Dynamic Facility Planning under Production and Material Handling Capacity Constraints

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Facility layout approaches have assumed infinite capacities for the production system and material handling in determining the 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 and production systems. 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.
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I. 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.

1.1. 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). In 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.

Dynamic facility layout approaches are needed when there are frequent changes in the facility. 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. All of these dynamic layout planning methods used only the from-to chart and hence essentially ignored material handling and production capacity constraints.

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 cost 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, 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.

1.2. 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.

II. COST ANALYSIS FOR CAPACITY CONSTRAINED DLP

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. In this research, the product sequences do not change from one time period to the next. Hence, 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, …, X,
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} = quantity of product p required 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
K^t= Time duration for each period 't'
Q_{it} - number of machines of type 'i" in period 't'
H_t - number of MHUs in period 't'
S – Speed of MHU
L – Loading time per trip
W_t – unloading time per trip
P_{pn} –Processing time required for product 'p' on department 'n'

$$Z_{pn} = \begin{cases} 1, & if\ product\ p\ is\ processed\ in \\ & department\ n, \\ 0, & Otherwise \end{cases}$$

b_{nt} - # of units of machine ‘n’ in period ‘t’

2.1. 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 1 below:

$$g_{ijt} = \sum_{p=A}^{X} f_{tp} * X_{ijtp}; i = 1, \dots, N-1, j = i+1, \dots, N, \quad (1)$$

Material Handling cost during time period ‘t’, M_t can be calculated as shown in Equation 2.

$$M_t = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijt} * D_{ijt} * C \quad (2)$$

2.2. 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 as shown in Equation 3.

$$F_t = F^*_{t-1,t} \quad (3)$$

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 as shown in Equation 4.

$$V_t = \sum_{i=1}^{N} \sum_{j=1}^{N} d_{n(t-1,t)} * Y \quad (4)$$

2.3. Cost of Adding Production and Material Handling Capacities

If 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 5.

$$A_t = n_t * a_n \tag{5}$$

Similarly, if additional material handling capacity is needed, they can be added and the cost of adding material handling capacity can be calculated as shown in Equation 6.

$$B_t = m_t * b_m \tag{6}$$

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 as shown in Equation 7.

$$C_{Dt} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijt} * D_{ijt} * C + F_t + \sum_{i=1}^{N} \sum_{j=1}^{N} d_{n(t-1,t)} * Y \pm (n_t * a_n) \pm (m_t * b_m) \tag{7}$$

Thus the model requires the minimization of the total costs for all time periods. However, the model is also subject to the production and material handling constraints. The total production capacity needed for each of the n departments is given by the left hand side of Equation 8 and it should be less than the total available capacity given by the right hand side.

$$\sum_{p=1}^{X} (f_{tp} * P_{pn} * Z_{pn}) \le b_{nt} * K^t \; \forall \; t \text{ and } n \tag{8}$$

The total material handling capacity needed in any time period ‘t’ is given by the term on the left hand side of Equation 9. Also, this capacity should be less than the available capacity for the time period, which is represented by the right hand side term.

$$\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (g_{ijt} * \frac{D_{ijt}}{S} + g_{ijt}(L_t + W_t)) \le H_t * K^t \; \forall \; t \tag{9}$$

In Equation 9, the unloaded travel time is considered negligible and the effect of downtime is also not considered. 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 (Equation 10) does not take into consideration, the additional capacity needed in production and material handling.

$$C_{Dtg} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} g_{ijt} * D_{ijt} * C + F_t + \sum_{i=1}^{N} \sum_{j=1}^{N} d_{n(t-1,t)} * Y \tag{10}$$

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 11 shows the total production cost over the planning horizon which is the sum of production costs incurred in each time period.

$$C_{DT} = \sum_{t=1}^{T} C_{Dt} \tag{11}$$

III. METHODLOGY FOR REDESIGN

This research involves facility layout development for dynamic time periods with capacity constraints. Single period facility layout problems have been shown to be NP-hard. Hence, when solving dynamic layout problems, researchers have adopted heuristics to solve dynamic layout problems. When production capacity constraints and material handling capacity constraints are also considered traditional optimization approaches are impossible. Several researchers have attempted analytical approaches for determining capacity requirements. However, analytical approaches have been proven to be failures in determining the actual capacity. Hence, in this research, a combination of heuristics and simulation has been used to solve the multi-period, dynamic facility layout problem with production capacity and material handling capacity constraints. The research uses genetic algorithms which have been proven to be effective for the solution of the facility layout problem. It then uses an iterative simulation and layout solving approach to solve the capacity constraints.

The product quantities in each time period are assumed to be known and fixed. There is only one process sequence for each product. The processing times for each product on each machine are known and deterministic. The steps of the algorithm are given 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 the methodology for redesign is shown in Fig 1.

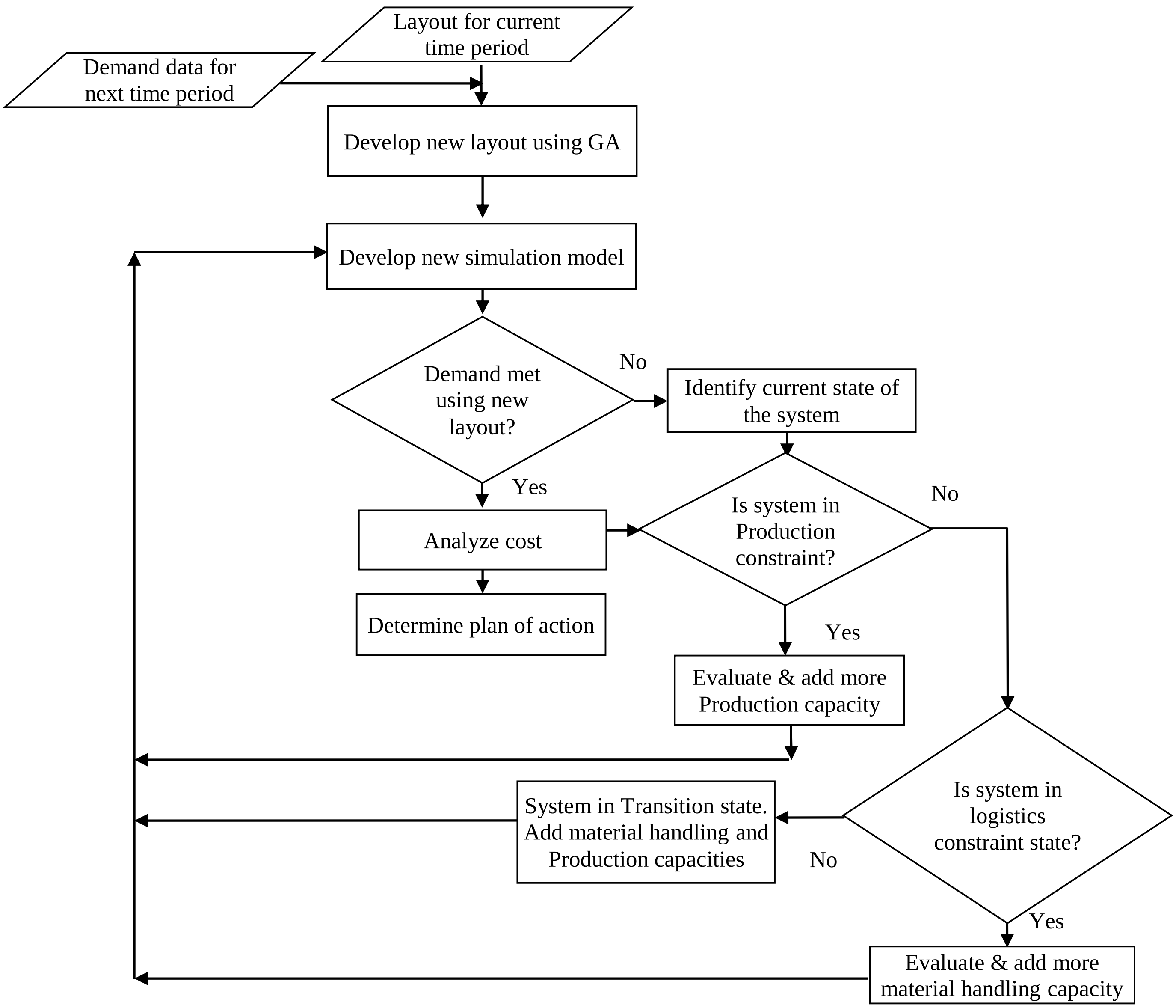

FIGURE 1. REDESIGN METHODOLOGY FLOWCHART

3.1. 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 Fig 2.

The GA cost function is provided in Equation 10. This cost function attempts to minimize the material handling cost for the projected demand. The fitness function is given in Equation 12 (Krishnan, Jithavech and Liao, 2009).

$$\text{Fitness Value} = v(i) = K(C_{Dtg})^{\alpha\text{-}1} e^{-((\frac{Z_i - Z^*}{Z^*})\beta)} \qquad (12)$$

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):

$$\beta = \begin{cases} 0.002Z^*, & \text{when } 0<n<I/5 \\ 0.004Z^*, & \text{when } I/5 \le n<2I/5 \\ 0.006Z^*, & \text{when } 2I/5 \le n<3I/5 \\ 0.008Z^*, & \text{when } 3I/5 \le n<4I/5 \\ 0.01Z^*, & \text{when } 4I/5 \le t \le I \end{cases} \qquad (13)$$

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.

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

FIGURE 2. DEPARTMENT PLACEMENT SCHEME

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.

3.2. 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 are determined using the "Rate of Part Generation" procedure detailed in section 3.2.1.

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 detailed in Section 3.3.

3.2.1. 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 'B' is created at six minutes on the simulation clock, first instance of product 'A' is created at ten minutes on the simulation clock, followed by two instances of product 'B' created at twelve and eighteen minutes respectively before second instance of product 'A' is created at twenty minutes on the simulation clock. To eliminate idle time for the material handling 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 14:

$$\forall P\ (for\ a\ given\ t): R_{pt} = Q_{pt}/t^* \tag{14}$$

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.

3.3. Determining Current State of Manufacturing System

Based on 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 MHU by the other, either during loading or travel, and hence the percent utilization is representative of actual usage of each MHU. MHU's travel can be classified into loaded travel or 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 MHUs.

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.

The following steps (Fig. 3) 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 as follows:

$$U_{MH} = \left(\sum_{i=1}^{n} U_{MHi}\right)/n \qquad (15)$$

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 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.

3.4. Illustration of Calculations

Consider a facility that has 4 machines and manufactures 2 products. Product demands for the facility in time periods are known and the product sequence is given in Table 1. The layouts recommended by the GA heuristic for different time periods are shown in Table 2.

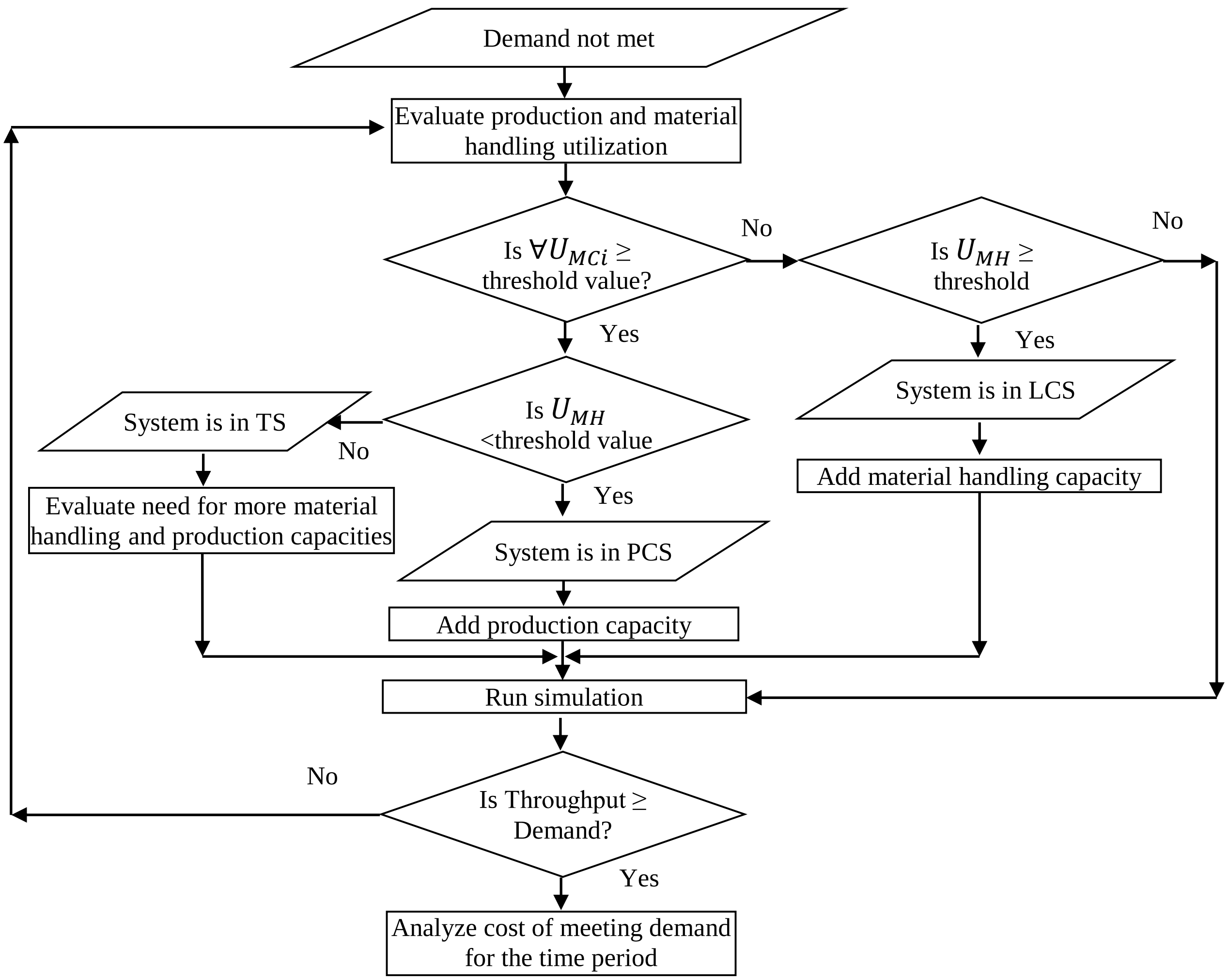

FIGURE 3. PROCEDURE FOR DETERMINING MANUFACTURING SYSTEM STATE

TABLE 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

TABEL 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

3.4.1. Cost Calculations for Time Period t=1

The f_{tp} values for all three time periods are shown in Table 3. The cost associated with meeting demand in time period t=1 is calculated below. 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}, and X_{341B} = X_{342B} = 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 4.

For this case study, it is assumed that the distance between adjacent machines (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.

TABLE 3. f_{tp} VALUES FOR EACH PRODUCT IN EACH TIME PERIOD

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

TABEL 4. g_{ijt} VALUES FOR EACH PRODUCT DURING EACH TIME PERIOD

$g_{121} = 3(1) + 7(0) = 3$ $\qquad$ $g_{131} = 3(0) + 7(1) = 7$

$g_{122} = 4(1) + 6(0) = 4$ $\qquad$ $g_{132} = 4(0) + 6(1) = 6$

$g_{123} = 5(1) + 5(0) = 5$ $\qquad$ $g_{133} = 5(0) + 5(1) = 5$

$g_{241} = 3(1) + 7(0) = 3$ $\qquad$ $g_{241} = 3(0) + 7(1) = 7$

$g_{242} = 4(1) + 6(0) = 4$ $\qquad$ $g_{242} = 4(0) + 6(1) = 6$

$g_{243} = 5(1) + 5(0) = 5$ $\qquad$ $g_{243} = 5(0) + 5(1) = 5$

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

No rearrangement was necessary during time period 1. The production capacities and material handling capacities were adequate to meet the demand. Total production cost in time period 1 is $200.

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

3.4.2. Cost Calculations for Time Period t=2

The costs associated with meeting demand in time period t=2 is calculated as shown below:
For time period t=2, the material handling cost calculated as follows and results in a total of $200.

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

Transitioning from time period t=1 to 2 requires a change to the layout. 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:

$$V_2 = (d_{3(1,2)} * Y) + (d_{4(1,2)} * Y)$$

$$V_2 = (d_{3(1,2)} * Y) + (D_{4(1,2)} * Y) = (10 * 10) + (10 * 10) = 200$$

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 is calculated as follows:

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

3.4.3. Cost Calculations for Time Period t=3

The cost associated with meeting demand in time period t=3 is calculated below. For time period t=3, the material handling cost calculated below results in a total of $200.

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

Transitioning 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 is 10 feet, and the cost to move the machines is $10/feet, the total variable cost for rearrangement is given as:

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

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

Based on capacity calculations, the production capacity for machine 1 has to be increased and an additional MHU 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 is calculated as:

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

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

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

IV. EXAMPLE (9-Department, 5 Product, 4-Period)

To demonstrate the effectiveness of this methodology a larger example with 9 departments and 4 time periods is used. The projected demands and sequences of manufacturing for each product in each time period are given in Table 5.

The following assumptions were made for the multi-period nine department case study:

- Rectilinear distance between machines is 50 feet
- All MHUs 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

The simulation warm up period is two weeks. The data is collected for 4 week production.

4.1. Time Period 1

Based on the product demand for time period t=1, a from between chart is constructed (Table 6). The layout for time period t = 2 obtained using GA is shown in the Fig. 4.

TABLE 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

TABLE 6. FROM-BETWEEN CHART (TIME PERIOD T=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 4. LAYOUT OBTAINED USING GA (TIME PERIOD T = 1)

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 6. The rest of the values are zero. The material handling cost associated with these dynamic flow values for time period t = 1 as calculated using Equation 2 is $1,131,000. 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 7 is $1,131,000.

4.2. Time Period 2

The from-between chart for time period t=2 is given below (Table 7). The layout for time period t = 2 obtained using GA is shown in the Fig. 5.

TABEL 7. DYNAMIC FROM-BETWEEN CHART (TINE PERIOD T=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 5. LAYOUT OBTAINED USING GA (TIME PERIOD T = 2)

Simulation data results shown in Table 8 show 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. The dynamic flow values (g_{ijt}) for time period t = 2 are shown in the Table 7. The material handling cost associated with these dynamic flow values for time period t = 2 as calculated using Equation 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 9 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 4 is used to calculate total variable cost of rearrangement. 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 7 is $1,266,000.

TABLE 8. SIMULATION RESULTS (TIME PERIOD T=2)

Name	Demand	Throughput
Part1	400	401
Part 2	460	460
Part 3	560	561
Part 4	350	351
Part 5	260	261

TABLE 9. REARRANGEMENT DISTANCE AND COST

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

4.3. Time Period 3

The from-between chart for time period 3 is shown in Table 10 and the layout is shown in the Fig. 6.

Simulation data suggests that for the layout obtained using GA and with the existing production and material handling capacities, demand for this period cannot be met, as can be seen in simulation results in Table 11.

TABLE 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 6. LAYOUT GENERATED BY THE GA (TIME PERIOD T = 3)

TABLE 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

The dynamic flow values (g_{ijt}) for time period t = 3 are shown in Table 10. The material handling cost associated with these dynamic flow values for time period t = 3 as calculated using Equation 2 is $1,060,500. The 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 12 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 4 is used to calculate total variable cost of rearrangement.

Thus the total cost of rearrangement going from time period t = 2 to t = 3 is $53,750 including the $1,000 of fixed rearrangement cost. However, throughput for this time period shows that the demand cannot be met. Further analysis of utilization of the machine times shown in Table 13 indicates that machine 8 is utilized 100% and hence is a bottleneck.

4.3.1. 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. At a cost of $10,000/machine, the cost of adding production system capacity is calculated to be $10,000. With increase in production capacity, machine is not a bottleneck any more, and simulations results (Table 14) indicate that demand can be met. The cost of meeting demand during this time period as calculated by Equation 7 is $1,124,250.

TABLE 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
D_{361}	150	$6,750
D_{375}	50	$2,500
D_{386}	50	$2,250
D_{398}	200	$10,000
Total		$52,750

TABLE 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

TABLE 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

4.4. Time Period 4

The from-between chart is given in Table 15 and the layout is shown in the Fig. 7.

Simulation data suggests that for the layout recommended by GA and with the existing production and material handling capacities in time period t = 3, demand for this period cannot be met as shown in simulation results (Table 16).

TABLE 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		
6								660	
7								660	400
8									
9									

9	7	8
4	5	6
2	3	1

FIGURE 7. LAYOUT OBTAINED USING GA (TIME PERIOD T = 4)

TABLE 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 15. The material handling cost associated with these dynamic flow values for time period t = 4 as calculated using Equation 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 17 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 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 $41,500 including the $1,000 of fixed rearrangement cost. However, throughput for this time period shows that the demand cannot be met. Further analysis of utilization of the machine times (Table 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 Machine 8.

TABLE 17. REARRANGEMENT DISTANCE AND COST

Machine Moves	Distance of move (Feet)	Cost of move
D_{419}	100	$5,000
D_{428}	50	$2,250
D_{438}	100	$7,500
D_{442}	100	$4,500
D_{457}	100	$5,000
D_{464}	50	$2,250
D_{473}	50	$2,500
D_{485}	200	$9,000
D_{491}	150	$7,500
Total		$40,500

TABLE 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

4.4.1. 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. At a cost of $10,000/machine, the cost of adding production system capacity is calculated to be $10,000 using Equation 5. With increase in production capacity the machines are not bottlenecks any more, however simulation results run with increased production capacity (Table 19) shows that demand for the time period is still not met.

This warrants analysis of the material handling system and its utilization. The analysis of the material handling system shown in Table 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 20 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.

4.4.2. Time Period 4 (Increased Production Capacity and Material Handling Capacity)

Material handling capacity constraint was handled by adding one more MHU at a cost of $5000. Simulation was run again after adding both production system and material handling capacity and analyzing results indicates that the demand can be met with the increased capacities and using the layout suggested by GA procedure. Throughput results of simulation are shown in Table 21.

Analysis of utilization of MHUs shown in Table 22 indicate that while the utilization is high, 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%, although machine 5 and 8 are high (Table 23).

TABLE 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

TABEL 20. MHU UTILIZATION: ORIGINAL CAPACITY VS. INCREASED PRODUCTION CAPACITY

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

TABLE 21. RESULT AFTER INCREASING MACHINE AND MATERIAL HANDLING CAPACITY

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

TABLE 22. UTILIZATION OF MHUs AFTER INCREASED PRODUCTION SYSTEM AND MATERIAL HANDLING CAPACITIES

Name	Utilization (%)
MHU1	98.758
MHU1	98.701
MHU1	98.88

TABLE 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. Thus it is possible that 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 are added. The cost of meeting demand during this time period is $1,613,250.

V. CONCLUSION AND FUTURE WORK

This paper has 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 paper, 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. 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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