	Sequence
A	A2	2-3-4-6
B	B3	7-5-3-4
C	C3	3-1-5-7
D	D2	6-5-2-1
E	E2	6-7-2-1

TABLE 3.20

UTILIZATION AND PRODUCTION COST FOR EACH MACHINE (TIME PERIOD 2)

Part	$t_{ntps}*d_{pt}$ *(minutes)*						
	n=1	**n=2**	**n=3**	**n=4**	**n=5**	**n=6**	**n=7**
A	0	200	1600	600	0	800	0
B	0	0	1200	1200	1200	0	1800
C	3000	0	5000	0	3000	0	3000
D	1200	2800	0	0	800	1600	0
E	7400	5400	7800	1800	5000	4800	8000
$\%UMC_{ncxt}$	77	56	81	19	52	50	83

As the $\%UMCncxt$ for each of the machine calculated using equation (3.13) is less than 100, this sequence combination can be selected to meet demand for this given time period without the need for adding machines.

Thus using this sequence combination we eliminated the possibility of production constraint. A comparison of this sequence combination to the one in time period 1 is shown in Table 3.21.

TABLE 3.21

SEQUENCE COMPARISON BETWEEN TIME PERIOD 1 AND 2

Part	Sequence	
	t = 1	**t = 2**
A	2-3-4-6	2-3-4-6
B	2-4-6-1	7-5-3-4
C	3-1-5-7	3-1-5-7
D	6-5-2-1	6-5-2-1
E	6-7-2-1	6-7-2-1

Comparison shows that only sequence change required was for part B. Changing this sequence the utilization of machine 1 is brought down to 77% instead of 115%. Thus we can eliminate the production constraint using alternative sequence combination. If we would have used sequence combination as in time period t = 1, the production cost would have been $38,862.00 but the cost of adding an additional machine would have been $100,000. While using alternative sequence for B the production cost is $39.714.00 which is 2% higher than using sequence combination as in time period 1 but saves us the cost of adding new machine.

Developing and running simulation with layout as suggested in time period t = 1 and all other parameters as in time period t = 2, we found that demand can be met. So we can stop further evaluation of need for a new layout and determine cost based on the modified flowchart. The simulation data results are shown in Table 3.22.

TABLE 3.22

THROUGHPUT DATA

Part	Demand	Throughput
A	200	200
B	600	600
C	1000	1000
D	400	400
E	800	801

As demand is met using layout as in time period t =1 and sequence combination as in time period t = 2, there is no need to evaluate if layout change is necessary. However it was evaluated for cost comparison purpose.

Using the sequences A2, B2, C3, D2, E2, and with known demand data for time period t = 2, a from between chart can be constructed. The from between chart is shown in Table 3.23.

TABLE 3.23

FROM BETWEEN CHART

	Source	1	2	3	4	5	6	7	Sink
Source			200	1000			1200	600	
1			1200	1000		1000			1200
2				200		400		800	
3					800	600			
4							200		600
5							400	1600	
6								800	200
7									1000
Sink									

Based on the demand data, GA generated the layout for time period t = 2 as shown in Figure 3.7.

Source	6	2
3	5	7
4	1	Sink

Figure 3.7. Layout generated by GA (time period t = 2).

The GA cost function primarily uses the material handling cost as a parameter and tries to find the best solution to reduce the material handling cost. Thus the layout suggested in time period t = 1, if used for time period t = 2 may have a higher material handling utilization.

Developing and running a simulation model with this new layout as suggested in time period t = 2, we can meet demand with the given material handling and capacity constraints. Thus the system was not in a logistic constraint with the new layout and we can conclude that the capacities are adequate.

Thus there was no need to add more production capacity or material handling capacity if we used layout suggested in time period t = 1 or time period t = 2.

As we were able to meet demand with layout as in time period t = 1, there was no need to change layout as generated by GA for time period 2 based on demand for that time period.

Comparison of the average MH utilizations using the layout as suggested by t = 1 and t = 2 are shown in the Table 3.24.

TABLE 3.24

MATERIAL HANDLING UTILIZATION COMPARISON

	GA Layout t = 1	GA Layout t = 2
Average material handling unit utilization *%UMHmcxt*	99.5	98.9

The results suggest the usefulness of GA procedure to determine the best layout based on MH cost and are in line with expectation that using layout suggested in time period 2 would have resulted in less material handling cost compared to using layout suggested in time period 1.

Thus the options we have are either keep existing layout or change the layout using the new sequence as found in time period t =2.

3.8.2.1 Option1: Keep Old Layout

Knowing the Process Sequence and data associated with the part sequence as presented in Table 3.14, using equations (3.1) and (3.2) as shown below, we can calculate the total production cost.

For machine 1, with initial value of n_t = 1; the utilization (hours) is calculated as shown:

$$UMC_{1c22} = \left(\sum_{p=A}^{P} t_{12ps} * d_{p2}\right) / n_t$$

$$UMC_{1c22} = (((0*200)+(0*600)+(3*1000)+(3*400)+(4*800))/60)/1 = 123.3$$

Table 3.25 below shows the utilization of each machine using selected sequence combination during t = 2

TABLE 3.25

UTILIZATION AND OPERATION COST FOR EACH MACHINE

Machine	Utilization (Hours)	Operating Cost/Hour	Total Operating Cost ($)
1	123.3	30	3700
2	90	40	3600
3	130	40	5200
4	30	55	1650
5	83.3	70	5832
6	80	80	6400
7	133.3	100	13332

Thus the total production cost is $39,714.

Material handling cost calculated using equations (3.2) and (3.3) with dynamic flow values (g_{ijt}) for time period t = 2 is $146,000.

As the layout used in this time period is same as in time period t = 1, there is no rearrangement cost. As the production capacities and material handling capacities are adequate, there is no need for any addition of capacities and hence there is no cost associated with it. Thus the total cost of meeting demand using equation (3.10) if same layout as in time period 1 was used along with the new sequence combination selected in time period t =2 is $185,714.

3.8.2.2 Option 2: Change Layout

Production cost depends on the sequence selection and not on the layout and hence is \$39,714 as in Option 1.

Material handling cost can be calculated using equation (3.4); the dynamic flow values are unchanged from option 1 as they depend on the sequence combination selected. However the distance travelled depends on the layout selected hence the material handling cost calculated based on the layout as generated using GA procedure for time period t = 2 is \$114,000.

As we are changing the layout in this option, the rearrangement cost can be calculated using equation (3.6). Table 3.26 below shows the distance each machine has to be moved to configure the new layout.

TABLE 3.26

REARRANGEMENT DISTANCE AND COST

Machine	Distance (ft)	Cost (\$)
Source	0	0
1	0	0
2	50	10000
3	150	37500
4	100	20000
5	100	25000
6	100	20000
7	0	0
Sink	100	25000

Thus the total cost of rearrangement is \$137,500.

Besides these two options, we can also use the sequence as suggested in time period 1 which would have resulted in production constraint and a need to add more production capacity. A cost comparison of all the options is shown in the Table 3.27.

Thus during time period 2, we had the following alternatives to meet demand:

1. Use GA layout from t = 1 and sequences from t = 1 (represented as GA1S1)
2. Use GA layout from t = 1 and sequences from t = 2 (represented as GA1S2)
3. Use GA layout from t = 2 and sequences from t = 1 (represented as GA2S1)
4. Use GA layout from t = 2 and sequences from t = 2 (represented as GA2S2)

TABLE 3.27

COST ANALYSIS FOR ALTERNATIVE OPTIONS

Option	**Production Cost**	**Material Handling Cost**	**Rearrangement Cost**	**Cost of adding Production Capacity**	**Cost of adding Material Handling Capacity**	**Total Cost**
GA1S1	$38,862	$146,000	$0	$100,000	$0	$284,862
GA1S2	$39,714	$146,000	$0	$0	$0	$185.714
GA2S1	$38,862	$114,000	$137,500	$100,000	$0	$390,362
GA2S2	$39,714	$114,000	$137,500	$0	$0	$291,214

Looking at the cost analysis results, it is very clear that the most economical solution is to change the sequence as suggested in time period 2 but keep the same layout as suggested in time period 1. Thus even though using alternative production sequence, initially it appears that we would be spending more to meet demand but without taking into account the constraints due to production and material handling capacities, we do not get a whole picture of the overall cost and hence it is important to look at alternative sequences along with layout changes within production and logistic constraints. Thus using alternative sequence, we were able to eliminate production capacity constraint by using alternative sequence in time period 2.

3.8.3 Seven Department Case Study: Time Period 3

Going from time period t = 2 to t = 3, as the number of sequences for each product is unchanged from previous time period, we have three sequences for each of the parts. Thus the total number of sequence combinations possible for time period t = 3 are 243. MATLAB results indicate that out of all the possible sequence combinations, the sequence combination found optimal in time period t = 1 is still the most optimal sequence in terms of manufacturing cost. Analysis of percent utilizations of the machines $\%UMC_{ncxt}$ using equation (3.13) for that sequence combination suggests that machine 1 is over utilized. Thus we can either add more production capacity for that machine or we can look at another alternative sequence combination. MATLAB results indicate that the sequence combination used in time period t =2 is the next optimal sequence based on manufacturing cost. However, machine utilization analysis $\%UMC_{ncxt}$ using equation (3.13) for that sequence combination again indicates that machine 7 is over utilized. So, to use that combination, we have to add another machine at location 7. Alternatively we can look for another alternative sequence.

Using MATLAB results, we find that out of all the 243 sequence combinations available, the sequence that uses A2, B2, C3, D2, and E2 is next optimal alternative sequence based on manufacturing cost. Table 3.28 below shows the list of sequence selected for each of the parts during this time period.

TABLE 3.28

SEQUENCE SELECTED FOR EACH PART

Part	Sequence id	Sequence
A	A2	2-3-4-6
B	B2	1-2-4-5
C	C3	3-1-5-7
D	D2	6-5-2-1
E	E2	6-7-2-1

The utilizations (UMC_{ncxt}) for each machine with an initial value of $n_t = 1$ calculated using equation (3.1) is shown in Table 3.29. The cost of production C_{cxt} using that sequence combination calculated using equation (3.2) is \$47,615. As the $\%UMC_{ncxt}$ for each of the machine calculated using equation (3.13) is less than 100, this sequence combination can be selected to meet demand for this given time period without the need for adding machines.

TABLE 3.29

UTILIZATION AND PRODUCTION COST FOR EACH MACHINE

Part	***t_{ntps}*d_{pt} (minutes)***						
	n=1	**n=2**	**n=3**	**n=4**	**n=5**	**n=6**	**n=7**
A	1400	600	200	0	400	0	400
B	800	2400	0	2400	4800	0	0
C	8000	7000	2000	0	0	8000	1000
D	0	1600	2800	0	2800	1200	0
E	6600	4400	0	6600	0	5500	7700
$\%UMC_{ncxt}$	98	91	69	31	90	59	77

Thus going from time period t = 2 to t = 3, based on the modified flow chart suggested in Figure 3.2 if we evaluate the usage of alternate sequences, we can eliminate the production constraint limitation. Using MATLAB result along with that methodology indicated that a sequence combination that uses second sequence for products A, B, D, and E; and third sequence for product C is most optimal and demand can be with existing production capacity.

As the layout was not changed in time period t = 2, the layout currently existing is same as was generated by GA in time period t = 1. Developing and running simulation with the layout as suggested in time period t = 1 and all other parameters as in time period t = 3, we found that demand cannot be met. Simulation data results are shown in Table 3.30.

TABLE 3.30

THROUGHPUT DATA

Part	**Demand**	**Throughput**
A	200	199
B	800	799
C	1000	999
D	400	399
E	1100	1100

Thus with the layout as in time period 1, demand cannot be met. According to the modified flow chart in Figure 3.2, we can check for the material handling utilization and add more capacity if necessary or we can evaluate new layout using GA algorithm.

Material handling unit utilization data as obtained from simulation results is shown in Table 3.31. The utilization data obtained from simulation results indicates that all the material handling units are extensively utilized resulting in an average utilization calculated using equation 3.15 is 99.9%.

TABLE 3.31

MATERIAL HANDLING UNIT UTILIZATION

Material Handling Unit Number	**Utilization (%)**
1	99.9
2	99.9
3	99.9
Average	99.9

According to the procedure for material handling capacity determination as the UMH_{c33} is greater than the threshold value of 99.5%, we need to add more material handling capacity. For sake of simplicity only one material handling unit is added at a time. Cost of adding additional MHU is $50,000. Running simulation again after adding an additional material handling unit and keeping all other parameters unchanged, it was found that the demand can be met and the results from the simulation run are shown in Table 3.32.

TABLE 3.32

THROUGHPUT DATA

Part	**Demand**	**Throughput**
A	200	200
B	800	800
C	1000	1000

TABLE 3.32 (continued)

Part	Demand	Throughput
D	400	400
E	1100	1100

As an alternative to adding material handling unit, we could have changed the layout. As we know the demand for the given time period, we can construct a from between chart show in Table 3.33.

TABLE 3.33

FROM BETWEEN CHART

	Source	1	2	3	4	5	6	7	Sink
Source		800	200	1000			1500		
1			2300	1000		1000			1500
2				200	800	400		1100	
3					200				
4						800	200		
5							400	1000	800
6								1100	200
7									1000
Sink									

The layout for time period t = 3 obtained using GA procedure is shown in Figure 3.8 below:

Source	6	7
3	1	Sink
4	2	5

Figure 3.8. Layout generated by GA (time period t = 3).

Simulation data results shown in Table 3.34 shown below show that we are able to meet demand with the layout obtained using GA with existing production capacity, the sequence as found optimal in time period t = 3 and the original material handling capacity with 3 material handling units.

TABLE 3.34

THROUGHPUT DATA

Part	Demand	Throughput
A	200	200
B	800	800
C	1000	1000
D	400	400
E	1100	1100

Thus we can either meet demand in time period 3 by adding more material handling capacity and using the old layout or by changing layout if we want to keep the material handling capacity unchanged.

To decide the best alternative, cost analysis was carried out for both the options:

3.8.3.1 Option 1: Keep Layout Same as Time Period t = 1; add Material Handling Capacity

Knowing the process sequence and data associated with the process sequence as presented in Table 3.14, using equations (3.1) and (3.2), we can calculate the total production cost.

For machine 1, with initial value of n_t = 1; the utilization (hours) is calculated as:

$$UMC_{1c33} = \left(\sum_{p=A}^{P} t_{13ps} * d_{p3} \right) / n_t$$

$$UMC_{1c33} = (((200*0)+(800*1)+(1000*3)+(400*3)+(1100*4))/60 = 9400/60)/1 = 156.7$$

Table 3.35 shows the utilization of each machine using selected sequence combination during time period t = 3.

TABLE 3.35

UTILIZATION AND OPERATION COST FOR EACH MACHINE

Machine	**Utilization (Hours)**	**Operating Cost/Hour**	**Total Operating Cost ($)**
1	156.7	30	4700
2	145.0	40	5800
3	110.0	40	4400
4	50.0	55	2750
5	143.3	70	10333
6	95.0	80	7600
7	123.3	100	12333

Thus the total production cost is $47,615.

Material handling cost calculated using equations (3.2) and (3.3) with dynamic flow values (g_{ijt}) for time period t = 3 is $176,000.

As the layout used in this time period is same as in time period t = 1, there is no rearrangement cost.

Machine utilization indicated that the production capacity was adequate and hence there was no need to add any more machines, however simulation data revealed that the material handling capacity was not sufficient and hence we needed to add one material handling unit. The cost of increasing material handling capacity is 50,000.

Thus the total cost of meeting demand using equation (3.10) if same layout as in time period 1 was used along with the new sequence combination selected in time period t =3 after adding one additional material handling unit is $273,615.

3.8.3.2 Option 2: Change Layout as Suggested by GA in Time Period t = 3

Production cost depends on the sequence selection and not on the layout and hence is $47,615 as in Option 1.

Material handling cost can be calculated using equation (3.4), the dynamic flow values are unchanged from option 1 as they depend on the sequence combination selected. However the distance travelled depends on the layout selected hence the MH cost calculated based on the layout as generated using GA procedure for time period t = 3 is $126,500.

As we are changing the layout in this option, the rearrangement cost can be calculated using equation (3.6). Table 3.36 shows the distance each machine has to be moved to configure the new layout.

TABLE 3.36

REARRANGEMENT DISTANCE AND COST

Machine	**Distance**	**Cost**
Source	0	0
1	50	12500
2	100	20000
3	150	37500
4	100	20000
5	100	25000
6	100	20000
7	50	12500
Sink	150	37500

Thus the total cost of rearrangement is $185,000.

Besides these two options, we can also use the sequence as suggested in time period 1 or time period 2 which would have resulted in production constraint and a need to add more production capacity. A cost comparison of all the options is shown in Table 3.37 below:

1. Use GA layout from t = 1 and sequences from t = 3 (represented as GA1S3)
2. Use GA layout from t = 3 and sequences from t = 3 (represented as GA3S3)
3. Use GA layout from t = 1 and sequences from t = 1 (represented as GA1S1)
4. Use GA layout from t = 1 and sequences from t = 2 (represented as GA1S2)

Comparing all alternatives, it is clear that most economical option is to consider alternative sequencing rather than changing the layout or adding more production capacity.

TABLE 3.37

COST ANALYSIS FOR ALTERNATIVE OPTIONS

Option	Production Cost	Material Handling Cost	Rearrangement Cost	Cost of adding Production Capacity	Cost of adding Material Handling Capacity	Total Cost
GA1S3	$47,615	$176,000	$0	$0	$50,000	$273,615
GA3S3	$47,615	$126,500	$185,000	$0	$0	$359,115
GA1S1	$45,080	$176,000	$0	$100,000	$50,000	$371,080
GA1S2	$46,216	$176,000	$0	$100,000	$50,000	$372,216

3.9 Conclusion

In this paper, a new procedure for developing dynamic layouts when product demands are changing from one time-period to the next has been developed. Traditionally in the development of dynamic facility layouts, the system capacity was assumed to be infinite. Previous research has developed procedures for identifying the capacity constraints that could lead to infeasible facility layouts. The capacity constraints were identified using a simulation based procedure. The capacity constrains were alleviated by adding material handling and production capacity as required and by redesigning the facility layout. However, in this paper use of alternate process plans were identified as a method for overcoming the capacity constraints. The procedure allows alternate process plans to be selected, when current material handling and production capacity restrictions make the production system infeasible. The increased cost of the less efficient process plans are typically offset easily by the savings in material handling equipment and production equipment.

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CHAPTER 4

HEURISTIC FOR DESIGN OF DYNAMIC FACILITY LAYOUTS UNDER PRODUCTION AND MATERIAL HANDLING CONSTRAINTS

4.1 Abstract

Market conditions are competitive and dynamic these days. In order to stay competitive in today's market driven conditions, it is necessary that the facility has to be able to meet customer demand in a timely manner. As the market conditions are dynamic, the demand keeps on changing. With changing demand, in order to be profitable, the manufacturing facility needs to be able to meet that demand with best use of resources. Resources can be constrained. The constraints could be due to facility layout, production constraint, or material handling constraints. Research till now has addressed facility layout problem under static or dynamic conditions, but in addressing the facility layout design problem, they have always considered infinite resources for production and material handling. Researchers have proposed methods to solve a dynamic facility layout problem to generate new layouts without taking into consideration the constraints that might exist in the facility. This study conducts research on addressing dynamic facility layout designs in dynamic demand conditions where demand changes from one time period to another and the material handling and production capacities are limited and can constrain the facility.

The research proposes a method to design facility layouts for each time period and select best layout for the planning horizon by minimizing the cost of meeting demand, so that the manufacturing facility can be profitable. It uses CRAFT to generate facility layouts. It also proposes a method to check for capacity constraints ahead of time to ensure that the demand is met. The research also develops functions that can be used to evaluate cost associated with

meeting demand. The aim of this research is to generate a facility layout such that it would help minimize the cost of meeting demand over given time period under dynamic conditions.

Key words: Capacity constraints, Dynamic conditions, Facility layout, CRAFT

4.2 Introduction

Facilities these days try to reduce the cost of meeting demand in order to be competitive and profitable. In order to do that, they have reduced the labor cost by moving production to cheaper labor markets. They have also tried cutting waste by utilizing Lean and other waste reduction methods. The frontiers that provide the next opportunity for cost cutting are material handling and production costs. Production cost is dependent on demand and the machine down time. Once the down time is reduced or eliminated, production cost is dependent primarily on demand. As demand keeps changing, the production cost keeps changing with it. Material handling cost thus provides the next frontier for cost savings. Material handling cost is directly dependent on the demand and the facility layout. As the conditions are dynamic, demand keeps changing and the cost changes due to material handling are not always controllable. Facilities have to be redesigned periodically to control total material handling cost. Facility design involves the physical rearrangement of the machines within a facility. If the machines are placed such that the material handling system has to travel more to take the parts from one machine to the other, the material handling system would be over utilized. As the usage of the material handling system is dependent on the flow of the parts from one machine to another machine, it is important that the machines are placed such that it minimizes the material handling cost.

4.2.1 Literature Review

Most of the research done in the area of solving a facility layout problem has focused on finding an optimal solution to a facility layout problem by generating new layouts. While finding new layouts, the researchers so far have assumed the capacities of material handling and production to be unlimited. Facility layout problem can broadly be classified into static facility layout problem (SFLP) or dynamic facility layout problem (DFLP).

- Static Facility Layout: Meller and Gau (1996) performed a comprehensive literature review on static layout research. In these static layout researches, the flow between departments does not change, neither does the demand change going from time period to time period.
- Dynamic Facility Layout: In dynamic conditions, the demand changes from one time period to another. There have been several attempts to address dynamic facility layout problem. The problem of dynamic facility layouts was first addressed by Rosenblatt (1986) who developed a procedure for determination of best layout for multiple time periods taking both material handling cost and rearrangement cost into consideration.

According to Heragu (1992), the machines or the workstations should be placed in such a manner that the material handling distance be reduced between the departments. According to Immer (1953), 40% of the industries production cost is associated with the cost of material handling or the transportation of materials between the departments. Thus for a facility to be profitable, it is inevitable that they reduce the material handling cost by having a good optimal layout. Thus designing a good facility layout is very important.

4.2.2 Need for Facility Layout Design

Facility layout problem is defined as the physical arrangement of the specified departments or machines in a predefined area. There is a material handling cost associated with the layout selected as selection of the layout defines the total distance that the material handling units travel. This cost can be reduced using two techniques: Fitting and moving facilities. Fitting is the process of allocation of unequal shaped departments into large objects by optimizing the given goals.

Moving the facilities involves changing the facility with respect to time to preserve the fitness of the facility. Multi-criteria decision making techniques are used in FLP to find the feasible layout of given departments which fulfills the multiple objectives. These objectives can be overall integration of all functions, minimum material movement, smooth work flow, employee satisfaction, safety etc. The cost of the flow between departments can be declared in two forms - either by quantitative measure such as weighted flow of the materials or by qualitative adjacency requirement.

Kusiak and Heragu (1987) divided the facility layout problem approaches into two types of algorithms - suboptimal algorithms and optimal algorithm such as branch and bound or cutting plane algorithms. According to Welgama and Gibson (1993), these two algorithms can be used only to solve small size problems with at the most 15 departments.

According to Chiang (2001), the heuristic algorithms can be divided into five methods - construction, improvement, hybrid, knowledge-based and graph-theory. The construction method is divided into two steps in which, the first step involves finding the best sequence with the allocation of the departments within the given dimension of the floor. The second step deals with fixing the departments in the above sequence until it satisfies all the constraints. Improvement method deals with interchanging the position of the departments arbitrarily in the existing layout so that it can improve the solution quality very high. This process of interchanging continues until the process gets saturated with no other best solution. The method which unites the optimal and suboptimal algorithms or unifies the construction and improvement method is known to be Hybrid method. The graph theory method starts initially with a predefined weighted uni-directional network which results in developing a dual maximal planar which establishes a best feasible solution of the facility. The knowledge based method uses the expert systems or the fuzzy logic which deals with the multi-criteria nature of the layout. This method is also called as artificial intelligence method which contains Simulated Annealing (SA), Genetic Algorithm (GA) etc.; being the top ranked problem among all other problems in the combinatorial optimization field, the facility layout problem can be solved with various mathematical approaches. The approaches are quadratic assignment problem (QAP), quadratic set covering problem, linear integer programming problem, mixed integer programming problem, linear integer programming problem and the graph theoretic problem.

Chittrantawa et al. (1999) presented a non-liner mixed integer program to solve the facility layout design problem. An integrated model that describes the importance of the material handling system and facility design for its production support role and cost impact was proposed. There are two common factors that are seen in both facility and material handling system design which shows that these two are directly related to each other. Those factors are 'material flow' and 'distance'. An effective facility design is obtained by minimizing the material handling cost. Mostly the facility layout problem is divided into facility layout and material handling system design from which it is very easy to obtain an optimal solution. It is very clear that the main objective of a facility layout problem is to minimize the relocation costs. Here with a non-linear mixed integer model they have integrated the facility layout, material handling with P/D location. The proposed model minimizes the equipment operating cost, fixed cost of conveyors and fixed cost of vehicles.

Welgama and Gibson in 1996 proposed three approaches to handle the facility layout and material handling system problems, which are: a) Determining or improving the material handling method for the given layout, b) Determining or improving the layout with the material handling methods given, c) Determining or improving both handling method and layout wit neither given.

The research focused on determining or improving the layout with the material handling methods given.

The flow cost for material handling is an increasing function of the length and number of product moves. The flow path for the material handling system is calculated using some predefined distance metric. This leads to the need of hypothesized design for the material handling system and a good measure for the distance metric in the optimization process. For minimizing the material handling cost, many approaches have been developed using centroid-to-centroid distance metric. The first successful approach was developed by Armour and Buffa (1963). Montreuil (1990) used mixed integer programming, Meller and Bozer (1996) used simulated annealing, Tate and Smith (1995), Kochar et al. (1998) used genetic algorithm as their approach to solve the facility layout problem. Welgama and Gibson (1996) proposed a conjoint approach for selection of material handling system and location of machine in the facility. In that approach, the input/output points are represented as mid points of the sides of a rectangle, which is considered as the shape of the machine. Every time, when new machines needs to be added to the layout, information for position, orientation and configuration (location of I/O points) are determined along the boundaries of the previously fixed machines. For selecting the material handling system, the author used a knowledge based system. Once the material handling equipment is selected and the block layout is constructed, the material handling system design requires the path for the system, the choice for the directions and the location of input/output stations.

Gaskins and Tanchoco (1987) proposed a model in which, if the location of the input/output point is known, a zero-one integer-programming model will design the flow path. In this model the material movement is unidirectional. Kapsi and Tanchoco (1990) modeled and solved the same problem with a branch and bound technique. Tanchoco and Sinriech (1992) also approached the same problem, but they examined all of the possibilities of the single loop flow path for a facility layout in order to find the one, which gives minimum material handling cost. In this approach, the authors used mixed integer programming for finding the pickup/drop off locations for the facilities along the loop. The authors assumed each and every department to have one pickup/drop off points and the flow path for material movement to be unidirectional. Sinriech and Samakh (1999) used genetic algorithm for solving the facility layout problem and they extended previously done research on layout problem by including departmental flows for the flow path design. Banerjee and Zhou (1995) proposed an integrated approach for the design of single loop flow path and for solving the facility layout problem. Banerjee et al. (1997) used mathematical programming for refining the solution from the genetic algorithm, which was used for finding the solution for the layout problem. In that research, the authors used genetic search for simultaneously finding the location of the departments in a bay area, pickup/drop off points for the departments and the flow path for the material handling system (Aiello, Enea and Galante, 2002).

4.2.3 Researches on Dynamic Facility Layout Problem

Recently the focus of most researchers is on the facility layout problem assuming greater change in the product design and variety and shorter cycle times. Most of the researches deal with the flexible manufacturing systems (FMS), virtual manufacturing cells and with the dynamic facility layouts. Quadratic assignment problem technique can be used to solve the dynamic facility layout problem (DFLP) with a slight modification in the normal approach used for static facility layout problem. The first approach to solve a DFLP was proposed by Reimert and Gambrell in 1966. According to Urban (1992), the main problem with the dynamic layout problem is that it is affected by the “curse of dimensionality”. Rosenblatt (1986) proposed a heuristic, which computes upper and lower bounds for each stage for limiting the number of states considered for the layout design. A stochastic model for DFLP was proposed by Palekar et al (1992) which generated a facility plan using dynamic programming approach with the upper and lower bounds similar to those of Rosenblatt (1986).

Graves and Taylor (1994) did a research on the flexibility nature of the facility design and material handling systems and he proved that plant layout is closely related to the material handling system. Dowlatshahi (1994) developed an approach to combine the material handling, facility layout and warehousing system design problem which is a dynamic facility problem. As suggested by Lacksonen (1994), the modeling of the design skeleton may cause some unanticipated costs, because the modeler may involve bias in modeling the design skeleton. For solving the DFLP, Lacksonen and Enscore (1993) used the QAP formulation. The limitation of this model like most other models is its assumption of equal area for all facilities. The authors suggested various modifications to branch and bound (Pardalos and Crouse 1989), CRAFT (Armour and Buffa, 1963), cutting plane (Burkard and Bonniger 1983), cut trees (Montreuil and Ratliff, 1989) and dynamic programming (Rosenblatt 1986) for incorporating the dynamic feature of the problem.

Balakrishnan *et al.* (1992) proposed a constrained DFLP formulation which was solved through genetic algorithm by Conway and Venkataraman (1994) and was solved by Kaku and Mazzola (1997) through tabu-search based heuristic. Montreuil and Venkatadari (1991) developed a strategic interpolative design technique in order to solve the dynamic layout problems for intermediary expansion or decline phases of manufacturing systems. Montreuil and Laforge (1992) explained the need of probability in addition to developing design skeleton for each scenario as proposed by Rosenblatt and Kropp (1992). For each scenario, the inputs needed are the cost of transportation between cells, size and shape dimensions for each cell and the cost for moving the cell from one location to another along with the skeleton of the design.

Urban (1993) proposed a heuristic which is based on steepest-descent pair wise procedure to develop the layout which can handle the dynamic changes. The approach deals with the pair wise interchange of the departments for N department problems with ${}_NC_2$ number of possible exchange combinations. This interchanging will take place until no further improvement is possible. As the Urban method yielded the effective results, the method has been improved by Balakrishnan, Cheng, and Conway (2000). They propose two possible heuristic by extending Urban's effort: one by working backward from the final solution of Urban's heuristic and second is to combine Urban's heuristic along with dynamic programming.

In Urban's proposed forward pass, the quality of the layout generated or going to be generated for the current period is a result of the layouts of the preceding period. Thus the previous layouts have significant influence on the subsequent layouts. Hence any inaccuracies in the layout lead back to the inaccuracies in the subsequent layouts. Backward pass approach relieves this constraint. Initially the same heuristic is used to solve the problem which generates solution as m forecast windows. Now, the backward pair wise exchange is performed on these m resulted options which results m possible solutions. In backward approach the exchange starts in time period (t-1) and ends up at first time period. The major advantage of backward approach is that it considers rearrangement cost for transitioning from time period t+1 to t while rearrangement cost in forward pass considers rearrangement cost from t-1 to t. The authors claim that the backward approach never yields worse results than the forward approach.

4.3 Research Objective

The literature review shows that while a lot of effort has been made to solve the dynamic facility layout problem and generate layouts, all efforts have been in isolation with the capacity constraints and other production parameters like capacity constraints. The objective of this research is to fill that gap by developing a methodology for designing layouts under dynamic conditions of product demands while taking into account production constraint for each time period and also consider alternate sequence as a method to relieve production capacity constraints. Under dynamic conditions of product demands, the demands keep changing from time period to time period. Shah, Krishnan, and Dhuttargoan (2014) introduced the methodology of developing a facility layout under dynamic conditions with capacity constraints. In another paper, Shah, Krishnan, and Dhuttargoan (2014) also introduced a methodology to use alternative sequence as a parameter to design facility layout to meet demand under dynamic conditions with capacity constraints. In both the research objectives, the layouts were generated using genetic algorithm. In this paper, they develop a method to find the solution to a dynamic facility layout problem using a modified pairwise exchange method using forward and backward pass within production capacity constraints as proposed by Balakrishnan, Cheng, and Conway (2000). The methodology generates a layout for a given time period and also evaluates if it is optimal for other time periods going forward. It also generates new layouts going forward constantly comparing the optimal solution with the new solutions and replacing it, if the new solution is better than the current optimal solution. It also generates layouts in a backward pass and evaluates its optimality for the previous time periods. During backward pass also, new layouts are generated and compared with the current optimal solution to find the most optimal solution. The best solutions from forward and backward passes are then compared to find one global best solution for the dynamic facility layout problem. Thus it introduces a heuristic method of developing layouts using modified pairwise exchange using forward and backward pass within production capacity constraints. The paper also develops a cost function that takes into account the material handling cost for the layout, the cost of rearrangement, the cost of adding capacities.

4.4 Cost Analysis

The main objective of a manufacturing facility is to be profitable and meet customer demand within a given time period. For being profitable, they have to be able to meet demand with least cost. As mentioned by Shah, Krishnan, Dhuttargoan (2014), the cost of meeting demand can be classified into operating cost, material handling cost, rearrangement cost, and cost of adding more material handling and/or production capacity. Thus the total cost of meeting the demand in a given time period is a function of the production cost, material handling cost, rearrangement cost and cost of adding production and material handling capacities. The cost functions are repeated here for completion.

Notations:

n = machine number; n = 1,…, N,

i = machine location; i = 1,…, N,

j = machine location; j = 1,…, N-1,

p = total number of products, ranges from p = A, …, P,

s = total number of sequences, ranges from s = 1, …, S,

t = time period under consideration

pst = total number of sequences for product p

ps = sequence number s for product p

t_{ntps} = Time product p takes on machine n selecting sequence ps during time period t

cx = specific combination with selected sequence for every product, x = 1, …, n,

c = total number of combinations possible with selected ps for every product

d_{pt} = demand for product p in time period t

T_{tps}= Total production time required for product p during time period t using sequence ps

UMC_{ncxt} = Average utilization of each machine type (n = 1 to N) for a selected sequence combination cx during time period t

TV = Threshold value

O_n = Operating cost of machine n

C_{cxt} = Cost of production using sequence combination cx for time period t

C_{pt} = Production cost of meeting demand during time period t

C_{ptg} = Cost for CRAFT function during time period t

C_{pT} = Total cost of meeting demand over all time periods

m = number of MHUs; m = 1,…, M,

$$X_{ijtps} = \begin{cases} 1, & if\ there\ is\ flow\ between\ departments\ i\ and\ j\ for\ product\ p\ during\ time\ period\ t, \\ 0, & Otherwise \end{cases}$$

g_{ijtps} = Dynamic flow between departments i and j during time period t for ps

D_{ijtps} = Distance between departments i and j during time period t for ps

C = Cost of carrying a part per unit distance

M_{tps} = Material handling cost during time period t using ps

F_t = Fixed cost of transition to current time period

V_t = Variable cost of transition to current time period

$D_{n(t-1,t)}$ = Distance each machine has to be moved going from time period $t-1$ to t

Y_n = Cost per unit distance of the moving machine from one location to another

A_t = Cost of adding production capacity in time period t

n_t = number of machines of type ‘n’ that are required in time period t

a_n = cost of each machine of type ‘n’

B_t = Cost of adding material handling capacity in time period t

m_t = number of MHUs that are required to be added in time period t

b_m = cost of each MHU 'm'

4.4.1 Production Cost

Among the parameters under consideration in this research, the production cost is dependent on the production sequence selected and is independent of the layout of the facility. Shah, Krishnan, and Dhuttargoan (2014) introduced methodology for optimal sequence selection. In this alternative sequence is used if the production system is over utilized. A selected sequence provides details associated with t_{ntps}. Average utilization of each machine associated with cx can be calculated as

$$UMC_{ncxt} = \left(\sum_{p=A}^{P} t_{ntps} * d_{pt} \right) / n_t \tag{4.1}$$

Cost of production is calculated using the utilizations of the machines and the operating cost of each machine. The equation used for this is

$$C_{cxt} = \sum_{n=1}^{N} \{ (UMC_{ncxt} * n_t) * O_n \} \tag{4.2}$$

4.4.2 Material Handling Cost

Material handling cost which is a non-value added cost needs to be reduced as much as possible. It is the cost associated with carrying the raw material from source to machines and finished part from machine to sink along with moving the unfinished part from machine to machine for giving it its final shape and form. Thus the material handling cost depends on the distance between machines. Thus it depends on the layout used for a given time period. It also depends on the quantity of parts flowing from one machine to another. If g_{ijtps} represents the dynamic flow between departments, and D_{ijtps} is the distance between departments and the cost of carrying a part per unit distance is C, then we can calculate dynamic flow between machines *i* and *j* which depends on whether or not a part flows from i to j depending on the sequence selected. Thus for a sequence selected, we can find dynamic flow between departments *i* and *j* using equation (4.3)

$$g_{ijtps} = \sum_{p=A}^{P} d_{pt} * X_{ijtps}, i = 1,..., N-1; j = i+1,..., N \tag{4.3}$$

Material Handling cost during time period 't' M_{tps} can be calculated as shown in equation (4.4).

$$M_{tps} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijtps} * D_{ijtps} * C \tag{4.4}$$

4.4.3 Rearrangement Cost

As the research focuses on layout generation, this cost along with material handling cost is important in determining whether a facility layout is changed or not. Rearrangement cost consists of fixed cost component given by equation (4.5).

$$F_t = F_{t-1,t} \tag{4.5}$$

Besides the fixed cost, the rearrangement cost has a variable cost component which depends on the distance the machines need to be relocated and the cost of moving the machines per unit distance. This gives us the variable cost of rearrangement. Variable cost going from time period 't-1' to 't' can thus be defined as a function of the cost associated with the movement of machines which depends on the distance ($D_{n(t-1,t)}$) that each machine is moved and the cost (*Y)* of moving the machine per unit distance. It can be calculated as

$$V_t = \sum_{i=1}^{N} \sum_{j=1}^{N} D_{n(t-1,t)} * Y_n \tag{4.6}$$

4.4.4 Cost of Adding Production and Material Handling Cost

If with the current capacities of production and material handling, demand cannot be met, it may indicate that the system is constrained by production capacity or material handling capacity or both. The cost of adding production capacity depends on the type of machine that needs to be added and the number of machines that are added. The cost of increasing production capacity in given time period t is calculated by equation (4.7).

$$A_t = (n_t - 1) * a_n \tag{4.7}$$

Similarly, if more material handling capacity is needed, material handling units can be added and the cost of adding material handling capacity can be calculated using equation (4.8).

$$B_t = m_t * b_m \tag{4.8}$$

4.4.5 Total Cost

According to Shah, Krishnan, and Dhuttargoan (2014), total cost of production for a given time period is given by sum of all costs, i.e. sum of production cost, cost of material handling, cost associated with facility rearrangement and cost associated with adding more material handling and production capacities. It is calculated as

$$\begin{aligned} C_{pt} = & \sum_{n=1}^{N} \{(UMC_{ncxt} * n_t) * O_n\} + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijtps} * D_{ijtps} * C + F_t \\ & + \sum_{i=1}^{N} \sum_{j=1}^{N} D_{n(t-1,t)} * Y_n \pm (n_t - 1) * a_n \pm (m_t * b_m) \end{aligned} \tag{4.9}$$

The plus or minus sign in the fourth term is used to account for an increase in overall cost (if production capacity needs to be added) and reduction of cost (if the production cost can be reduced) respectively. A similar approach is used for the material handling cost calculation in the fifth term. As this research does not consider the capacities of the material handling units, the term for the addition of material handling system is removed and equation (4.9) is modified to result in equation (4.10).

$$C_{pt} = \sum_{n=1}^{N}\{(UMC_{ncxt} * n_t) * O_n\} + \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} g_{ijtps} * D_{ijtps} * C + F_t + \sum_{i=1}^{N}\sum_{j=1}^{N} D_{n(t-1,t)} * Y_n \pm (n_t - 1) * a_n \tag{4.10}$$

Equation defined by (4.10) has to be modified for best layout selection process. Criteria of deciding whether or not a layout generated gets selected depends on whether the new layout is better than the existing solution based on the rearrangement cost and the material handling cost associated with the new potential solution. It is independent of the production cost and the cost of adding more capacity and hence those terms are dropped in the cost function. Thus the cost C_{ptg} for layout selection process is calculated by equation (4.11).

$$C_{ptg} = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} g_{ijtps} * D_{ijtps} * C + F_t + \sum_{i=1}^{N}\sum_{j=1}^{N} D_{n(t-1,t)} * Y_n \tag{4.11}$$

The planning horizon consists of ‘T’ time periods. Equation (4.12) shows the total production cost over the planning horizon which is the sum of production costs incurred in each time period.

$$C_{pT} = \sum_{t=1}^{T} C_{pt} \tag{4.12}$$

4.5 Methodology

The objective function of a manufacturing facility is to minimize overall cost of meeting demand. The objective function is defined in equation (4.13).

$$Min(C_{pt}) \tag{4.13}$$

In dynamic environment, the part demand keeps changing. As the demand keeps changing, the facility has to determine if it has adequate resources to meet demand. If adequate resources are not available, then the current state of manufacturing system has to be determined. The procedure to determine the manufacturing sate of the system was introduced by Shah, Krishnan, and Dhuttargoan (2014). The facility may need additional machines of the same type or it may have to add machines that are completely different from what they currently have depending on the changes in the demands for product and to their product demand mix. An alternative to relieving capacity constraints under dynamic environment in which using alternate process sequences was introduced by Shah, Krishnan, and Dhuttargoan (2014). Thus, a facility can add more machines of the same kind or change sequences. Addition of capacity or brand new machine types warrants a need to reevaluating the facility layout. On the other hand changing product sequence changes the flow between machines and while it may be relieving production capacity constraints, it may result in material handling constrained state. Thus, in either case of adding machines or using alternative sequencing, it becomes essential for the facility to reevaluate and change layouts if necessary.

All alternatives have a cost associated with it and hence the decision to use them must be accompanied by a cost effectiveness analysis. This research focuses on developing a methodology that can be used to find the best solution by using combination of all the parameters. The objective of this research is to develop a heuristic methodology to find best solution with layout changes, part sequence changes, and adding more capacity as required or combination of all of them as required.

This paper introduces a methodology of finding an best facility layout by introducing a new heuristic approach to find best facility layout (modified pairwise exchange) so that as the product demand and mix changes due to dynamic environment, the facility layout is still best throughout the planning horizon. In order to do that, the research assumes that the product demand quantities and part sequences for each time period are known at the beginning of the first time period. All possible alternative sequences for every part are known and remain the same throughout the planning horizon.

Following steps describe the methodology proposed to find best solution:

Step 1: Obtain demand data, product sequence data, for every time period and check if the capacity is adequate, if not add more resources as necessary. Shah, Krishnan, and Dhuttargoan (2014) introduced a methodology for checking capacity constraints and adding more capacity as necessary. The process is repeated here in brief for completion and logical flow.

Step 2: Generate multiple facility layouts using CRAFT in a forward pass.

Step 3: Calculate material handling cost and rearrangement cost for each facility layout.

Step 4: Select layout with least cost of meeting demand.

Step 5: Repeat the procedure in backward pass.

Step 6: Determine best layout for each time period that minimizes overall cost.

A flow chart showing steps of the procedure for finding the best solution by minimizing the cost of production is shown in Figure 4.1.

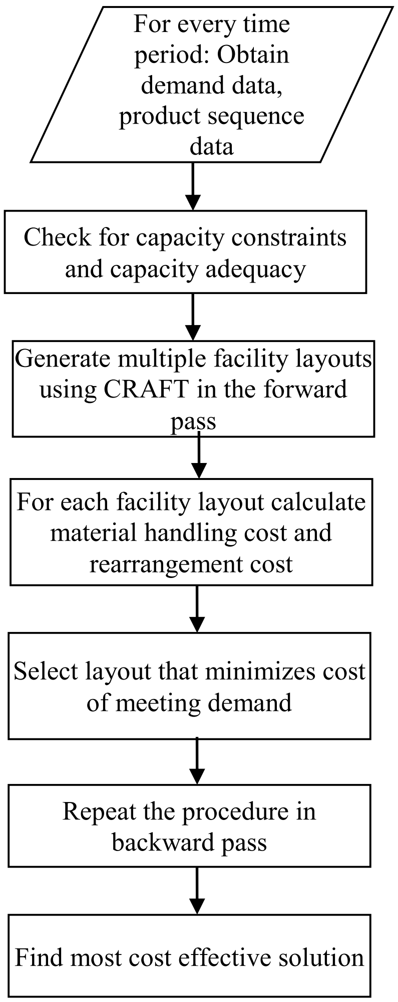

Figure 4.1. Redesign methodology flowchart.

4.5.1 Procedure for Determining Production Capacity Required

Shah, Krishna, and Dhuttargoan (2014) described the methodology for determination of production capacity requirement. The procedure is described here for completion.

For a manufacturing facility to meet demand, it is important that they utilize all their resources optimally. Along with best utilization, it is also important that they add more capacity as required to be able to meet the demand requirements. The flowchart shows the procedure to determine production capacity requirement.

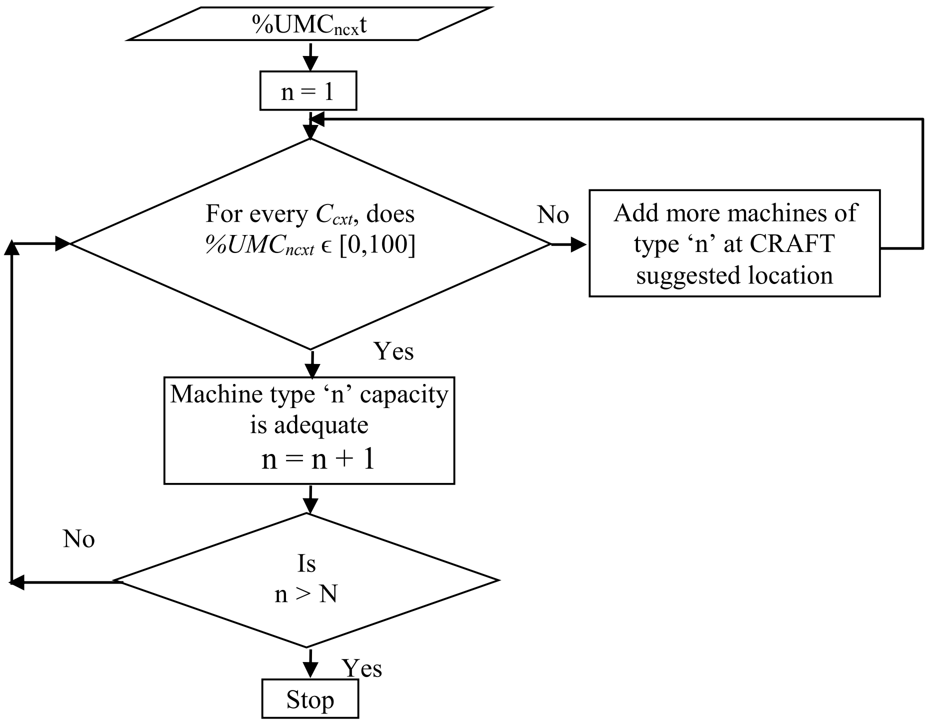

Figure 4.2 Flowchart for determining production capacity requirement

Following steps describe the process of evaluation of more production capacity and addition as necessary.

Step 1: For a sequence selected, we calculate $\%UMC_{ncxt}$ as

$$\%UMC_{ncxt} = \left(\frac{UMC_{ncxt}}{TV} \right) * 100 \tag{4.14}$$

Step 2: For n = 1; for every C_{cxt} check if $0 \leq \% \ UMC_{ncxt} \leq 100$, if so the machine capacity for machine type ‘n’ is adequate. If not, add 1 more machine of type ‘n’.

Step 3: Set n = n + 1; if new n >N; stop else go to Step 2.

4.5.2 Layout Generation Using CRAFT and Best Solution Selection

Solving a dynamic facility layout problem is hard because of the number of solutions that need to be evaluated for finding the best solution. For a facility with ‘N’ number of departments and ‘*t*’ time periods, for a total enumeration strategy, $(N!)^t$ solutions have to be evaluated. For a

12 department facility layout problem over 5 time periods, the number of solutions would be 2.53 x 10^{43}, which would be too large to manage. With help of the modified heuristic proposed in the paper, the number of solutions reduce to $((\sum_{1}^{t-1} t) + 2)$ in forward pass and 2t-1 in backward pass. Thus the number of solutions is only dependent on the number of time periods and not on the number of department and is fairly small and traceable. For a 12 department facility layout problem over 5 time periods, the number of solutions reduces to 12.

After we determine the required production capacity, the machines that have to be added to meet demand for a given time period can be calculated. The from-between charts (FBC) which is used as an input to developing facility layout arrangements (LA) for each time period can be determined based on the sequence of visits to the machines. The underlying fundamental heuristic in improving a layout is to use a pair-wise exchange method. In this research we use CRAFT to generate layout arrangements. CRAFT (Armour and Buffa, 1963) uses pair-wise exchanges to determine the best layout and uses a greedy algorithm to determine the best solution in each iteration.

Urban (1993) proposed steepest descent pair-wise exchange heuristic for solving dynamic facility layout problem. This was further extended and modified by Balakrishnan, Cheng, Conway (2000) who added a backward pass. Their research was limited to just designing facility layout. This research adds more parameters like capacity constraints and alternative sequence into the dynamic facility layout problem. It also modifies the forward and backward pass suggested by Balakrishnan, Cheng, and Conway (2000).

The proposed method however uses the same fundamental approach of finding an best solution by taking into consideration a combination of material handling cost and rearrangement cost. Proposed methodology finds multiple solutions for each time period in the planning horizon in a forward pass. It compares each of these solutions to the current best solution and replaces the current solution for a given time period if a better solution is obtained. It then uses the best solution from the forward pass to develop solutions in a backward pass. Similar to the forward pass, in the backward pass also, more than one solution is generated for a given time period and the cost associated with meeting demand is calculated. If any solution from the given time period is better than the current solution, then this new solution is selected as the candidate solution. Thus, after the forward and backward pass is completed, the best solution is obtained. The objective function used for finding best layout solution given in equation 4.11.

4.5.2.1 Forward Pass

Forward pass uses the 'looking forward' approach suggested by Urban's pair-wise exchange method. Balakrishnan, Cheng, and Conway (2000) suggested using iterations for finding an best solution in forward pass. In this paper, a layout is developed for a given time period using the from between chart for that time period and also using a combined from between chart from all previous time periods to find best solution. The methodology is shown in Figure 4.3.

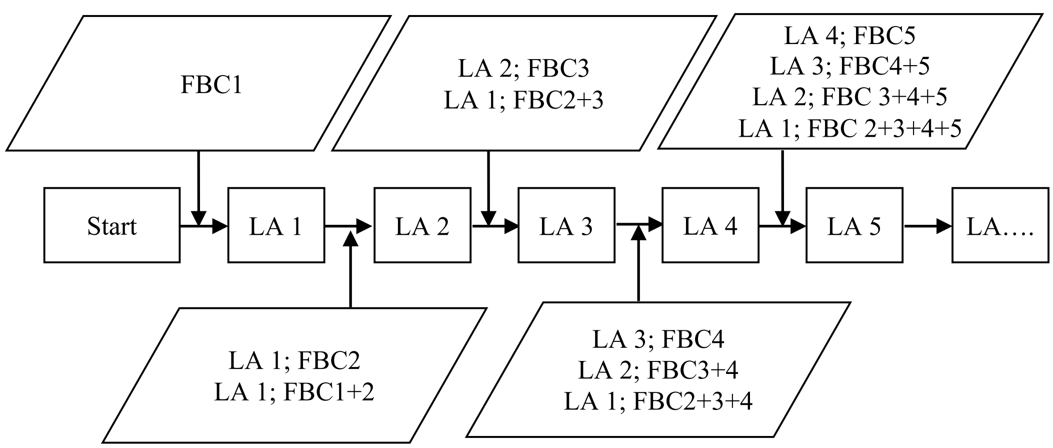

Figure 4.3. Flowchart for forward pass.

Detailed steps of the forward pass are listed below:

Step 1: For time period 1: generate a from between chart for time period 1 (FBC1) and that is the only input that goes into CRAFT for generating a layout arrangement (LA 1) for that time period. Calculate the cost of meeting demand for time period 1 using LA 1. As this is the first time period and there is no layout to begin with, there is no cost of rearrangement for this time period.

Step 2: For time period 2: generate a from between chart for time period 2 (FBC2) based on the demand for that time period and use layout generated in time period 1 (LA 1) as a starting layout, add capacity and generate a layout (LA 2) using CRAFT. Calculate total material handling cost and rearrangement cost for time periods 1 and 2 together.

Alternatively, generate a combine from between chart for time periods 1+2 and use layout generated in timer period 1 (LA 1) as a starting layout, add capacity and generate a layout for time period 2 (LA 2) using CRAFT. Calculate material handling cost and rearrangement cost for time periods 1 and 2 together.

Out of the two options, select the one with least cost as the best solution till time period 2.

Step 3: For time period 3: generate a from between chart for time period 3 (FBC3) based on the demand for that time period and use best layout at time period 2 (LA 2) as a starting layout, add capacity and generate a layout (LA 3) using CRAFT. Calculate total material handling cost and rearrangement cost for time periods 1, 2, and 3 together.

Generate a combine from between chart for time periods 2+3 and use layout generated in time period 1 (LA 1) as a starting layout, add capacity and generate a layout for time period 3 (LA 3) using CRAFT. Calculate material handling cost and rearrangement cost for time periods 1, 2, and 3 together.

Out of the two options, select the one with least cost as the best solution till time period 3.

<u>Step 4</u>: For time period 4: generate a from between chart for time period 4 (FBC4) based on the demand for that time period and use best layout at time period 3 (LA 3) as a starting layout, add capacity and generate a layout (LA 4) using CRAFT. Calculate total material handling cost and rearrangement cost for time periods 1, 2, 3, and 4 together.

Generate a combine from between chart for time periods 3+4 and use layout generated in time period 2 (LA 2) as a starting layout, add capacity and generate a layout for time period 4 (LA 4) using CRAFT. Calculate material handling cost and rearrangement cost for time periods 1, 2, 3, and 4 together.

Generate a combine from between chart for time periods 2+3+4 and use layout generated in time period 1 (LA 1) as a starting layout, add capacity and generate a layout for time period 4 (LA 4) using CRAFT. Calculate material handling cost and rearrangement cost for time periods 1, 2, 3, and 4 together.

Out of the three options, select the one with least cost as the best solution till time period 4.

<u>Step 5</u>: For time period 5: generate a from between chart for time period 5 (FBC5) based on the demand for that time period and use best layout at time period 4 (LA 4) as a starting layout, add capacity and generate a layout (LA 5) using CRAFT. Calculate total material handling cost and rearrangement cost for time periods 1, 2, 3, 4, and 5 together.

Generate a combine from between chart for time periods 4+5 and use layout generated in time period 3 (LA 3) as a starting layout, add capacity and generate a layout for time period 5 (LA 5) using CRAFT. Calculate material handling cost and rearrangement cost for time periods 1, 2, 3, 4, and 5 together.

Generate a combine from between chart for time periods 3+4+5 and use layout generated in time period 2 (LA 2) as a starting layout, add capacity and generate a layout for time period 5 (LA 5) using CRAFT. Calculate material handling cost and rearrangement cost for time periods 1, 2, 3, 4, and 5 together.

Generate a combine from between chart for time periods 2+3+4+5 and use layout generated in time period 1 (LA 1) as a starting layout, add capacity and generate a layout for time period 5 (LA 5) using CRAFT. Calculate material handling cost and rearrangement cost for time periods 1, 2, 3, 4, and 5 together.

Out of the four options, select the one with least cost as the best solution till time period 5.

The process continues for all time periods until we are done with the last time period. This would result in identifying the best solutions in forward pass.

4.5.2.2 Backward Pass

Urban's steepest pair-wise approach simply was a forward pass approach. According to Balakrishnan, Conway, and Cheng (2000) once the layout is generated in Urban's approach, it is never changed. Thus the earlier layouts have significant influence on the final outcome. They proposed an alternative to that by introducing a backward pass. They started with all the best layouts form each of the forecast window in the forward pass as the beginning layout for the backward pass. In their backward pass approach, they used a forecast window of 1 which means they used a from between chart from only one time period. Thus they generate only one layout during each time period. As their approach always used the best layout in the forward pass and they still use pair-wise exchange, their approach ensured that in the backward pass the solution was never worse than the results they obtained in the forward pass.

In this research, we introduced a new way to generate layouts in a backward pass. Instead of using the best layout from the forward pass as a starting point for the last layout, we develop a new layout for the last time period. This layout could be different from the ones generated during the forward pass as in the forward pass we generate a new layout for a given time period using the best layout in the previous time periods.

The methodology is shown in Figure 4.4.

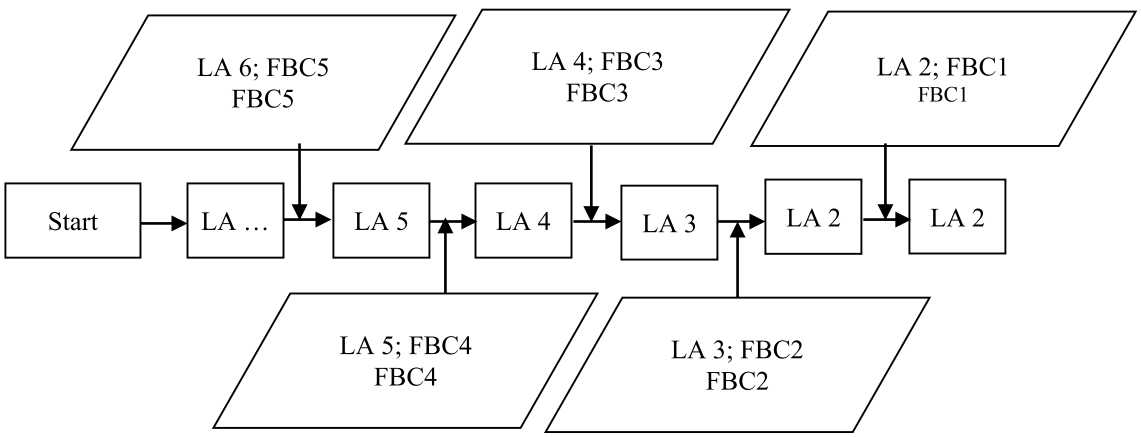

Figure 4.4 Flowchart for backward pass

Detailed steps for a 5 time period backward pass are listed below:

<u>Step 1</u>: For time period 5: generate a from between chart for time period 5 (FBC5) and generate a new layout for time period 5 (LA 5).

Alternatively, start with the best layout from the previous time period, remove additional capacity, rearrange and generate a new layout for time period 5 (LA 5) using FBC5.

Out of the two options, select the one with least cost as the best solution.

<u>Step 2</u>: For time period 4: generate a from between chart for time period 4 (FBC4) and generate a new layout for time period 4 (LA 4). Calculate total material handling cost and rearrangement cost for time periods 4, and 5 together.

Alternatively, start with the best layout from time period 5, remove additional capacity, rearrange and generate a new layout for time period 4 (LA 4) using FBC4. Calculate total material handling cost and rearrangement cost for time periods 4, and 5 together.

Out of the two options, select the one with least cost as the best solution.

Step 3: For time period 3: generate a from between chart for time period 3 (FBC3) and generate a new layout for time period 3 (LA 3). Calculate total material handling cost and rearrangement cost for time periods 3, 4, and 5 together.

Alternatively, start with the best layout from time period 4, remove additional capacity, rearrange and generate a new layout for time period 3 (LA 3) using FBC3. Calculate total material handling cost and rearrangement cost for time periods 3, 4, and 5 together.

Out of the two options, select the one with least cost as the best solution.

Step 4: For time period 2: generate a from between chart for time period 2 (FBC2) and generate a new layout for time period 2 (LA 2). Calculate total material handling cost and rearrangement cost for time periods 2, 3, 4, and 5 together.

Alternatively, start with the best layout from time period 3, remove additional capacity, rearrange and generate a new layout for time period 2 (LA 2) using FBC2. Calculate total material handling cost and rearrangement cost for time periods 2, 3, 4, and 5 together.

Out of the two options, select the one with least cost as the best solution.

Step 5: For time period 1: generate a from between chart for time period 1 (FBC1) and generate a new layout for time period 1 (LA 1). Calculate total material handling cost and rearrangement cost for time periods 1, 2, 3, 4, and 5 together.

Alternatively, start with the best layout from time period 1, remove additional capacity, rearrange and generate a new layout for time period 1 using demand for time period 1.

Calculate total material handling cost and rearrangement cost for time periods 1, 2, 3, 4, and 5 together.

Out of the two options, select the one with least cost as the best solution.

This would result into an best solution in backward pass.

4.6 Case Study (12-machines, 5-time periods, 5-parts)

To demonstrate the effectiveness of this methodology a case study with 12 departments and 5 time periods is used. In this case study the focus was on generating layout arrangements for the planning horizon. Shah, Krishnan, and Dhuttargoan (2014) previously evaluated capacity constraints using alternate sequence. However, for this research alternate sequence is not the primary parameter for the case study. In this paper, the possibility of using alternate sequences along with designing dynamic facility layout arrangements is considered. Hence, alternate sequences are considered for only two products. Summarized product information along with demand quantities and possible sequences for each part is shown in Table 4.1. The table also shows demand for each of the part in each time period.

TABLE 4.1

DEMAND AND SEQUENCE DATA

Part	Projected Demand						
	t=1	t=2	t=3	t=4	t=5	p1	p2
A	100	400	700	600	800	2-3-4-6	9-10-6
B	400	500	200	500	500	1-2-4-5	2-3-6
C	500	200	1000	800	1000	3-1-5-4	11-12
D	-	400	600	900	900	2-7-4-1	1-2-5-7
E	-	-	300	600	600	1-8-3-2	1-5-4-6

During this research, the number of machines of the same type is limited to be less than or equal to two. If adding more capacity was required, alternative sequence was used.

Some other considerations made for this multi-period case study are listed below:

- Rectilinear distance between machines is 50 feet
- Process sequence for each product is known and is fixed for all time periods
- Product demands are deterministic and known for each time period
- Material handling cost during each time period is \$1/foot
- Cost of moving machines is \$140/foot
- Cost of buying new machine is \$10,000
- Fixed cost of rearrangement for each time period is \$1,000
- Each time period is 4 weeks (160 hours)

4.6.1 Capacity Constraints

In order to be profitable, it is important that the manufacturing facility utilizes the resources optimally. On the other hand, in order to be profitable, it also needs to ensure that it has the right amount of resources. To ensure that it has the right amount of resources, the manufacturing system has to be identified using the procedure introduced by Shah, Krishna, and Dhuttargoan (2014). In this part of the research, the problems have been constrained to be in the production system dominant zone. If the system is in production system dominant zone, the procedure introduced by Shah, Krishna, and Dhuttargoan (2014) repeated above for completion can be used (Figure 4.1).

Table 4.2 shows the processing time for each part on the machine based on selected process sequence. As the focus of this research is to demonstrate a methodology for solving a dynamic facility layout problem by finding best solution using a forward and backward pass approach and only two part sequences were considered for every part. As two part sequences were considered for every product, a total of 32 sequence combinations are possible according to the methodology proposed by Shah, Krishnan, and Dhuttargoan (2014). The sequence combinations used are shown in Table 4.3 along with the sequence combination number *cx* and the respective *ps*.

TABLE 4.2

MACHINE TIME PER PART BY SEQUENCE

Part	Sequence	Machine Number											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	2-3-4-6		10	7	6		12						
	9-10-6						12			8	8		
B	1-2-4-5	10	4		5	8							
	2-3-6		10	20			30						
C	3-1-5-4	10		8	6	6							
	11-12											4	4
D	2-7-4-1	3	8		10			8					
	1-2-5-7	20	5			15		20					
E	1-8-3-2	4	5	20					10				
	1-5-4-6	10			5	20	15						

TABLE 4.3

SEQUENCE SELECTION

Time Period	*cx*	Sequence Number (*ps*)				
		1	2	3	4	5
t=1	c1	a1	b1	c1		
t=2	c2	a1	b1	c1	d1	
t=3	c3	a1	b1	c1	d1	e1
t=4	c4	a2	b1	c1	d1	e1
t=5	c5	a2	b1	c2	d1	e1

The utilizations ($\%UMC_{ncxt}$) for each machine with n_t = 1 for each time period using sequence combinations mentioned in Table 4.2 calculated using equations (4.1) and (4.14) is shown in the Table 4.4.

Once the machine capacities are determined, the system is checked for production system dominance. It can be seen from Table 4.3 that for time periods 1, 2, and 3, sequence number 1 is selected for all of the parts. For time period 4, sequence number 2 was selected for part A. All other parts retained sequence number 1. For time period 5, sequence number 2 is used to make parts A and C, while sequence number 1 is used to make parts B, D, and E.

TABLE 4.4

MACHINE UTILIZATION FOR EVERY MACHINE FOR EACH TIME PERIOD

Time Period	***%UMC**$_{ncxt}$*											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	94	27	49	58	65	13						
2	85	96	46	105	54	50	33					
3	156	147	197	179	79	88	50	31				
4	189	127	192	170	92	75	75	63	50	50		
5	105	127	125	120	42	100	75	63	67	67	42	42

Table 4.5 summarizes cost of production C_{cxt} using selected sequence combination *cx* for time period *t* using equations (4.1) and (4.2).

TABLE 4.5

PRODUCTION TIME AND COST FOR SELECTED CX FOR TIME PERIOD *t*

Sequence Combination	$t_{ntps} * d_{pt}$ **(hours)**												C_{cxt} **($)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
c1	150	43	78	93	103	20							$24,417
c2	137	153	73	168	87	80	53						$37,583
c3	250	235	315	287	127	140	80	50					$74,167
c4	302	203	307	272	147	120	120	100	80	80			$86,500
c5	168	203	200	192	67	160	120	100	107	107	67	67	$77,833

4.6.2 Forward Pass

Based on the demands listed in Table 4.1 and sequence combination selected for each time period listed in Table 4.3, from-between charts were generated for each time period. The from-between charts are used as input to CRAFT for generating facility layout arrangement. A 4 x 4 grid was selected to place machines for each time period.

4.6.2.1 Time Period 1

Using the methodology proposed in Figure 4.3, for time period 1 the layout was generated using from-between chart developed from the demand for time period 1. The from-between chart for this time period is shown in Table 4.6:

TABLE 4.6

FROM BETWEEN CHART (DEMAND: TIME PERIOD 1)

	1	2	3	4	5	6
1		400	500		500	
2			100	400		
3				100		
4					900	100
5						
6						

With this as input to CRAFT, best layout was generated for this time period as shown in Figure 4.5.

5	1	3	
4	2	6	

Figure 4.5. CRAFT generated layout using demand data from time period 1.

With this layout and using equations (4.3) and (4.4), material handling cost for this time period is calculated to be $170,000. There is no rearrangement required for this time period and hence there is no rearrangement cost associated with it.

For the purpose of this case study the cost of production and capacity addition is not taken into account until best layout solution is found as these costs have to be incurred irrespective of the solution. Thus the total cost of material handling and rearrangement for this time period is $170,000.

4.6.2.2 Time Period 2

Using the methodology proposed in Figure 4.3, two different from between charts are generated for this time period.

4.6.2.2.1 Solution 1

A from-between chart is generated using demand data for time period 2 shown in Table 4.7.

TABLE 4.7

FROM BETWEEN CHART (DEMAND: TIME PERIOD 2)

	1	2	3	4	5	6	7
1		500	200	400	200		
2			400	500			
3				400			
4					700	400	400
5							
6							
7							

With the from-between chart as input to CRAFT and using best layout from time period 1, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. The CRAFT generated layout is shown in Figure 4.6.

5	1	2	
4	4	3	
6	7		

Figure 4.6. Layout generated using demand data from time period 2.

Based on this layout and the layout for time period 1, total material handling cost for time periods 1 and 2 is calculated to be $480,000. The total rearrangement cost when the cost of moving machines is $140/foot, is $42,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1 and 2 combine is $522,000.

4.6.2.2.2 Solution 2

In this solution, a from-between chart is generated using demand data for both time period 1 and 2 collectively as shown in Table 4.8. With this from between chart and using best layout for time period 1 as the input, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. The CRAFT generated layout is shown in Figure 4.7.

TABLE 4.8

FROM BETWEEN CHART (DEMAND: TIME PERIODS 1+2)

	1	2	3	4	5	6	7
1		900	700	400	700		
2			500	900			400
3				500			
4					1600	500	400
5							
6							
7							

5	1	2	
4	4	3	
6	7		

Figure 4.7. CRAFT generated layout using best layout for time period 1 and demand data from time periods 1+2.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 1 and 2 is calculated to be \$522,500. As the same layout will be used for time period 1 and 2, there is no rearrangement cost associated with this layout arrangement option. Thus the total material handling, and rearrangement cost with this floor layout arrangement option for time periods 1 and 2 combine is \$522,500.

4.6.2.2.3 Selection

As the methodology of selection of best solution is based on pair-wise exchange method, the solution that returns less cost of material handling and rearrangement calculated by equation 4.10 should be selected. Thus the best solution for time period 1 and 2 is to use layout generated with demand for time period 1 in time period 1 and layout generated using demand for time period 2 with demand for time period 2 in time period 2.

4.6.2.3 Time Period 3

According to the proposed methodology, two different from-between charts are generated for time period 3.

4.6.2.3.1 Solution 1

For this solution, a from-between chart is generated based on demand for time period 3. A layout is generated using CRAFT with this from-between chart and the layout from best solution till time period 2. The from-between chart is shown in Table 4.9.

TABLE 4.9

FROM BETWEEN CHART (DEMAND: TIME PERIOD 3)

	1	2	3	4	5	6	7	8
1		200	1000	600	1000			300
2			1000	200			600	
3				700				300
4					1200	700	600	
5								
6								
7								
8								

With this as input to CRAFT and using the best layout from time period 2, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. The layout generated is shown in Figure 4.8.

2	3	1	8
2	3	1	6
7	4	5	
	4		

Figure 4.8. CRAFT generated layout using best layout for time period 2 and demand data from time period 3.

With this layout, using equations (4.3) and (4.4), the total material handling cost for time periods 1, 2, and 3 is calculated to be $1,227,500. The total rearrangement cost when the cost of moving machines is $140/foot, is $147,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, and 3 combine is $1,374,500.

4.6.2.3.2 Solution 2

For this solution, a from-between chart is generated using demands for time periods 2 and 3 put together as shown in Figure 4.10. With this from between chart, and using best layout from time period 1, a layout is generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. This layout is shown in Figure 4.9

With this layout, using equations (4.3) and (4.4), the total material handling cost for time periods 1, 2, and 3 combine is calculated to be $1,285,000. As the same layout will be used for time period 2 and 3, there is rearrangement cost associated with this layout arrangement option compared to layout in time period 1. This cost of rearrangement is $56,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, and 3 combined is $1,341,000.

TABLE 4.10

FROM BETWEEN CHART (DEMAND: TIME PERIODS 2+3)

	1	2	3	4	5	6	7	8
1		700	1200	1000	1200			300
2			1400	700			1000	
3				1100				300

TABLE 4.10 (continued)

	1	2	3	4	5	6	7	8
4					1900	1100	1000	
5								
6								
7								
8								

2	3	1	8
2	3	1	
7	4	5	6
	4		

Figure 4.9. CRAFT generated layout generated using best layout for time period 1 and demand data from time periods 2+3.

4.6.2.3.3 Selection

As the methodology of selection of best solution is based on pair-wise exchange method, the solution that returns less cost of material handling and rearrangement calculated by equation (4.10) should be selected. Thus the best solution for three time periods together is to use layout generated with demand for time period 1 in time period 1 and layout generated in time period 3 using demand from time period 2 and 3 combined for time periods 2 and 3.

4.6.2.4 Time Period 4

According to the proposed methodology, three different from between charts are generated for time period 4.

4.6.2.4.1 Solution 1

For this solution a from-between chart is generated based on demand for current time period only. A layout is generated using CRAFT with from-between chart for time period 4 and the layout from the best solution from time period 3. This from-between chart is shown in Table 4.11.

TABLE 4.11

FROM BETWEEN CHART (DEMAND: TIME PERIOD 4)

	1	2	3	4	5	6	7	8	9	10
1		500	800	900	800			600		
2			600	500			900			
3								600		
4					1300		900			
5										
6										600
7										
8										
9										600
10										

With this as input to CRAFT and using best layout from time period 3, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. This CRAFT generated layout is shown in Figure 4.10.

2	3	1	8
2	3	1	
7	4	5	6
	4	9	10

Figure 4.10. CRAFT generated layout using demand data from time period 4.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 1, 2, 3, and 4 is calculated to be \$2,087,500. The total rearrangement cost for the 4 time periods is \$56,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, and 4 combine is \$2,143,500.

4.6.2.4.2 Solution 2

For this solution, a from-between chart is generated using demands for time periods 3 and 4 combine.

With the from-between chart shown in Table 4.12 and using best layout from time period 2, a layout was generated using pair-wise exchange method after adding adequate capacity based on the capacity constraint calculations. The CRAFT generated layout is shown in Figure 4.11

TABLE 4.12

FROM BETWEEN CHART (DEMAND: TIME PERIODS 3+4)

1		700	1800	1500	1800			900		
2			1600	700			1500			
3				700				900		
4					2500	700	1500			
5										
6										600
7										
8										
9										600
10										

2	3	1	8
2	3	1	
7	4	5	9
	4	6	10

Figure 4.11. CRAFT generated layout using best layout for time period 2 and demand data from time periods 3+4.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 1, 2, 3, and 4 is calculated to be $1,980,000. The total rearrangement cost for tis solution is $140,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, and 4 combine is $2,120,000.

4.6.2.4.3 Solution 3

For this solution, a from-between chart is generated using combined demands for time periods 2, 3 and 4. With this from-between chart shown in Table 4.13 and using best layout from time period 1, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. This layout is shown in Figure 4.12.

TABLE 4.13

FROM BETWEEN CHART (DEMAND: TIME PERIODS 2+3+4)

	1	2	3	4	5	6	7	8	9	10
1		1200	2000	1900	2000			900		
2			2000	1200			1900			
3				1100				900		
4					3200	1100	1900			
5										
6										600
7										
8										
9										600
10										

	2	4	
3	2	4	7
3	1	5	6
8	1	9	10

Figure 4.12 CRAFT generated layout using best layout for time period 1 and demand data from time periods 2+3+4

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 1, 2, 3, and 4 is calculated to be \$2,195,000. The total rearrangement cost is \$77,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, and 4 combine is \$2,72,000.

4.6.2.4.4 Selection

As the methodology of selection of best solution is based on pair-wise exchange method, the solution that returns less cost of material handling and rearrangement calculated by equation (4.10) should be selected. Thus the best solution for time periods 1 to 4 is to use layout generated with demand from time period 1 in time period 1, use layout generated with demand from time period 2 in time period 2 and then use layout generated with demands from time periods 3 and 4 combined in time periods 3 and 4.

4.6.2.5 Time Period 5

According to the proposed methodology, four different from-between charts are generated for time period 5.

4.6.2.5.1 Solution 1

For this solution a from-between chart is generated based on demand for current time period only. A layout is generated using CRAFT with from-between chart for time period 5 and the layout from best solution in time period 4. This from-between chart is shown in Table 4.14.

With the from-between chart as input to CRAFT and using best layout from time period 4, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. This CRAFT generated layout is shown in Figure 4.13.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 1, 2, 3, 4, and 5 is calculated to be $2,642,500. The total rearrangement cost to transition from period 4 to 5 is $182,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, 4, and 5 combine is $2,824,500.

TABLE 4.14

FROM BETWEEN CHART (DEMAND: TIME PERIOD 5)

	1	2	3	4	5	6	7	8	9	10	11	12
1		500		900				600				
2			600	500			900					
3								600				
4					500		900					
5												
6										800		
7												
8												
9										800		

TABLE 4.14 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12
10												
11												1000
12												

2	3	8	11
2	3	1	12
7	4	1	9
5	4	6	10

Figure 4.13. CRAFT generated layout using demand data from time period 5.

4.6.2.5.2 Solution 2

For this solution, a from-between chart is generated by combining demands for time periods 4 and 5. With the from-between chart shown in Table 4.15 and using best layout from time period 3, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. The CRAFT generated layout is shown in Figure 4.14.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 1, 2, 3, 4, and 5 is calculated to be \$2,800,000. The total rearrangement cost to transition from layout in time period 3 to this layout is \$112,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, 4, and 5 combine is \$2,912,000.

TABLE 4.15

FROM BETWEEN CHART (DEMAND: TIME PERIODS 4+5)

	1	2	3	4	5	6	7	8	9	10	11	12
1		1000	800	1800	800			1200				
2			1200	1000			1800					
3								1200				
4					1800		1800					

TABLE 4.15 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12
5												
6										1400		
7												
8												
9										1400		
10												
11												1000
12												

2	1	3	8
2	1	3	9
7	4	11	10
5	4	12	6

Figure 4.14. CRAFT generated layout using best layout for time period 3 and demand data from time periods 4+5.

4.6.2.5.3 Solution 3

For this solution, a from-between chart is generated using the combined demands for time periods 3, 4 and 5. With this from between chart shown in Table 4.16 and using best layout from time period 2, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. This layout is shown in Figure 4.15.

TABLE 4.16

FROM BETWEEN CHART (DEMAND: TIME PERIODS 3+4+5)

	1	2	3	4	5	6	7	8	9	10	11	12
1		1200	1800	2400	1800			1500				
2			2200	1200			2400					
3				700				1500				
4					3000	700	2400					
5												
6										1400		
7												
8												
9										1400		

TABLE 4.16 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12
10												
11												1000
12												

2	3	1	8
2	3	1	11
7	4	5	12
6	4	10	9

Figure 4.15. CRAFT generated layout using best layout for time period 2 and demand data from time periods 3+4+5.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 1, 2, 3, 4, and 5 is calculated to be $2,742,500. The total rearrangement cost for transitioning from layout in time period 2 to the new one is $126,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, 4, and 5 is $2,868,500.

4.6.2.5.4 Solution 4

For this solution, a from-between chart is generated using combined demands for time periods 2, 3, 4 and 5. With this from between chart shown in Table 4.17 and using best layout for time period 1, a layout was generated using pair-wise exchange method after adding adequate capacity based on capacity constraint calculations. This layout is shown in Figure 4.16.

TABLE 4.17

FROM BETWEEN CHART (DEMAND: TIME PERIODS 2+3+4+5)

	1	2	3	4	5	6	7	8	9	10	11	12
1		1700	2000	2800	2000			1500				
2			2600	1700			2800					
3				1100				1500				
4					3700	1100	2800					
5												

TABLE 4.17 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12
6										1400		
7												
8												
9										1400		
10												
11												1000
12												

2	3	1	8
2	3	1	12
7	4	4	5
9	10	6	11

Figure 4.16. CRAFT generated layout using best layout for time period 1 and demand data from time periods 2+3+4+5.

With this layout, using equations (4.3) and (4.4), the total material handling cost for time periods 1, 2, 3, 4, and 5 is calculated to be \$2,717,500. The total rearrangement cost for transitioning from the layout in time period 1 to the new layout is \$70,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, 4, and 5 combine is \$2,787,500.

4.6.2.5.5 Selection

As the methodology of selection of best solution is based on pair-wise exchange method, the solution that returns less cost of material handling and rearrangement calculated by equation (4.10) should be selected. Thus the best solution is to use layout generated with demand from time period 1 in time period 1 and then use layout generated with demands from time periods 2, 3, 4, and 5 combined for time periods 2, 3, 4, and 5.

4.6.3 Backward Pass

According to the methodology suggested in Figure 4.4, layouts are generated for each of the time periods.

4.6.3.1 Time Period 5

As proposed in Figure 4.4, as our case study has only five time periods. For the backward pass we used the best layout for the last time period from the forward pass as a starting layout. The layout is in Figure 4.17.

2	3	1	8
2	3	1	12
7	4	4	5
9	10	6	11

Figure 4.17. Best layout from forward pass.

With this layout, using equations (4.3) and (4.4), the total material handling cost for time periods 5 is calculated to be $717,500. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time period 5 is $717,500.

4.6.3.2 Time Period 4

Using the methodology proposed in Figure 4.4, two different from-between charts are generated for this time period.

4.6.3.2.1 Solution 1

Using from-between chart for time period 4 shown in Table 4.11, a new layout is generated for this time period using CRAFT as shown in Figure 4.18.

5	4	7	
1	4	2	
1	3	2	6
8	3	9	10

Figure 4.18. CRAFT generated new layout using demand data from time period 4.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 4 and 5 is calculated to be $1,490,000. The total rearrangement cost to transition from time period 5 to 4 is $287,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 4 and 5 is $1,777,000.

4.6.3.2.2 Solution 2

Using from-between chart for time period 4, we generate a layout for time period using best layout from time period 5. Rearrangement was done if reduction in material handling cost was found using CRAFT. Machines used in time period 5 but not required for time period 4 were removed before pair-wise exchange. The new layout for this time period using CRAFT is shown in Figure 4.19.

2	3	1	8
2	3	1	
7	4	4	5
9	10	6	

Figure 4.19. CRAFT generated new layout using best layout for time period 5 and demand data from time period 4.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 4 and 5 is calculated to be $1,515,000. No rearrangement was required for this time period and hence there is no cost of rearrangement. Thus the total material handling and rearrangement cost with this layout arrangement option for the combined time periods 4 and 5 is $1,515,000.

4.6.3.2.3 Selection

As the methodology of selection of best solution is based on pair-wise exchange method, the solution that returns less cost of material handling and rearrangement calculated by equation (4.10) should be selected. Thus the best solution for time period 4 and 5 is to use layout from time period 5 in time period 5 and then then use the same layout after reducing capacity for time period 4.

4.6.3.3 Time Period 3

Using the methodology proposed in Figure 4.4, two different from-between charts are generated for time period 3.

4.6.3.3.1 Solution 1

Using from-between chart for time period 3 shown in Table 4.9, a new layout is generated for time period 3 using CRAFT as shown in Figure 4.20.

5	4	6	
1	4	7	
1	3	2	
8	3	2	

Figure 4.20 CRAFT generated new layout using demand data from time period 3.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 3, 4 and 5 is calculated to be $2,207,500. The total rearrangement cost to transition from the layout in time period 4 to the one in time period 3 is $259,000. Thus the total material handling and rearrangement cost for this solution for time periods 3, 4 and 5 is $2,466,500.

4.6.3.3.2 Solution 2

Using from-between chart for this time period (t = 3) shown in Table 4.9, we generate a layout for this time period using best layout from time period 4. Rearrangement was done if reduction in material handling cost was found using CRAFT. Machines used in time period 4 but not required for time period 3 were removed before pair-wise exchange. The new layout for this time period using CRAFT is shown in Figure 4.21.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 3, 4 and 5 is calculated to be $2,212,500. No rearrangement was required for this time period and hence there is no cost of rearrangement. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 3, 4 and 5 is $2,212,500.

2	3	1	8
2	3	1	
7	4	4	5
		6	

Figure 4.21. CRAFT generated new layout using best layout for time period 4 and demand data from time period 3.

4.6.3.3.3 Selection

As the methodology of selection of best solution is based on pair-wise exchange method, the solution that returns less cost of material handling and rearrangement calculated by equation (4.10) should be selected.

Thus the best solution for time period 3, 4 and 5 is to use layout from time period 5 in time period 5 and then use the same layout after reducing capacity for time period 4. Then further reduce capacity for time period 3 and use it in that time period.

4.6.3.4 Time Period 2

Using the methodology proposed in Figure 4.4, two different from-between charts are generated for this time period.

4.6.3.4.1 Solution 1

Using from-between chart for time period 2 shown in Table 4.7, a new layout is generated for time period 2 using CRAFT as shown in Figure 4.22.

5	1	2	
4	4	3	
6	7		

Figure 4.22. CRAFT generated new layout using demand data from time period 2.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 2, 3, 4 and 5 is calculated to be $2,522,500. The total rearrangement cost using $140/foot of machine moving cost is $105,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 2, 3, 4 and 5 combine is $2,627,500.

4.6.3.4.2 Solution 2

Using from-between chart for this time period (t = 2) shown in Table 4.7, we generate a layout for this time period using best layout from time period 3. Rearrangement was done if reduction in material handling cost was found using CRAFT. Machines used in time period 3 but not required for time period 2 were removed before pair-wise exchange. The new layout for this time period using CRAFT is shown in Figure 4.23.

With the layout, using equations (4.3) and (4.4), total material handling cost for time periods 2, 3, 4 and 5 is calculated to be $2,527,500. The total rearrangement cost using $140/foot of machine moving cost is $14,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 2, 3, 4 and 5 combine is $2,541,500.

3	2	1	
7	4	4	5
		6	

Figure 4.23. CRAFT generated new layout using best layout for time period 3 and demand data from time period 2.

4.6.3.4.3 Selection

As the methodology of selection of best solution is based on pair-wise exchange method, the solution that returns less cost of material handling and rearrangement calculated by equation (4.10) should be selected.

Thus best solution for time period 2, 3, 4 and 5 is to use layout from time period 5 in time period 5 and then use the same layout after reducing capacity for time period 4. Then further reduce capacity for time period 3 and use it in that time period, followed by capacity reduction and rearrangement in time period 2 to use it in that time period.

4.6.3.5 Time Period 1

Using the methodology proposed in Figure 4.4, two different from-between charts are generated for time period 1.

4.6.3.5.1 Solution 1

Using from-between chart for time period 1 shown in Table 4.6, a new layout is generated for time period 1 using CRAFT as shown in Figure 4.24.

5	1	3	
4	2	6	

Figure 4.24. CRAFT generated new layout using demand data from time period 1.

With the layout, using equations (4.3) and (4.4), total material handling cost for time periods 1, 2, 3, 4 and 5 is calculated to be \$2,697,500. The total rearrangement cost using \$140/foot of machine moving cost is \$84,000. Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, 4 and 5 combine is \$2,781,500.

4.6.3.5.2 Solution 2

Using from-between chart for this time period (t = 1) shown in Table 4.6, a new layout is generated for this time period using best layout from time period 2. Rearrangement was done if reduction in material handling cost was found using CRAFT. Machines used in time period 2 but not required for time period 1 were removed before pair-wise exchange. The new layout for this time period using CRAFT is shown in Figure 4.25.

3	1	2	
7		4	5
		6	

Figure 4.25. CRAFT generated new layout using best layout for time period 2 and demand data from time period 1.

With this layout, using equations (4.3) and (4.4), total material handling cost for time periods 1, 2, 3, 4 and 5 is calculated to be $2,742,500.

Not accounting for the $1,000 of fixed rearrangement cost, using equations (4.5) and (4.6), total rearrangement cost using $140/foot of machine moving cost is $14,000 for this time period and $14,000 for time period 2. This results in 28,000 total rearrangement cost.

Thus the total material handling and rearrangement cost with this floor layout arrangement option for time periods 1, 2, 3, 4 and 5 combine is $2,770,500.

4.6.3.5.3 Selection

As the methodology of selection of best solution is based on pair-wise exchange method, the solution that returns less cost of material handling and rearrangement calculated by equation (4.10) should be selected.

Thus best solution for time period 1, 2, 3, 4 and 5 is to use layout from time period 5 in time period 5 and then use the same layout after reducing capacity for time period 4. Then further reduce capacity for time period 3 and use it in that time period, followed by capacity reduction and rearrangement in time period 2 to use it in that time period. Finally for time period 1 the capacity is further reduced followed by rearrangement to obtain best layout for that time period.

4.6.4 Best Solution Selection

Based on the results of the forward and backward pass, we can see that the best solution found using forward pass would cost $2,717,500 in material handling cost and $70,000 in rearrangement cost, resulting in a total cost of 2,787,500. The best solution found using backward pass would result in a material handling cost of $2,742,500 and a rearrangement cost of $28,000 resulting in a total combine cost of $2,770,500. Thus the backward pass solution resulted in $17,000 savings over forward pass solution in material handling and rearrangement costs. Thus the backward pass solution should be selected as best solution.

4.6.5 Cost Calculation

Cost calculated in each time period included only material handling and rearrangement cost as they were the costs influencing the solution selection. All other costs had to be incurred to meet demand irrespective of the solution selection and hence are taken into account here as total cost of meeting demand.

Production cost is independent of the layout selection as was calculated in Table 4.4. The total cost of production for all time periods combine calculated using equations (4.1) and (4.2) is $300,500.

Using the backward pass solution as best solution, we already know that the cost of material handling is 2,742,500.

The rearrangement cost is 28,000. This rearrangement cost calculated cumulatively in each time period ignored the fixed cost of rearrangement. As rearrangement was required in two time periods, time period 1 and 2, total fixed cost of rearrangement is $2,000. Thus the total cost of rearrangement is $30,000.

Cost of adding capacity is also independent of the layout generated as it depends only on production capacities. To meet demand in time period 2, we needed to add one machine, which can be calculated using equation (4.7). This will cost us $10,000. In time period 3, we have to add three machines, which will cost us $30,000. In time periods 4 and 5 we have to add 2 new machines each which will cost us $20,000 in each time period. Thus total cost of capacity addition is 80,000.

Using equation (4.12), the total cost of meeting demand over the planning horizon of 5 time periods is $3,153,000.

4.7 Conclusion and Future Work

This paper has developed a methodology for the design of a facility layout under dynamic conditions of product demands that change from period-to-period, while considering capacity constraints for each time period. The methodology uses a two-step procedure. The first step involves evaluating production capacity constraints. If production demand cannot be met, we eliminate the production constraint by adding more capacity. This is followed by a forward pass and backward pass approach to find the best layout that can be used for all time periods under the capacity constraints with dynamic demand conditions. In this procedure a new modified methodology is introduced for finding best layout. In forward pass, the best solution is found using material handling and rearrangement cost combine as a selection criteria for pair-wise selection process. In backward pass, the best solution is found using the same pair-wise selection criteria. Comparing the two best solutions, one global best solution is selected that would minimize the cost of material handling and rearrangement over all time periods for the planning horizon.

In this paper, material handling constraints were not taken into consideration. In future work material handling constraints can be taken into consideration. The case study in this research evaluates the methodology for deterministic conditions. More case studies could be conducted with variable demands and variable machine times.

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CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

This chapter summarizes the important findings of this dissertation and also discusses possible future work. This dissertation developed methodology to design dynamic facility layout under production and material handling capacity constraints. The main motivation behind the choice of this topic is the necessity to look at dynamic facility layouts in conjunction with capacity constraints and to find optimal solutions to meet demand with capacity constraints in place. Under current manufacturing paradigms where manufacturing facilities have to respond to the market conditions in a timely manner, ability to meet demand with resources on hand in a timely manner is of utmost importance to be profitable and sustainable in business. The demand keeps changing from time period to time period as the environment is dynamic. Along with the demand, the product mix changes with time as well. As the demand and product mix change with time, facility layout, which may be efficient, and a material handling and production system, which may also be efficient, could quickly be rendered to be inefficient. Thus manufacturing systems have to constantly evaluate the facility layouts, and capacities to ensure that demand can be met from time to time.

Chapter 2 evaluated the effects of capacity constraints and facility layouts under dynamic conditions on demand fulfillment. A procedure to redesign a facility layout under dynamic capacity constraints was developed. A methodology to evaluate ability of a facility to meet demand and propose changes needed (in a facility layout or capacities of production or material handling) to meet demand was developed. This chapter used the concept of system state to identify the capacity constraint and propose a solution to meet demand. It also developed a cost function used to calculate the cost of meeting demand. The selection of the optimal solution was based on minimizing the cost of meeting demand.

Chapter 3 extended the research conducted in Chapter 2 and added another parameter to the dynamic facility layout problem: production sequence. Ability of a facility to meet demand is a function of distance the part has to travel along with the time a part takes on each machine. These are the key features that help determine the production and material handling capacity requirements with a given facility layout under dynamic conditions. This chapter proposes a methodology to check if the facilities have adequate production capacity to meet demand. With the proposed methodology in this chapter, we can check for production capacity ahead of time and consider using alternative sequences for manufacturing parts in lieu of adding more machines. It also developed a cost function to determine the cost of meeting demand. The selection of the best solution is based on minimizing cost of meeting demand.

In both Chapters 2 and 3, the layout was generated using GA. In Chapter 4, a methodology for generating layout was developed. The layout was generated using a modified heuristic that uses a pair-wise exchange method. This research developed a methodology to develop an optimal layout using forward pass and backward pass approach using this modified heuristic with capacity constraints and alternative production sequences. Thus it built up on the research in Chapters 2 and 3. Using the proposed methodology, the best solution was found for the facility at the least cost of meeting demand. The cost of meeting demand was calculated based on the equations proposed in the chapter.

Thus Chapters 2, 3, and 4, we develop methods to evaluate the ability of a manufacturing system to meet demand. If demand cannot be met, the chapters provide methods to add more capacity or use alternate sequences or change facility layout. In either case, the study was conducted under deterministic conditions of demand and machine times. The heuristic method proposed in Chapter 4 uses specific combinations of from-to chart to develop an optimal solution based on the demands throughout the planning horizon. The areas of research which can be explored in the future are discussed in the next section.

5.2 Future Work

In all the chapters, the methodology proposed was tested under deterministic conditions of demand. They should be tested with variability in demand and variability in production system and material handling system performance. In Chapters 2 and 3, the methodology uses the layout in the previous time period to build the layout in the next, using demand from just the next time period. In the future, the methodology proposed in Chapter 4 should be used in conjunction with the methodologies proposed in Chapter 2 and 3 to find the best solution. Also, in Chapter 4, where only the production system constraint was considered, the research can be extended by developing a simulation for each time periods and considering the material handling capacity constraint as well. Besides that impact of more combinations of from-between charts on the optimal solution should be studied.

Most of this research was considered under deterministic conditions. When variability and uncertainty are considered, the health of the facility to meet new demands and meet demand in each period must be identified. A systems based approach that considers other factors such as scheduling strategies, market conditions, control strategies for material handling and a host of other factors should be used to determine the overall state of the manufacturing system. Once the system state conditions are identified, then research into development of appropriate actions for transformation of systems states must also be developed to optimize the system under uncertainty.