A Non-deterministic Approach to Dynamic Layout Planning of Flexible Manufacturing Systems

A thesis submitted for the degree of Doctor of Philosophy in the Department of Engineering

University of Warwick

By

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<u>Dedication</u>

I dedicate this thesis to my dear wife

Fatemeh

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The author wishes to thank Dr.T.C.Goodhead for his continuous suparvision, guidance and encouragemert during the course of this research work.

The author would also like to express his thanks to Dr.S.Grinsted for her help in modification of the software used in this research.

Finally the author wishes to thank his parents and family for their patience and constant encouragement throughout the duration of this work.

ABSTRACT

A new approach to the dynamic layout planning problem is proposed which provides solutions to highly variable material flow patterns occurring over a multi-period planning horizon and is especially suitable for flexible manufacturing systems. A non-deterministic environment is considered in which there is assumed to be uncertainty in the future material flow data. The performance of the method is assessed by comparing the solution produced by this method with a set of data provided in the literature for which the claimed optimal solution is known. There is close agreement with the stated solution and the result is obtained with a fraction of the computational effort.

The computational efficiency is due to a new construction method to generate static layout solutions. This method uses an algorithm in which the number of stages is proportional to the number of facilities rather than an exponentional relationship as found in most other methods. The method also uses an element of forward planning to ensure that early location assignments provide minimum restriction to assignments made later in the procedure.

Results of extensive tests show that the new static layout planning procedure produces solutions generally better than existing construction techniques and comparable with improvement techniques such as CRAFT. The execution speed of the procedure makes it possible to solve large scale problems (>30)in very short time scales on Micro-computers.

Incorporation of the fast new construction method into dynamic layout planning allows decision making concerning when and how to re-layout facilities in response to changes in predicted material flow.

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CHAPTER ONE

INTRODUCTION

1.1 Problem Statement

Shifting market demand pattern and frequent fluctuation in production output level together with variation in product mix and design has created the requirement for responsive flexible manufacturing systems (FMS).

Flexibility inherent in the elements of FMSs, such as Computer Numerical Control (CNC) machines and Automated Guided Vehicles (AGV), may well cope with variations of parts produced (either in quantity or in design), simply by reprogramming these elements. But reprogramming the automated elements of FMS does not necessarily guarantee the efficiency of production of the total system. Apart from effective utilization of facilities in production systems, the way in which facilities are laid out and located relative to each other is a key factor in achieving system efficiency and economic production. Harmonious allocation of facilities in the layout and ensuring the adjacency or nearness of facilities (in the system layout) with high volume of parts flow between them, is the most commonly exercised way, in industry, of reducing material handling requirements. This in turn has the benefit of reduction in material handling costs.

Therefore one of the factors influencing the total cost of manufacture is that of material handling cost and this is fundamentally linked to the layout of facilities.

To maintain their competitiveness, companies employing FMSs have to keep manufacturing cost to a minimum, while being able to respond to the changes mentioned earlier. This implies that the layout of facilities should be continuously reviewed.

Continuous evaluation of layout, generally termed as Dynamic Layout Planning (DLP) in the literature, [Moore(1974),Rosenblatt(1986), Afentakis(1990)], has been suggested as a means of maintaining efficiency in batch production systems where part mix/design and production changes are regularly introduced.

Since the occurrence of frequent change is a feature of FMS's, it is clear that consideration of the configuration of machines is of great importance for FMSs every time material flow changes are necessary to satisfy the market demand.

DLP, has been developed from Static Layout Planning (SLP) to enable layouts to evolve dynamically over multiple planning periods within the total planning horizon. This area is however relatively new and has raised other questions which have not yet been fully investigated.

These questions can be categorised as follows:

* What are the criteria for planning the practical optimum facility layout in the dynamic situation?

* If one of the criteria is minimization of material movement cost, what considerations are given to this cost if there is a need to change the initial layout in order to cope with variation in product mix and design?

* How should the length of the time periods between which re-layouts are considered be determined?

* Is there any way in which re-layout can be delayed?

* If re-layout is decided upon at the end of a time period should the new arrangement be implemented instantly or in a

phased manner? i.e. exactly when to instigate the layout.

In addition to the above questions there also exists the problem of uncertainty in the data regarding future product volume and the mix of product design to be produced. Many companies employing FMSs do so because of the volatile nature of the market in which they operate and they may commonly experience the cancellation of orders they have previously received, or alternatively receive orders unexpectedly which they could not have anticipated accurately in advance. Therefore ignoring the effects of uncertain future data on the facilities layout can lead to undesirable and costly consequences.

The problem of dynamic layout planning (DLP), in the FMS context, can be stated briefly as involving the following elements which are additional to those addressed in 'conventional' DLP:,

(i) determination of time periods within the planning horizon in which re-layout will be necessary to maintain system efficiency,

(ii) consideration in advance of forecast data of unknown accuracy, and its impact on the multi-period layout configuration policy.

In all existing solution procedures to the DLP problem none takes account of both of the above aspects. In some of the approaches, for example, changes in material flow data are assumed to occur at fixed time periods, while a totally deterministic view of product design and production volume is considered within these time periods (Rosenblatt(1986)). Other approaches in which some limited variability is tolerated in the data, are only applicable to systems containing a small number of facilities.

A further significant problem with existing solutions is the constraint on problem size. This arises due to an exponential increase in solution time with the increase in the number of facilities. Full solutions to problems containing no more than nine facilities have been reported in the literature, [Afentakis(1990), Shore and Tompkins(1980)], because of the enormous amount of computing time needed to produce solutions by their proposed methods.

The main objective in this research is therefore to develop a dynamic layout planning procedure which will determine:

(a) WHEN is the cost effective time to re-arrange the layout and,

(b) WHAT is the most appropriate layout for the current period.

The procedure must take account of the fact that forecast material flow data is unlikely to be accurate and that the rate at which the system needs to respond to change must be matched by the rate at which the procedure can produce solutions.

In the following sections of this chapter, areas related to this work will be briefly outlined for the purpose of identifying the background to the work. The problem of dynamic facilities re-layout and a new solution procedure is detailed following an extensive review of existing methods and solutions to the problem of static layout planning.

1.2 Flexible Manufacturing Systems (FMSs)

Definition: An FMS is a highly automated production system consisting of flexible machines or workstations connected by an automated material handling system, all under the control of one or more computers.[Hartley(1984), Sule(1988)]

Alternatively an FMS can be defined as" an integrated computer controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium-sized volume of a variety of part types" .[Browne(1984)]

1.2.1 Production System Arrangements

Typical production systems are classified according to the layout of machines and departments within the manufacturing plant. According to Hartley(1984), these are:

* Random Layout; machines are laid out randomly on the shopfloor.

* Functional (process) Layout; similar machines are grouped together within the plant to form a department. Usually used for jobbing & small batch type production that produces many different products in relatively small volumes.

* Modular (product) Layout; identical modules perform similar processes in parallel. Suitable for batch production in which numerous items are produced but not so large a variety as required in a job shop type of production.

* Cellular Layout; designed specifically for cellular and flexible manufacturing (also suitable for batch manufacturing) in which a

large number of common parts are grouped together and produced in a cell consisting of all the machines that are needed to produce that group. This system lends itself to the introduction of FMS for different types of workpieces.

The emergence of flexible manufacturing systems in the batch manufacturing environment, has presented a significant departure from conventional manufacturing approaches. Yet little attention has been paid to the importance of the study of dynamic layout planning of this type of manufacturing system, in the sense that re-layout costs could be justified by savings in material movement costs. Some of the reasons for this area not having been fully investigated are summarised below:,

- assumption that an FMS makes handling costs very insensitive to layout.
- difficulty in evaluation of material movement cost.
- assumption that dynamic layout planning is only relevant to large production systems.
- assumption that dynamic layout planning

is only suitable for production systems in which variations in material flow only occur at fixed time intervals.

- assumption that DLP is only relevant to systems operating to or near full capacity.

It is probably the first of the above points that leads to the belief that FMS layout does not contribute significantly to operating costs. But the cost of providing flexible automatic materials handling in FMS, typically using automated guided vehicles(AGV's), is very high so small increases in the total material handling requirement may increase costs significantly. Furthermore popular trends to minimise work-in-progress in order to move nearer to just-in-time production leads to a need to move smaller quantities of parts more frequently thus leading to a general growth in the material handling requirement. Handling costs are therefore significant.

1.3 Material Handling Systems (MHS)

In developing a new FMS or modification of an existing plant, analysis of the material handling system is one of the most important aspects.[Montalenti(1985)]

There have been several definitions in the literature for a material handling system. One of the most comprehensive definitions is provided by the Material Handling Institute (MHI), USA, which states:" Material handling embraces all of the basic operations involved in the movement of bulk, packaged, and individual products in a semi-solid or a solid state by means of machinery and within the limits of place of business".[Sule(1985)]

D.R.Sule estimated that material handling can account for 30-70 percent of the total manufacturing cost and efficient material handling can be primarily responsible for reducing a plant's operating cost by 15-30 percent. In another claim by Tomkins and White(1984) it is estimated that between 20 and 50 percent of the total manufacturing expenditure can be attributed to material handling.

The main objectives in selection of a MHS for an FMS are:

* To increase the efficiency of material flow by ensuring the availability of required materials when and where they are needed.

* To reduce material handling cost.

* To improve facility utilization.

* To increase productivity.

* To minimise work in progress.

Recent developments in Automated Guided Vehicle Systems (AGVs) have further increased their capability in achieving the above objectives as well as providing flexibility in route layouts which is required within an FMS.[Turpin(1988), Grossman, (1988) and Goodhead et.al.(1988)]

In a large proportion of recently implemented flexible manufacturing systems AGVs have become an essential component of the material handling system. [Vosniakos et.al.(1989), Hammond (1986) and Gunsser(1988)]

Most current AGV systems are not however as quick and easy to change as may be required. Free ranging AGVs which are now commercially available offer the degree of flexibility required. [Evans(1988)]

However, the system flow pattern determined by the process requirements governs material flow paths and this implies that any attempt at a system optimisation process should begin with the layout design.[Putrus(1986)]

In other words a particularly flexible material handling system may be able to accommodate the effect of a layout that is inappropriate to the material flow but it can never operate as cost effectively as when the handling distance is minimised. The time to change the layout occurs when the cost penalties accrued over a period incurred through operating an inappropriate layout exceed the costs of changing to a more efficient layout.

1.4 Facilities Layout Techniques

Facilities layout techniques, often called plant layout, [Foulds and Robinson(1976)], is a method which describes the process of design arrangement and coordination of physical facilities. Plant layout techniques can be used in many areas including the design of service facilities, such as hospitals, libraries and etc.

However the concern in this thesis is only with the arrangement of manufacturing machines and workcentres in an FMS shopfloor, in a multi-period planning horizon.

Since the beginning of organized manufacturing, considerable effort has been expended to make the facilities layout as efficient as possible. In this goal the importance of effective planning of facilities has been realised and the potential benefits are well documented.[Tomkins and White(1984), Sule(1985)] In general there are four stages of historical development in the techniques treating the layout planning problem:-

I. Use of graphical techniques and template manipulation by a layout engineer followed by development of the layout and subjective evaluation of it.

II. Systematic layout planning, suggested initially by Muther(1974). He has attempted to provide procedures with sufficient structure permitting practical problems to be solved economically through a systematic approach.

III. Use of quantitative techniques, when facilities relationships are expressed quantitatively, for example by material flow quantities in a From-To chart. The objective function is then to minimize the material handling cost, that is, the product of the distance between facilities, the material flow, and unit-handling cost.

IV. Computer aided layout planning.

With the recent use of operational research techniques and computer technology more analytical procedures can be applied to the generation and comparison of layouts. A detailed account of these are provided in chapter two.

1.4.1 Static and Dynamic Layout Planning

The general approach, until recently, to the facility layout problem has been a static one. In Static Layout

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Planning(SLP) the aim is to optimize some evaluation criteria either qualitatively or quantitatively with a fixed (or static) set of material flow data applicable to a fixed period of time.

A common procedure employed with qualitative criteria is to establish a relationship-chart based on the closeness desirability of the facilities, [Sule(1988), Muther(1974), Francis and White(1974)].

The most common quantitative criteria, however, used in evaluation of layout is based on From-To charts obtained from predicted intensity of material flow between facilities.

In an international survey of progress in the subject of Computer-Aided Facilities Layout (CAFL), it has been observed that material movement is the most common layout evaluation criteria, [Driscoll and Sangi(1985)].

In SLP, minimization of the total material movement cost is associated with assigning different facilities to different locations and is formulated as a quadratic assignment problem, which is discussed in detail in chapter 3 of this thesis.

Although SLP can be a useful procedure in designing a new plant layout, it cannot be deployed as a one off procedure in FMS where frequent re-arrangement of the layout may be required in order to respond to the variation in demand and product design [Moore(1969), Nicol and Hollier(1983)].

Dynamic evaluation of plant re-layout, involving the consideration and methodology of changing from an old to a new layout has not received much attention until recently [Driscoll and Sawyer(1985)]. With the progress made in computer aided layout planning, dynamic layout planning (DLP) approaches to the problem have been suggested. [Rosenblatt (1986) and Afentakis(1990)]

In these approaches, the layout design strategy is studied not just for a single time period, but for a multiperiod planning horizon, during which variations occur in the material flow that is anticipated. The objective is to minimise the sum of the costs attributable to facility location over the whole planning horizon not simply for individual discrete periods.

In almost all of the solutions provided to date, a deterministic environment, in terms of material flow data, has been considered. A significant contribution made by this research is to extend the DLP concept to deal with uncertainty in the material flow that may be expected to occur in both the near future and in the longer term.

The very nature of FMSs means that products and the product mix can change and the inherent flexibility in the processes and handling system can permit a variety of the products to be made.

But the production cost is not necessarily minimized if the layout and handling methods remain the same as was originally defined for a considerably different set of products and flow paths. In order to minimize costs, the system must respond to changes in demand and the response rate must be sufficiently high to deal with large and rapid fluctuations. Frequent fluctuations in material flow are sometimes not economically dealt with by re-layout due to the costs of machine movements but can be addressed by re-programming the guide paths of free-ranging AGVs. For longer term fluctuations dynamic re-layout can be a viable option but the uncertainty and variability of the data used is considered to require techniques which creates variable planning horizons and assigns different weighting factors to data depending on the level of certainty that can be attributed to it.

This thesis therefore aims to provide methods that will allow decisions to be made which will ensure that an FMS can be adapted to suit the dynamic and uncertain nature of demand. The concept is to continuously monitor change in demand and to respond by changing the layout to a more cost effective configuration whenever it is profitable to do so. Economic considerations are to be used to introduce damping into the system so that only significant or sustained changes result in a decision to change the layout. The use of arbitrary fixed time periods over which to measure demand are considered to be totally inappropriate in a dynamic situation, as is the notion of an 'optimal layout' which can only be optimal for a given set of demand data.

All existing techniques assume demand data to be accurate and constant over a time period selected for convenience rather than for economic reasons. A method is proposed to introduce an anticipated level of uncertainty into the data together with a means of processing this into useable form. In this method arbitrary fixed length time periods are not assumed, rather a time period is determined when facilities re-layout is required.

As mentioned earlier, in dynamic layout planning continuous monitoring of changes in material flow is needed. This in turn necessitates development of a static layout design whenever a change occurs, so that a dynamic layout policy decision can be made based on the static layouts at each time period. It was found that existing methods of generating solutions to the SLP problem were unacceptably slow for use in the proposed method of solving the DLP problem. This is primarily because the major criterion for such methods is to generate an optimal solution or as near as to the optimal solution as the method was capable of producing. However in circumstances where data is changing and its accuracy is uncertain, the justification for finding the very best solution based on unreliable or unrepresentative data is considered to be not valid. It was instead considered to be far more important to use a method that was fast enough to enable real-time decisions to be made in response to market changes provided that the accuracy of results produced were consistent with the accuracy of the data used.

A heuristic procedure for generating solutions to the SLP problem was therefore developed purely to generate initial solutions for DLP. This was subsequently found to produce solutions at least as good as many established methods but with far greater computational efficiency than any of them since it permitted large problems (30 facilities) to be solved manually even without the aid of a computer.

Although it was not an original objective of the research it is nevertheless considered to be an original and significant contribution to work in the area of layout planning and essential for the practical application of DLP.

The new static layout procedure named Initial Layout Generator (ILG) is presented in chapter four of this thesis following the survey of the existing SLP methods and Quadratic Assignment Problem (QAP) in chapters two and three. In chapter five capability and performance of the new static layout planning procedure (ILG) is examined vigorously using the data in the literature and other data originated by the author. Chapter six contains the proposed methodology for DLP of FMSs together with an example. In chapter seven the results obtained in chapters five and six are discussed and finally the concluding remarks are given in chapter eight.

CHAPTER TWO

STATIC LAYOUT PLANNING

2.1 Introduction

The problem of facilities layout has been the subject of analysis for many years [Apple(1973), Francis and White(1974)]. Different names have been applied to this problem in the literature. Muther(1974) prefers "Layout Planning", Koopman(1957) uses "Location of Economic Activities", Buffa et.al.(1964) uses "Facilities Allocation", while Hillier(1963) and others, Apple(1976), Lee and Moore(1967), Reed(1961) prefer "Plant Layout".

On the importance of the problem, Muther(1974), one of the early pioneers of a systematic solution approach to the problem states,"Plant layout is an industrial fundamental. It determines the efficiency, and in some instances the survival of an enterprise".

In one of the very early surveys, Muther(1957) conducted in 1947, it was indicated that of all the improved plans "improve plant layout" was second only, in importance, to "install new production machinery and equipment" as a cost-cutting technique.

At early stages of its development, the plant layout problem was generally treated qualitatively and traditional approaches relied heavily on intuition and engineering judgement [Francis and White(1974)]. In solving the facilities layout problem, iconic and analogue models were used as scalar representation of objects. In these approaches a number of alternative solutions were generated, basically dependant on the subjective criteria of the analyst, by manoeuvering templates and scale models on a floor plan and then these alternatives were compared on the basis of qualitative objectives. With the recent development of symbolic and mathematical models, much of the research work has been directed towards quantitative techniques for analysis of the layout problem.

For mathematical models, two general types have been developed, (i)descriptive models which are used to describe the behaviour of the system involved, and (ii)prescriptive (or normative) which are used to suggest a course of action to be taken in order to obtain the best solution procedure. Deciding which solution is the best among alternative results, depends on the selection of appropriate criteria.

As stated in the introduction chapter, minimization of production cost while maximizing manufacturing system efficiency has been the major criterion for selecting the best facilities layout solution and this is also in accordance with Majid(1980).

The direct link between material handling cost and production cost has been the prime reason for justification of employing the criterion of minimizing some function of distance travelled by parts. Popularity of minimization of material movement cost illustrated by a survey by Driscoll & Sangi(1985) indicates its importance and the degree of emphasis given to this criterion. However the approaches by which a single factor being selected as basis for selection of a solution has been criticised by Vollmann & Buffa (1966).

Vollmann & Buffa state that " the layout problem should be considered in the light of problem uniqueness, the concomitant uniqueness of specific problem criteria, and the need to reflect this uniqueness in problem approaches. The facilities layout problem is inherently multi-valued and is not properly handled by a single criterion model. Problems cannot be forced into models, models must be adapted to problems."

This criticism is valid in the sense that the facilities layout problem is a complex problem and all elements of the production system could have some degree of influence on the designated layout for a specific production situation.

However, the following points are considered to justify the selection of minimum material handling distance as the prime criteria:.

(i) In an FMS environment reduction of work in progress and storage as an objective requires minimization of distance travelled by parts in the system which in turn can lead to reduction in material movement/handling cost.

(ii) Reduction of total material handling distance in the system will reduce total traffic (distance * part volume) circulating in the system hence easing the traffic control problem.

(iii) In the FMS layout, criteria other than material handling distance may not remain valid during the layout planning horizon, whereas adjacency of facilities with high volume of flow between them is always desired as one of the most important, if not the only, criteria.

(iv) Popularity of minimization of material movement cost by means such as reduction of distance travelled by materials practiced in industry represents the importance and practicality of this criteria.

2.1.1 Distance Measurement

Distances travelled by parts are measured with respect to the centre of locations of machines/workcentres between which parts travel, and are either Rectilinear (also known as Manhattan,[Tam and Li (1991)]) or Euclidian distance, shown in Fig.2.1.

$$\text{Rec.Distance} \qquad |X_i - X_j| + |Y_i - Y_j|$$

$$\text{Euc.Distance} \qquad [(X_i - X_j)^2 + (Y_i - Y_j)^2]^{1/2}$$

where (X_i, Y_i) and (X_j, Y_j) are the coordinates of centre points of locations i and j.

Euclidean distance is generally used as a measure of distance between centroids of facilities and Rectilinear distance travelled by parts in the system along a rectangular route around the facilities.

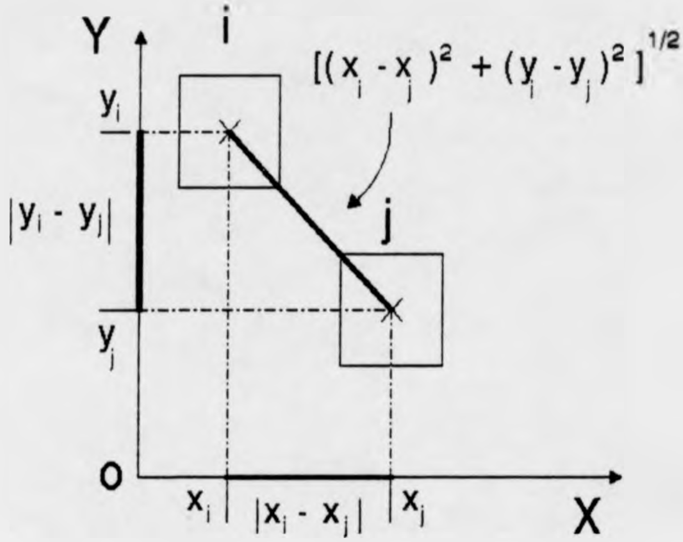

Fig.2.1 Schematic diagram representing Euclidean and Rectilinear distance measurement.

Rectilinear distance corresponds more closely to the usual mode of industrial transport since it simulates travel along a set of orthogonal aisles. Hence the distance measurement in the proposed ILG method (in chapter four) is considered to be rectilinear. A point worth mentioning here is that if travel cost is not proportional to travel distance, then the parameter representing the distance in the layout objective function (see equations 4.1 and 4.4) can be adjusted so that it becomes an appropriate measure of material movement cost.

2.1.2 Model Validity

Based on the selected criteria, models are developed to represent and aid the analysis of plant layout. There are two methods of validating these models:.

a) Testing to establish whether they are capable of leading to reasonable predictions of a known system's performance and producing subsequent improvements in the system.

b) Comparison of the solutions obtained from the model with answers obtained for the same problem from different models.

The latter method is used throughout this thesis to promote consistency and to permit direct comparison with other techniques.

2.1.3 Steps of Layout Design Process

After criterion and model selection, the layout design process is followed. A general approach for this is suggested by Kirck(1965) which specifies the following steps:-

I. Formulation of the problem

II. Analysis of problem, which consists of problem characteristics and restrictions.

III. Comparison of alternative solutions.

IV. Selection of the final solution, based on the following considerations:-

* Material movement cost.
* Savings and profitability.
* Flexibility of layout.
* Space utilization.
* Equipment utilization.
* Allowance for future expansion.

V. Specification of the solution, which is the final stage in the design process and involves detailed representation of design specifications.

This procedure would seem to be incomplete in practice. Observation of the practical behaviour of the system is required after implementation of the selected layout in order to assess the benefits and shortcomings of this final solution.

Francis and White(1974) suggest three complementary phases of (i)implementation (ii)follow-up and (iii)reactivation, to complete the above procedure as a design cycle, shown in Fig.2.2.

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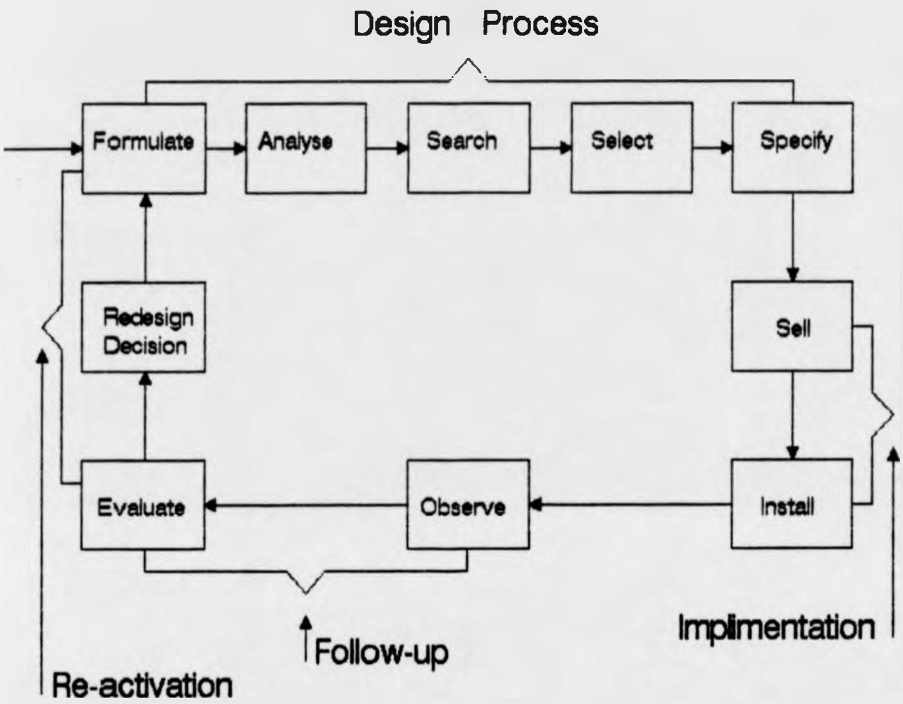

Fig.2.2 Design cycle proposed by Francis and White

However, follow up and reactivation stages may not be beneficial after facilities have been installed according to the selected layout. Any redesign of this layout, suggested after evaluation and findings of dissatisfactory results, could be costly financially and time wise. Therefore great attention must be paid to search and select phases in order to ensure the right selection of layout and eliminate the redesign requirement after installation.

2.2 Static Layout Planning

Static layout planning in a manufacturing environment can be defined as allocation of production facilities to locations within a fixed time period such that optimality is achieved based on some pre-selected criteria and using a static set of material flow data. The approaches to the problem of SLP, in the manufacturing context can be divided into two categories of:- (i)traditional, and (ii)analytical and computerised approaches. Both techniques are applicable to flexible manufacturing system (FMS) although there is very little reported work in either category specially concentrating on FMS.

2.2.1 Traditional Approaches to SLP

All major approaches proposed so far, with small procedural variations, follow a common sequence of operations.

J.M.Moore (1969) defines the SLP problem as an optimal arrangement of industrial facilities and all other supporting services with the consideration of product design changes, introduction of new product, changes in volume of demand and achievement of total cost reduction. Although Moore does not specifically explain what is an optimum arrangement and how it is obtained, he states :"it is practically impossible to propose a generalized schedule for the evolution of a plant layout because of the wide variation of problems for various types of industries. Not only do different industries have different problems but different companies within the same industry face different problems". But he sets the objectives as the following:-

* Over-all system integration.
* Minimum distance moved.
* Flow of the product.
* Space utilization.
* Employee satisfaction & safety.
* Flexibility.

Moore then suggests that planning should start first with an overall layout and then consideration of the detailed layout plan in support of the overall plan. The procedure proposed by Moore for the design and completion of a layout plan is in four phases shown in Fig.2.3.

Phase(I) is the initial draft of overall layout to give a general idea of where the facilities are to be located on the floor and why?

Phase(II)is a preparation step for detailed layout in which block diagrams of facilities are drawn with consideration of material flow and other constraints.

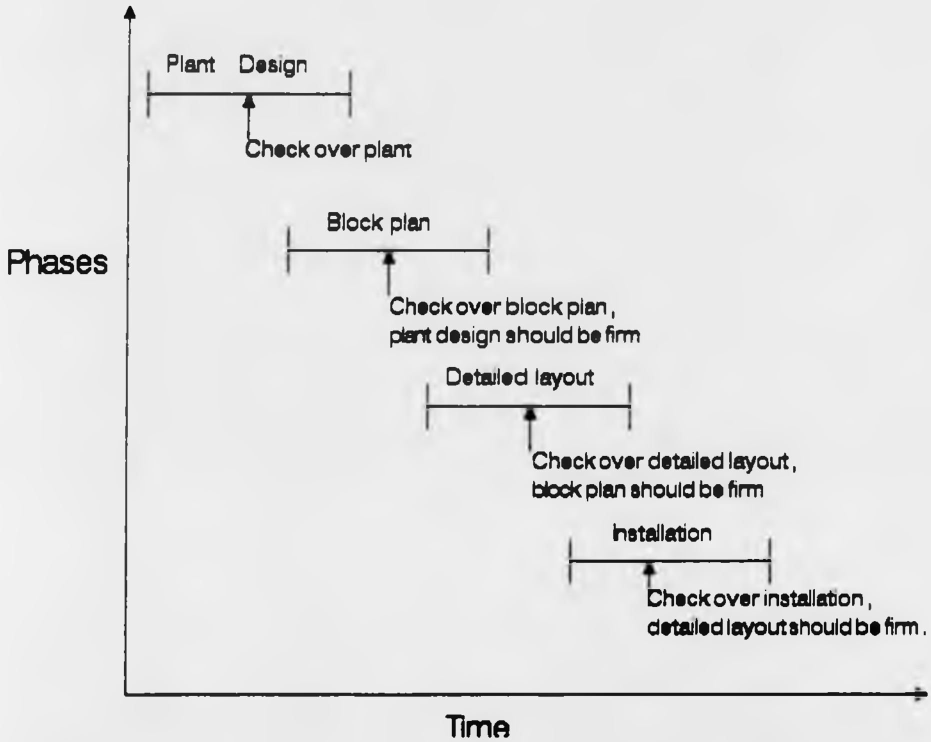

Fig.2.3 Various phases of layout development proposed by Moore.

Phase(III) the layout is detailed and other supporting equipment are included.

Phase (IV) is the installation phase of the selected layout.

In this procedure, detailed data regarding materials and processes such as, product specifications, product volume, component parts and machinery must be collected before the block plan phase and used at the detailed layout phase. Gathered data related to the product flow, are used to form the flow-process chart and flow diagram to prepare the flow pattern and determination of space requirements is then followed.

For the construction of the detailed layout one of the following three basic means is proposed by Moore (1969):-

1- Drafting
2- Templates
3- 3-D Models

The first option above could be dismissed due to difficulty in visualization and the expense of changing a layout alternative after the drafting is completed.

Installation of the layout is followed by selection of a layout from amongst the alternatives which satisfies the objectives initially set.

For evaluation purposes two general techniques are proposed by Moore:-

1- systematic evaluation techniques such as:

(I)pilot plan. This is a very expensive way of evaluating any specific layout, especially in FMS cases, hence cannot be recommended.

(II)cost comparison. Must include total factory cost plus other required service investments. This may be practically possible but due to the presence of uncertain factors in a variable market demand situation the results must be assessed cautiously.

(III)factor analysis method. In this method factors such as space utilization, equipment utilization, or economic factors such as capital required, savings, return on investment and profitability are ranked in terms of their importance and alternative layouts are evaluated accordingly. This can be a useful evaluation tool if the importance of the factors remain unaltered at different time periods in a dynamic situation.

2- Optimizing method. Moore suggests that the performance of a layout can be measured by means of a mathematical model against the production capacity of the system. Using linear programming method the objective could be:

$$\text{Max. } \sum_{i=1}^{m} c_i x_i \qquad 2.1$$

subject to:

$$\sum_{i=1}^{m} a_{ij} x_i = b_j \qquad j=1,2,.....,n \qquad 2.2$$

$$x_i \geq 0$$

where c_i is the profit per unit of product x_i, a_{ij} the quantity of product x_i and b_j the max. production capacity of x_i. In this method the first constraint clearly shows that the model is not dictated by market demand but rather it assumes that demand for various components exist and the objective is how many of which components to produce so as to maximize the profit.

Therefore this cannot cope with demand variation if it is not restricted by production capacity.

Another traditional method, developed by Muther(1974), is the systematic layout planning approach to the problem.

Muther argues that every layout problem rests on two basic elements of (i) product and (ii) quantity, and suggests three other elements of routing, process and supporting services as key and essential requirements for solving the problem.

Systematic layout planning starts with data gathering regarding product (material), quantity (volume), routing (operational sequence), supporting services and timing and then proceeds with analysis of flow of material and activity relationships between facilities to obtain a relationship diagram. In this procedure, the importance of flow of materials is emphasized as being the heart of the layout philosophy. Flow of materials is analysed by means of where c_i is the profit per unit of product x_i, a_{ij} the quantity of product x_i and b_j the max. production capacity of x_i. In this method the first constraint clearly shows that the model is not dictated by market demand but rather it assumes that demand for various components exist and the objective is how many of which components to produce so as to maximize the profit.

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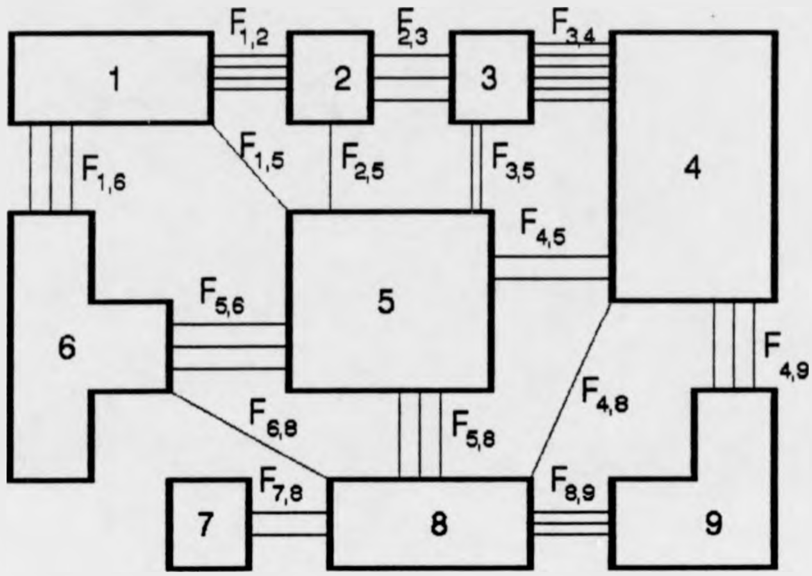
From \ To (Facility)	1	2	3		n-1	n
1		$f_{1,2}$	$f_{1,3}$		$f_{1,n-1}$	$f_{1,n}$
2	$f_{2,1}$		$f_{2,3}$		$f_{2,n-1}$	$f_{2,n}$
3	$f_{3,1}$	$f_{3,2}$			$f_{3,n-1}$	$f_{3,n}$
n-1	$f_{n-1,1}$	$f_{n-1,2}$	$f_{n-1,3}$			$f_{n-1,n}$
n	$f_{n,1}$	$f_{n,2}$	$f_{n,3}$		$f_{n,n-1}$	

Fig.2.4 From-To chart representing material flow between facilities.

The charted information of material flow and relationship between facilities is converted to a relationship diagram. Once the geographic arrangement of the various activities involved is worked out, the space requirements is then analysed and space availability established. Geographic arrangement of activities is directly dependent on the strength of relationship between them. Initially relative locations of activities with the strongest relationship are determined, forming clusters of connected activities. These clusters are then linked together according to the relationship of activities in different clusters. The space or area available for each activity is then fitted to the activity relationship diagram to form the space relationship diagram which is actually a crude layout of the facilities as shown in Fig.2.5.

Having developed a rough layout plan, modifications regarding different considerations such as building limitations can be made in order to construct a detailed layout. The main categories suggested by Muther to be taken into account when modifying a layout are:

- Handling methods.
- Storage facilities
- Building features



$$F_{i,j} = f_{i,j} + f_{j,i}$$

Fig.2.5 Space relationship diagram

In the systematic layout planning procedure it is emphasized that the material handling methods are the dominant consideration at the modification stage. The procedure is continued with analysis of practical limitations which are the constraints imposed on the overall layout planning. These restrictions result in a reduction of the number of alternative layouts being developed. To decide which of the alternative plans to select, Muther recommends the balancing of advantages against dis-advantages of different layouts. This is contrary to the idea of construction of a pilot plan suggested by Moore but Muther endorses the other two methods of factor analysis and cost comparison as possible approaches.

The systematic layout planning technique only utilizes graphic and schematic analysis for material flow but does represent a well-organised enumeration of pertinent qualitative factors. These factors are incorporated into a methodology for the determination of which facilities most require adjacent placement as well as for the evaluation of several proposed layout solutions.

Graphical visualization, schematic analysis and template shuffling which are the core methodologies in traditional approaches to the static layout planning problem may, or may not result in a good layout. But there are shortcomings in these methods in the sense that:

(i) They have placed too much emphasis on the intuition Of the layout designer. An individual's intuition maybe wrong and it cannot be guaranteed whether or not a better solution exists.

(ii) It is very difficult for the efficiency of the method to be tested when very complex problems are encountered. Planning a layout for a manufacturing system with a large number of facilities is an example of such cases.

(iii) Consideration of practical limitations has been placed at final stages of the procedure. This would have the implication of some impractical layout alternatives not being detected before modifications have been considered.

To overcome disadvantages (i) and (ii) above of the traditional approaches Francis and White (1974) have suggested the use of analytical models to be included in layout planning as an activity that parallels the development of the space-relationship diagram.(See Fig.2.6.)

The use of analytical models can of course eliminate, to some extent, the problems (i) and (ii) above, but there still remains the third limitation of the procedure. Therefore it is proposed by the author to consider practical limitations after the data gathering phase, (seeFig.2.7,) in order to prevent evaluation of layouts which cannot be implemented.

The use of analytical techniques have also been suggested by Reed(1967) and Apple (1963).

Reed, initially presents a layout planning approach similar to systematic layout planning with some additional steps to the procedure and suggests a modification to Wimmert's method (provided in appendix(A)), to be used as a

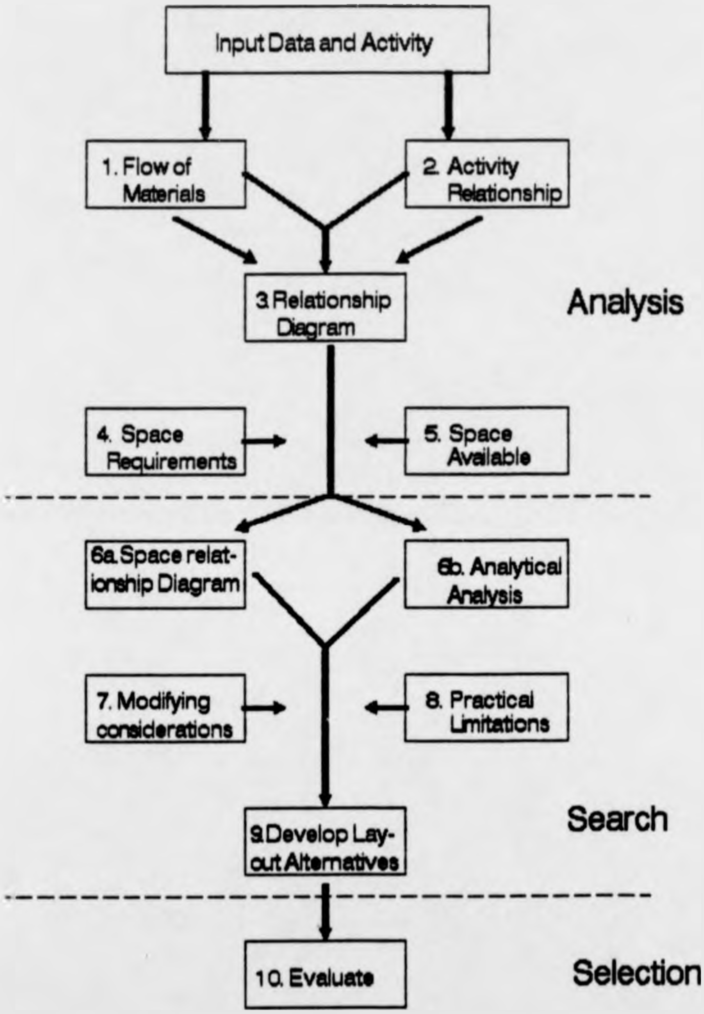


Fig.2.6 Modified Systematic Layout Planning proposed by Francis and White.

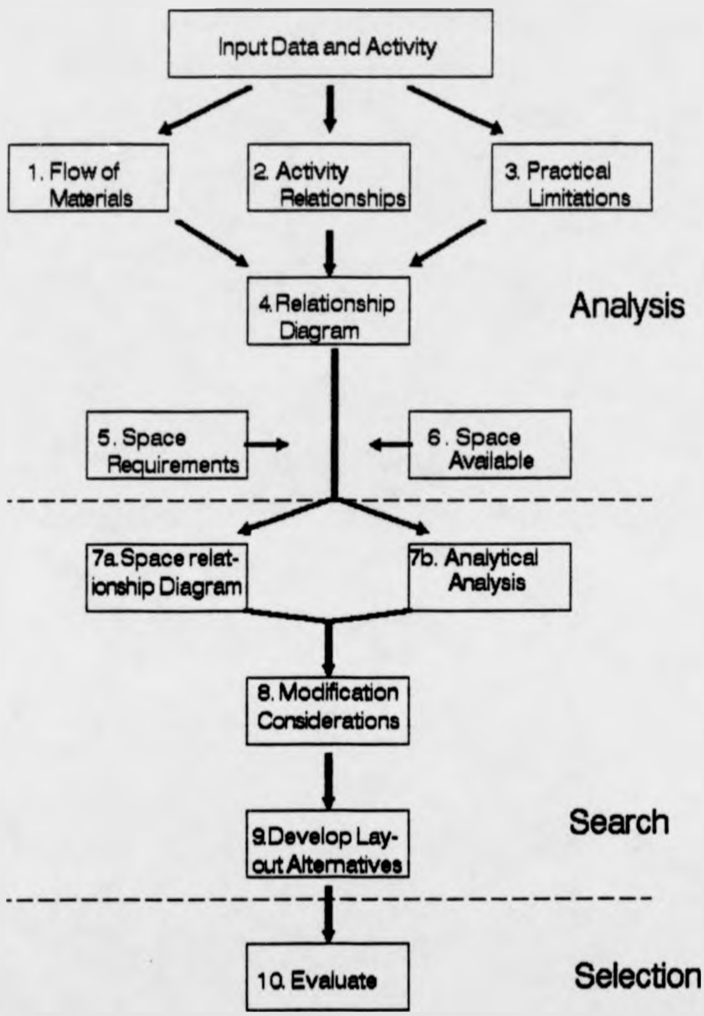


Fig.2.7 Proposed systematic layout planning procedure.

quantitative technique for facilities arrangement. However, in the modified Wimmert method the assumption is made that areas occupied by facilities have a common denominator of unit area. This assumption maybe rather unrealistic in practice and may not be applicable to many manufacturing layout problems, where facilities can vary considerably in size.

Reed proposes a 10-step procedure for facilities layout. The difference with the previous methods is the addition of the establishment of minimum aisle widths at the design stage of the layout and inclusion of provision for future expansion of the layout.

Apple provides a 20-step sequencial procedure for the treatment of the static layout problem. This procedure is virtually a detailed version of the method proposed by Muther.

The condensed form of the sequences is as follows. The procedure starts with data gathering and analysis followed by design of the production process. Then planning of material flow pattern, calculation and selection of required equipment including material handling equipment. The next stage is design of activity relationships, determination and planning of services and space requirements. The procedure is continued by construction of a master (detailed) layout for evaluation and approval. Finally installation and follow-up on implementation of the selected layout completes the procedure.

Apple recommends application of quantitative techniques such as mathematical modelling, for analysis of material flow in production system.

Additional considerations in the above two procedures plus application of quantitative techniques for analysis of material flow could be useful for design of an FMS layout in which free-ranging AGVs serve as the material handling system.

Quantitative techniques can be especially useful to enable a designer to study the availability of different AGV routes for delivering required material to different manufacturing facilities in the plant.

2.2.2 Analytical and Computerised Techniques for SLP

Traditional approaches to solve the facilities layout problem become less efficient and more complicated as objectives become more complex or if a large number of facilities are involved.

Analytical models have in fact been developed in conjunction with development of computerised algorithms for mathematical models. These models assist design of the more complex layout processes and generate alternative layouts quickly and compare them on an objective basis.

Analytical models are basically quantitative techniques which aim to optimize some objective function such as minimization of distance travelled by materials, or optimum location of facilities.

Computerised layout algorithms can be classified according to the way the final layout is generated. There are two ways of generating the final layout. These are by(i) construction methods. Construction algorithms consist of the successive selection and placement of activities(facilities) until a layout design is achieved. (ii)Improvement methods. In this case a complete existing (initial) layout is required upon which the algorithm makes improvements of the layout by interchanging the locations of facilities.

Computerised layout algorithms like analytical models are based on some mathematical models which aim to optimise some objective function such as minimization of distance travelled by parts between facilities in a production system.

But in a dynamic situation where a layout created in one time period maybe altered in the next period, then the generation of an optimal solution in any single time period is not so critical. However the requirement for the development of an algorithm which is able to cope with large problems in a relatively short time, does not diminish.

Viewing the FMS layout problem as a geometric arrangement of machines that minimizes the production cost, then it can be formulated as a quadratic assignment problem.

In chapter four of this thesis, a new heuristic algorithm is proposed for solution of the quadratic assignment problem which constructs a near optimal initial layout that can be improved, if required using a computerised layout planning programme, such as CRAFT.

2.3 Dynamic Layout Planning

2.3.1 Dynamic Layout Planning Problem

Over time, due to variations in product and in the design of products the routing of parts throughout the system will change. These changes are the main reasons for utilizing FMS rather than a set of dedicated facilities which may have higher rate of production. Although the FMS may be able to make a variety of products, it may not do so efficiently due to the need for excessive material handling. If the material flow requirements vary considerably and with high frequency then it is unlikely that changes to layout could ever be made fast enough to react to such changes. In this case it is necessary to utilise flexibility within the material handling system to compensate as far as possible for inefficiencies in the facilities layout. However for longer term variation in material flow it is possible to consider dynamically adapting the layout to best suit changes in flow that occur from time to time.

Moore(1974) has stated that the rearrangement of existing facilities was a more frequent problem in industry than either new plant layout design or complete plant relocation problem.

Although no statistics are reported in the literature regarding the frequency of layout changes in currently implemented FMSs, Moore's statement may be equally true in the FMS context.

In the static FMS layout design the objective is to connect the machines in the system with a material handling system such as AGVs, so that the total traffic in the system is kept as low as possible. This implies that the total material flow is minimized. Hence the total travelling time would be as short as possible. This will tend to reduce the work-in-progress as well as throughput times, with an increase in return on investment. Lowering traffic intensity in the system can be established by reducing the distance between machines with a high volume of material flow between them. Another implication of distance reduction is lower material movement cost.

In the dynamic situation, the problem most commonly faced is that of determining a set of alternative machines/facilities layouts over a relatively longer planning period. Selection of alternative layouts at each time period should be such that the cumulative material movement cost and all costs associated with relocating the facilities are kept at minimum while system efficiency is maintained and demand satisfied.

A good solution procedure for this problem should therefore meet the following objectives:.

(I) Be capable of producing a number of alternative static layouts for each period within a longer term planning horizon.

(II) Be capable of evaluating facility layout alternatives over time and hence indicate when it is desirable to change the layout in response to changes.

(III) Allow for interdependence of costs among the facility locations during a single time period and across multiple periods. i.e. the location of facilities cannot be selected independently of one another or of the locations chosen in the other planning periods.

(IV) Be computationally feasible and produce cost effective results.

2.3.2 Existing Solution Procedures

Due to the flexibility in the perception of FMS elements together with the feasibility concern of producing a layout solution within a reasonable length of time, at low cost, there has been little progress in development of DLP procedures in the context of FMS. Nevertheless recently there has been progress in this field by researchers such as Rosenblatt(1986) and Afentakis(1990).

Rosenblatt proposes a recursive method. First a deterministic environment is assumed, where the number of orders and the quantities, arrival and due dates for different products are known for a given finite planning horizon. Second this finite horizon is divided into fixed time periods with equal duration in terms of months, quarters, years, etc. A third assumption is that the initial cost of assigning any department i to any location j is independent of the location. Also shifting costs which are the cost of shifting physical facilities resulting from any layout rearrangement are veiwed as a fixed cost and represented by a cost vector.

The DLP problem is then defined as what should be the layout in each period, and to what extent, if any, should changes in the layout be made.

The objective function in this method is minimization of material flow costs and those involved with rearrangement of the layouts.

Rosenblatt's procedure starts by finding the best R_t solutions for the SLP problem in each period. The best R_t solutions are obtained by using Sweeney and Tatham's theorem(1976), (this theorem and its proof is provided in appendix(B)) and inclusion of the following constraint to the formulation of SLP;

$$\sum_{(i,j) \in A_k} X_{ij} - \sum_{(i,j) \in B_k} X_{ij} < n - 2 \qquad 2.3$$

$$A_k = \{ (i,j) : x_{ij} = 1\} \quad , \quad B_k = \{ (i,j) : x_{ij} = 0\}$$

This constraint eliminates consideration of the best layout obtained in the previous iteration. Depending on the number of desired R_t best solutions the above constraint can be used accordingly.

Rosenblatt then suggests the establishment of the following recursive relationship:

$$L^* = \min \{ L^*_{t-1,k} + C_{km} \} + Z^*_{tm} \qquad t=1,\ldots\ldots,n \qquad 2.4$$

and $L^*_{01} = 0$, assuming there is a single initial layout.

Where:

Z_{tk} = Material handling cost for layout A_k in period t,

C_{km} = Rearrangement (shifting) cost from layout A_k to layout A_m ,

L^* = Minimum total cost for all periods up to t where layout A_k is being used at period t.

Two heuristic approaches are proposed. The first heuristic method is similar to Ballou's(1968) analysis of the Dynamic Warehouse Location Problem. Ballou in turn uses Bellman's Principle of Optimality(1962) which states "in a sequence of decisions, whatever the initial decision, the remaining decisions must constitute an optimal policy for the state resulting from the initial decision." By applying this theory the procedure begins with obtaining optimal layouts for each period in isolation.

Starting from the layout in the final period a decision is made whether to keep this layout or to move to the layout found in the previous period .

More recently Afentakis et.al.(1990) have proposed another dynamic layout strategy specifically for FMSs. Although these authors do not provide a formulated approach to the DLP problem they emphasize the requirement for continuous monitoring, evaluation and intervention of FMS layout designer, and propose strategies by which a time when re-layout is beneficial can be determined.

In order to examine the FMS layout problem in the dynamic context the above authors have utilized a simulation approach. They have assumed that general information about parts likely to be introduced to the FMS in the future are known but specific part attributes such as routings and volumes are not.

In their investigations, the authors have implemented two distinct approaches for determining the point at which a re-layout should be performed.

The first strategy is based on a periodic approach which suggests a re-layout should take place after every n periods (where n = 1,2,4,8,20,40) in, for example, a 40 period, planning horizon.

The second approach relates to three different aspects of the part mix. An arbitrary percentage threshold is considered. Whenever any one of the following three measures pass the threshold value a re-layout is performed. The measures are :.

(a) the percentage change in the part mix. This change is measured by the number of new parts added to the system divided by the total number of parts in the system.

(b) the percentage change in routings. This change is calculated by dividing the total number of routes introduced to the system resulting from the addition of new parts by the total number of routes in the system.

(c) the percentage change in the volume of part movements. This change is obtained by dividing the sum of the absolute values of total part movements between machines by the total number of parts moved across machines.

Another alternative simulation approach to the DLP problem is proposed by Driscoll and Sawyer(1985), in which a changeover simulation model developed. Three types of relocation sequencing can be investigated (a)freeze layout (no change) over planning period, (b) instant changeover and (c) phases changeover from old to new layout. In this simulation model, which is part of an integrated suite of programmes (undertaking data validation, static layout design and changeover simulation), the aim is to provide the capability of both designing layouts and evaluating them on a financial basis. The discounted cash flow concept is also introduced as a fact in the objective function of the analysis.

The three methods described here originated by Rosenblatt, Afentakis et.al. and Driscoll et.al. all provide some means of decision making for dynamically adapting the layout of facilities to suit changing demand. However none of them are considered to adequately address the problem of uncertain future flow data and provision of dynamic layout solution in reasonably short time for systems containing large number of facilities.

The existing methods are analysed in detail in chapter six where the author proposes an alternative approach.

CHAPTER THREE

QUADRATIC ASSIGNMENT PROBLEM

3.1 Introduction

The FMS plant layout problem was defined in the previous chapter as the most effective arrangement of physical facilities to allow the greatest efficiency in the combination of resources to produce a product.

To evaluate alternative layouts, minimization of the flow of materials has been the main criterion used. A satisfactory measure of this criterion is the cost of the materials handling [Malakooti et.al.(1984)] which requires the analyst to input into the model the handling cost per unit product moved per unit distance.

The Quadratic Assignment Problem (QAP) arises when attempting to model the facilities layout problem where facilities are to be assigned to locations and when there are interactions between the facilities that depend upon their location.[Hillier and Connors(1966), Foulds(1983), Wilhelm and Ward(1987), Christofides and Benavent(1989)]

3.2 Formulation of Facilities Layout Planning (FLP) as QAP

Among the diverse applications of the QAP techniques

[Bukard(1985)], the one related to the present research is the formulation of facilities layout planning as a QAP.

The QAP was first suggested by Koopman and Beckmann(1957), in the context of analysis of the location of economic activities. This formulation of the problem is described by Lawler(1963) as in the following form:.

"It is required to assign n plants to n locations such that the total interplant transportation cost is minimized. Two n*n matrices of, $D = d_{jq}$ representing the cost of transporting one unit of commodity from location j to location q, and $T = t_{ip}$, representing the number of units of commodity to be transported from plant i to plant p, are given."

Assignment of plants to locations are represented by an n*n permutation matrix $X = \| x_{ij} \|$ where:

$$x_{ij} = 1 \text{ if plant } i \text{ is assigned to location } j$$

$$= 0 \text{ otherwise.}$$

Then it is desired to minimize the dot product of the above D and T matrices with respect to a symmetric permutation of the rows and columns of one of the matrices. That is to:

$$\text{minimize} \quad T.(XDX^t) \qquad 3.1$$

Since this proposed method by Koopmans and Beckmann, there have been two major ways of formulating FLP as the QAP. These are:.

1-Assignment of n facilities to n locations with no allocation cost.

2-Incorporation of allocation cost to the formulation.

3.2.1 Assignment of n Facilities to n Locations with no Allocation Cost

The assignment of facilities to locations is a combinatorial problem and has been of interest to many investigators such as Conway and Maxwell(1961), Nugent et.al.(1968) and many recent researchers in this field. Considering the problem of determining the relative location of facilities in a production shop floor, it can be assumed that a finite number of locations are available to be occupied by the same or less number of facilities. This problem can then be formulated [Lawler(1963), Armour and Buffa (1963), and Parker(1976)] as follows:.

$$\text{Minimize} \quad E = 1/2 \sum_{i=1}^{n} \sum_{k=1}^{n} \sum_{j=1}^{n} \sum_{l=1}^{n} C_{ikjl} \, X_{ik} \, X_{jh} \qquad 3.2$$

$$\text{subject to:} \quad \sum_{i=1}^{n} x_{ik} = 1 \qquad k = 1,2,\ldots,n \qquad 3.3$$

and

$$\sum_{k=1}^{n} x_{ik} = 1 \qquad i = 1,2,\ldots,n \qquad 3.4$$

$$x_{ik} \text{ and } x_{jl} \in \{0,1\} \qquad i,j,k,l = 1,2,\ldots,n \qquad 3.5$$

where,

C_{ikjl} = the cost of product flow when facility i is located at location k and facility j at location l, for each period in the future.

Both x_{ik} and x_{jl} are decision variables and are equal to 1, when facility i is located at location k and facility j is at l, in which case the cost term c_{ikjl} is included in the total cost calculation. Therefore the cost term could be interpreted as:.

$$f_{ij} * d_{kl} \qquad 3.6$$

where:

f_{ij} = the number of moves per time period of the work flow from facility i to facility j,

and

d_{kl} = the cost per movement over the distance from location k to location l.

3.2.2 Incorporation of Allocation Cost to the Formulation

Where there is the requirement for consideration of the cost of assigning a facility to a location then the problem can be formulated as:

$$\text{Min.} \sum_{i,k=1}^{n} a_{ik} X_{ik} + 1/2 \sum_{i,j,k,l=1}^{n} C_{ikjl}\, X_{ij}\, X_{kl} \qquad 3.7$$

subject to constraints 3.3-3.5 [Gilmore(1962), Ritzman (1972), Ligget(1981), Picone(1984)].

The benefit of this formulation is that it can be modified and utilized in the context of dynamic layout planning, i.e. the first term in the above objective function can show the effects of the 'shifting cost'from one time period to another. i.e. the cost of shifting facilities between locations so that a new layout can be created for each period.

3.3 Applicability of the QAP in Layout Planning Aspect of FMS

There is little evidence in the literature that a great amount of research work has been devoted to the fact that QAP techniques could be applied to FMS plant layout. This may again be due to the flexibility inherent in the elements of FMS which could be considered to reduce the benefits of the QAP in this context.

Only recently one critical article about the applicability of QAP technique to FMS has appeared in the literature by Heragu and Kusiak of Monitoba University, Canada(1988).

The above authors in their paper state that "Although most facility layout problems can be formulated as QAP, the MLP (machine layout problem in FMS) cannot .... The machine layout problem cannot be formulated as a QAP because the machine sizes are generally not equal, and, hence the distance between the sites is not fixed." The authors to support their argument, also mention that " the flow data in the MLP is usually not accurate because the flow between machines depends on the production schedule which cannot be predicted accurately, due to changing market demand, unexpected repairs etc."

As an alternative to the QAP the authors then propose two different heuristic algorithms for FMS machine layout problem. A brief outline of these algorithms are given here in order to be able to comment on them.

The first algorithm is based on the formation of an "adjusted matrix " which is :

$$[\tilde{f}_{ij}] = [f_{ij} * t_{ij}] \qquad 3.8$$

where

$$f_{ij} = \sum_{k=1}^{n_{ij}} [v^k_{ij} / u^k]$$

=frequency of trips between machines i and j

and

t_{ij} = time matrix, indicating the time required to move parts from machine i to machine j when they adjacent to each other.

v^k_{ij} is the volume of part type k to be carried from machine i to j.

n_{ij} is the number of different part types.

u^k is the number of parts type k to be carried in a single trip.

The second algorithm is a two phased procedure. Phase

1 is based on formation of a maximum spanning tree. The links of this spanning tree are determined from the adjusted flow matrix. In phase 2, machines are assigned to locations with the assumptions that (a) there is one site for each machine and (b) all the sites are of equal area. In this algorithm n sets of assignments are generated and hence n different layouts are constructed. The solution cost is calculated from:

$$\sum_{i=1}^{n} \sum_{j=i+1}^{n} f_{ij} \, t'_{ij} \qquad 3.9$$

where t'_{ij} = time required to carry parts between machines i and j.

Then the layout with corresponding minimum cost is selected.

The validity of Heragu and Kusiak's criticisms of the applicability of QAP technique to FMS layout design are in the author's view questionable because:

(i) In QAP methodology, equality of the size of facilities is not required, neither is the fixing of sites where facilities are to be located.

(ii) Consideration of location distances is not absolutely necessary in developing a heuristic algorithm to solve the QAP.

(iii) Fluctuation of flow data in FMS and its influence on the machines layout can be investigated in the dynamic re-layout planning context. Flow data charts and closeness desirability charts play an essential part in the development of any layout problem (both in traditional and flexible manufacturing) and their accuracy only suffers if they are assumed to be constant over regular, long time periods.

(iv) The algorithms 1 and 2 suggested by Heragu and Kusiak, do not take into account their own criticisms, since they themselves employ the QAP technique. It is stated by the authors "Algorithm 1 may also be thought of as a heuristic algorithm for the "open" travelling salesman problem."

The open travelling salesman problem is a special case of the general travelling salesman and this in turn is a special case of QAP according to Lawler(1963) and Bukard(1985). Therefore the conclusion is that the open travelling salesman problem is a special case of the QAP. Hence the FMS layout planning problem may well be formulated as a QAP.

3.4 Existing Solution Procedures for the QAP

Since formulation of FLP as the QAP,there have been several different procedures developed for this problem [Bukard (1985), Wilhelm and Ward(1987)].

Depending on the complexity of the problem, such as the number of facilities involved, the procedures can be categorised as either (i) exact solution algorithms, or (ii) heuristic (producing sub-optimal solutions) algorithms.

Before investigating the above algorithms, it is appropriate here to give a brief explanation of the complexity of the QAP and then proceed with the procedures.

3.4.1 Complexity of the QAP

Sahni and Gonzalez(1976), in their analysis have shown that the QAP is a member of the class NP-complete (Non-deterministic Polynomial Complete) problems. This has been supported by another claim by Cheristofides(1989), that since the travelling salesman problem, which is a special case of QAP, belongs to NP-Complete [Parker and Rardin(1982)] so does the QAP. Also according to Parker and Rardin NP-Complete problems are not members of P-Complete problems, which are polynomially deterministic.

The implication of the QAP being classed as NP-Complete is that the computation run time required to optimally solve the problem cannot be bounded from above by a polynomial that is a function of the problem size. But rather the run time is bounded from above by a function that increases exponentially as a function of problem size, so that it may not be feasible to obtain an optimal solution for large problems within an acceptable time.

Parker and Rardin have stated that "there is no solution technique which has a polynomially bounded solution time for problems of this class". Burkard also claims that QAPs are NP-hard and only implicit enumeration methods are known for solving them optimally. In particular Flouds (1983), has suggested that QAP solution times are likely to be an exponential function of the problem size n.

3.4.2 Optimizing Methods

Despite the complexity of the QAP, numerous researchers have attempted to develop exact solution algorithms.

Koopmans and beckmann, first formulated the assignment of facilities to locations as the QAP in 1957. They applied optimisation procedures to solve the QAP but encountered formidable difficulties. Continuous research has led to the development of several exact algorithms. Apart from implicit enumeration methods most of the approaches in exact procedures are based on the branch and bound strategy. [Bazaraa and Elshafei(1979)]. These techniques can be classified according to the methods they use to assign facilities to locations. The assignment methods are:

(i)single assignment algorithms, such as those developed by Graves and Whinston(1970), Gilmore(1962), and Lawler (1963). The basic concept in single assignment algorithm is that it proceeds by assigning one unassigned facility to a vacant location. Supposing N is the number of facilities then,

$$N = N1 + N2 \qquad 3.10$$

where N1 = {1,2,.......,N1} are the assigned facilities to fixed locations and, N2 = {1,2,.....,N}/N1 contains the free unassigned facilities.

Therefore the objective function for an arbitrary permutation ß becomes:

$$Z(\beta) = \sum_{i=1}^{n} \sum_{k=1}^{n} a_{ik}\, b_{\beta(i)\beta(k)} \qquad 3.11$$

$$= \sum_{i \in N1} \sum_{k \in N1} a_{ik} \; b_{s(i)s(k)}$$

$$+ \sum_{i \in N1} \sum_{k \in N2} (a_{ik} \; b_{s(i)s(k)} + a_{ik} \; b_{s(k)s(i)})$$

$$+ \sum_{i \in N2} \sum_{k \in N2} a_{ik} \; b_{s(i)s(k)}$$

where the first term in the objective function is an already known fixed constant representing the cost of assigned facilities. For the second term a lower bound can be obtained in order to evaluate the alternative assignments of unassigned facilities based on this lower bound. According to Bukard(1985) this lower bound can be established from:

$$C_{kl} = \sum_{i \in N1} (a_{ik} \; b_{s(i),l} + a_{ki} \; b_{l,s(i)}) \qquad 3.12$$

$$k, l \in N2$$

Another lower bound can be obtained for the third term by arranging the entries of the a_{ik} matrix above the diagonal in non-increasing order and the entries of $b_{s(i),s(k)}$ matrix above the diagonal in non-decreasing order. The value obtained by scalar product of these two vectors is a lower bound.

(ii) Pair-assignment and pair-exclusion algorithms.

Pair-assignment algorithms such as developed by Gavett and Plyter(1966), and Nugent and et.al.(1968), are also based on branch and bound techniques. In these algorithms a pair of facilities (i,k) are assigned to two locations(j,$\bar{l}$) at a time and corresponding increase of the objective function or a lower bound is computed. The assignments that yield less increase are selected.

In pair-exclusion methods, such as described by Pierce and Crowston(1971), assignments which should not be in the final solution are excluded in pairs.

Computational studies have revealed that pair-assignment and pair-exclusion algorithms are not very efficient and single-assignment procedures are superior to them in obtaining optimum solutions.[Bukard(1985)]. However as a result of several experimental comparisons of exact procedures by Francis and Mc.Ginnis(1983), Picone and Wilbert(1984) and Wilhelm and Ward(1987), it has been concluded that no computationally feasible optimal layout producing procedure exists at present to deal with problems involving more than 20 facilities.

Due to the general infeasility of optimal-producing procedures for large sized problems, much research effort has been devoted to devising heuristic solution procedures. The heuristic procedures aim to produce solutions of acceptable quality in reasonable computation times.

3.4.3 Heuristic Approaches to the QAP

Over the last 30 years different heuristic approaches to the QAP and hence FLP have been under development. [Foulds(1983)] These approaches are either of the construction or the improvement method and both are reported in the literature [Wilhelm et.al.(1985), and Jacobs(1987)].

Construction procedures attempt to build a solution from the null solution by making successive assignments of facilities to sites, such as MAT developed by Edward et.al.(1970) and the Hanan and Kutzberg(1972) algorithm.

Improvement methods start with a feasible solution and try to improve it by interchanges of single, pair or triple assignments. Examples of improvement techniques are CRAFT, [Armour and Buffa(1963)], FRAT, [Khalil(1973)] and Biased Sampling Technique (BST) [Nugent et.al.(1968)].

3.5 Alternative Approach to the QAP for Formulating FLP

Several years after formulation of FLP as QAP, in the early 1960s, it was suggested that the mathematics of graph theory could be used in layout planning [Carrie et.al.(1978)]. This was further investigated by Seppanen and Moore (1970 and 1975), followed by other researchers such as Hassan and Hogg (1987), who have attempted to apply graph theory to facilities layout.

The above researchers propose that FLP can be posed as a graph theoretic problem by defining a weighted graph (G,W) where G=(V,E). V representing the set of facilities and E the set of possible facilities adjacencies. Then the problem is :

$$\text{Maximise} \sum_{(i,j)\in E} W_{ij}\; x_{ij} \qquad 3.13$$

$$\begin{aligned} \text{s.t.} \quad & (V, E' \cup N) \text{ is a planar graph} \\ & x_{ij} = 1 \quad \{i,j\} \in N \\ & x_{ij} = 0 \quad \{i,j\} \in F \end{aligned}$$

where

$$x_{ij} = \begin{cases} 1 & \text{if facilities i and j are located adjacent} \\ 0 & \text{otherwise,} \end{cases}$$

$E' = \{\{i,j\} : x_{ij} = 1, \{i,j\} \in E\}$

F = the set of pairs of facilities which cannot be adjacent in any feasible solution.

[A planar graph is a graph that when drawn in a two dimensional plane, its edges intersect only at vertices.]

The term W_{ij} in 3.13 is the weight of the relationship, obtained from closeness desirability rating between facilities i and j.

Therefore graph theory methods are basically qualitative techniques rather than quantitative.

The lack of conclusive comparison between graph theory and QAP techniques in the literature may be due to the above fact. However Hassan and Hogg (1987), have listed eight drawbacks of graph theory techniques and Foulds(1983) claims that the QAP approaches are superior and states that there is requirement for further improvements and refinement of graph theoretic techniques.

One strong advantage of QAP over the graph theoretic approach is the fact that by arbitrary attribution of high material flow volume between any two desired facilities their adjacencies can be guaranteed. Therefore this qualitative criterion can be incorporated in the QAP technique which is essentially a quantitative procedure.

As concluding remarks to this chapter, the literature survey can be summarised by the following points:.

* FMS layout problem can be formulated as a QAP.

* QAP is an NP-Complete problem and an optimum solution may not be obtained in an acceptable computation time because the number of possibilities (hence computations) increases exponentially with the number of facilities.

* Heuristic approaches have been developed to solve FLP to achieve near optimal solutions and QAP techniques are superior to others.

* The reduced amount of computational effort required in heuristic approaches form the basis for their preference where many static layouts must be determined in a short time.

It is clear that the solution of the Static Layout Planning (SLP) problem in solving real problems requires a degree of compromise. The only way to guarantee finding the optimal solution is to compute all possible solutions. Few researchers have done this for more than six facilities due to the computation time involved. In practice it is necessary to accept a near optimal solution in an acceptable computation time. Most researchers have survey can be summarised by the following points:.

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It is clear that the solution of the Static Layout Planning (SLP) problem in solving real problems requires a degree of compromise. The only way to guarantee finding the optimal solution is to compute all possible solutions. Few researchers have done this for more than six facilities due to the computation time involved. In practice it is necessary to accept a near optimal solution in an acceptable computation time. Most researchers have concentrated on obtaining a solution as close as possible to the optimal solution and have accepted the computation time involved. However in dynamic layout planning the speed with which decisions can be made is arguably more important, since it is pointless computing the best layout for a set of data which no longer applies, or which may have been inaccurate in the first place. It was therefore considered necessary to develop a heuristic construction method for solving the QAP, which had fast solution time as an equally high priority to the optimality of the solution. The considerations involved in the development of this new method are described in the next chapter.

CHAPTER FOUR

A New Solution to the Static Layout Planning Problem - The Initial Layout Generator.

4.1 Introduction

From approaches to the SLP detailed in the previous chapter, it is evident that heuristic methods which do not necessarily guarantee optimality must be used to provide solutions in reasonable computation times.

Heuristic techniques are defined by Hitchings and Cottam (1976), as a method of solving problems (not feasible to be solved by exact methods) by an intuitive approach in which the structure of the problem can be interpreted and exploited intelligently to obtain a reasonable solution.

The heuristic construction techniques devised to solve the facilities layout problem are n-stage, step by step decision process for intelligently building up a feasible sub-optimal solution from scratch. In construction techniques such as MAT [Edwards et.al.(1970)] successive assignment of facilities is made in the layout, until all facilities are allocated. Although the quality of the solutions obtained from these techniques are usually not as good as those produced by improvement methods, [Snehamay and Sylla(1989)] the required computational run time is much less and can be run on small computers.

The requirement for generating a good quality SLP solution with minimum computational effort lead the author to develop a construction method which was capable of producing an initial static layout solution with few data processing stages and as close to the optimum solution as possible.

The solution obtained by this method can be improved upon if required, by application of an improvement procedure such as CRAFT. This method of solution improvement, called a hybrid technique, is also recommended by other researchers, such as Houshyar and Mc.Ginnis(1990), and Tam and Li(1991).

4.2 A New Construction Technique for Generating Near Optimal Solution - The Initial Layout Generator

This method was created by the author as a rapid means of generating initial solutions for subsequent improvement by CRAFT. The original objective was simply to reduce the number of iterations performed by CRAFT before it reached a solution that it could not improve upon. However it was found that the quality of the initial solution had such a significant influence on the run time of CRAFT, that it was considered beneficial to develop a technique that produced as near an optimal solution as possible within as short a time as possible. The trade-off between level of optimality and processing time depends on the improvement rate of CRAFT, but the target was to minimize the total number of computations in the construction algorithm.

The new method was called the Initial Layout Generator (ILG) which reflects the objective of producing an initial layout for subsequent improvement.

The ILG is a heuristic construction technique and consists of three phases of: (1) formation of the link table based on flow volume f_{ik} ,say, between facilities i and k, (2) the selection procedure and (3) the allocation procedure.

The objective function is to minimise material movement cost i.e.

$$\text{Min.} \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} \sum_{l=1}^{n} a_{ijkl} \; X_{ij} \; X_{kl} \qquad 4.1$$

subject to:

$$\sum_{i=1}^{n} X_{ij} = 1 \qquad j = 1,2,\ldots\ldots,n \qquad 4.2$$

and

$$\sum_{j=1}^{n} X_{ij} = 1 \qquad i = 1,2,.....,n \qquad 4.3$$

X_{ij} and $X_{kl} \in \{0,1\}$ for $i,j,k,l = 1,2,.....,n$

where

$$a_{ijkl} = (b_{ik} * f_{ik}) * d_{jl} \qquad 4.4$$

and

b_{ik} = cost of transporting one unit load per unit distance between facilities i and k,

d_{jl} = distance between locations j and l,

n = number of facilities.

To minimize the above objective function, attempts should be made to reduce the value of the parameter a_{ijkl} in 4.4 above for each pair of linked facilities so that the total summation is kept to a minimum. This parameter is the result of multiplication of the three variables b_{ik}, f_{ik}, and d_{jl}. The only variable which the layout designer can have control of is d_{jl} i.e. the element representing the distance between pairs of facilities.

In the existing construction methods, selection of facility locations is made in one of the following two ways:.

Either (a) a location (site) or an activity (facility) is fixed and then all (n-j+1) possible assignments are evaluated (n=number of facilities and j=number of the step at which a facility is to be allocated0. Or (b) Selection is based on the evaluation of all $(n-j+1)^2$ activity-location combinations.

According to Ligget(1981), the construction techniques which use the selection procedure described in (a) above have a higher probability of producing low quality solutions. While in the second methods (b) this problem may be eased but the computation requirement can be prohibitive for problems with large number of facilities e.g >20.

In the newly proposed ILG technique, neither sites nor facilities are assumed fixed. The criteria used in selection and allocation procedures is based on the provision of the maximum number of unoccupied sites for the facilities already assigned. When the possible number of free neighbours for allocated facilities are maximized, then the shorter the distance between these facilities and the others which are to be linked to them. Each reduction in the distance of the connected facilities will in turn contribute to a reduction in the objective function.

In the ILG method the facilities are assigned to locations in an alternating horizontal/vertical orientation. i.e.if the first pair of facilities are connected vertically to each other (imagining the production floor as a rectanglular grid)then the subsequent assignment should be horizontal and vice versa (for the purpose of convenience the abbreviation a.h.v. for this alternating horizontal/vertical method of assignment will be used hereafter). This method of assignment is continued until all facilities are allocated to locations. It is highly probable that by using this method of assignment some locations will remain unoccupied while there remain some facilities to be assigned to these locations. In this case the remaining facilities have to be allocated to places where they can make maximum reduction to the objective function.

Assignment of facilities by the a.h.v method in the ILG procedure is the means by which (i) pairs of facilities with high volume of parts moving between them are placed adjacent to each other and (ii) the maximum number of unoccupied locations with shorter distance are provided for facilities which have parts moving between them in large quantities. This method is illustrated in the examples presented in section 4.4.

Evaluation of all $(n-j+1)^2$ facility-location combinations is not embodied in the ILG procedure hence the number of computations is significantly reduced over all other methods which require this.

Although ILG is a "locally" oriented construction technique, it also partially takes the "global" aspect into account.i.e. the ILG evaluates facility-location assignment at each step and selects the ones which minimize the total material movement cost (local improvement) but also attempts to account for possible future moves by means of providing maximum number of unoccupied neighbours for unassigned facilities.

The ILG procedure is simple to apply and can handle large scale problems on a small computer because of the small number of computations involved.

The quality of the solution produced by the procedure could not be predicted in advance but since the logic encouraged as many locations as possible with high flows between them to be arranged so as to be adjacent, it was considered to be likely to produce good results. This was subsequently examined by extensive testing and was found to produce good quality solutions.

The three phases of the ILG technique are described in the sections below followed by two illustrative examples.

4.2.1 Formation of The Link Table

The preliminary step in establishing the link table is conversion of the full From-To matrix (F/T matrix), representing the material flow between facilities i and k, to a lower or upper diagonal half matrix. This is due to the fact that the F/T matrix is usually asymmetrical since the flow volumes in each direction between any two facilities are likely to differ but directionality is not important.

Supposing f'_{ik} be the volume of material transferred from facility i to facility k and f'_{ki} the volume of material in opposite direction then :

$$f_{ik} = f'_{ik} + f'_{ki} \qquad 4.5$$

is the total material flow between facilities i and k . If a lower half matrix is assumed then the flow volumes between any facility i and other facilities are represented by:

$$\begin{cases} f_{ik} & \text{for } k = 1,2,\ldots.,i \\ f_{ki} & \text{for } k > i \end{cases}$$

$$\text{and} \quad f_{ii} = 0$$

Considering the facilities as nodes and their connections with other facilities as links, then the first column of the link table is formed by listing the nodes in the order of 1 to n, (n is the number of facilities in the system). For each node a link string is formed which represents the flow between each node and the others. The links are then labelled with weights which are the intensity of material flow between related nodes in decreasing order obtained from the flow matrix. This procedure is repeated for all nodes until all nodes are exhausted.

The number of rows in the link table is always n, but the number of columns may be n or less. This is due to the possibility that one facility may have equal flow volume with more than one other facility in which case they appear in the same column.

The weights (material flow intensities) are basically required for the selection procedure.

4.2.2 The Selection Procedure

The selection procedure commences after establishing the link table. This procedure combined with the allocation procedure consists of N(=n) steps. At each j^{th} step, one of the facilities is selected to be located in the j^{th} site according to the allocation rules. If we let A_j denote the set of (j+1) facilities already assigned at the j^{th} step and U_j the set of unassigned facilities then;

$$A_j \cup U_j = (1,2,....,n).$$

Also let S represent set of the strongest links (number of elements of S may be 1 or >1) and M the set of the weakest links respectively , in the first column of the link table.

At the selection phase, a facility has to be selected from amongst (n-j+1) unassigned facilities, at the j^{th} step, such that the increase in the objective function is as small as possible.

The criteria used for selection of a candidate facility to be allocated to a site, in the layout are as follows:

(a) Select a pair of nodes in set U_j in which their link belongs to set S (initially the set A_j is an empty set),

(I) if there is more than one pair of nodes in (a) then select the linked pair in which one of its nodes has max. number of links >= M.

(II) if there are more than one pair of nodes in (I), then select the pair in which one of its nodes has the strongest link among the links of the nodes selected in (I),

(III) if there are more than one pair of nodes selected in (II) stage, then select a pair randomly and go to next stage.

(b) Position the selected node and its linked pair to the sites according to the allocation procedure rules.

(c) Eliminate the link between the selected pair of nodes from the link table

(d) Go to (a) and search for a node in the set U_j which competes to occupy an empty neighbouring site of the selected nodes. If such a node is found then it leaves the U_j set and becomes a member of A_j set, otherwise move to the next column of the link table and follow the steps (a) to (d).

(e) Repeat the procedure until U_j becomes an empty set.

4.2.3 The Allocation Procedure

The allocation procedure follows the selection procedure at each j^{th} step where a candidate node has been selected.

The initial assumption in the ILG technique is that all facilities are square shaped and of the same size. However this constraint can be relaxed, but not totally removed, by some minor modifications to the data representing non-square facilities.

The circumstances in which these modifications need to be employed are given in section 4.3.

In the allocation procedure the area of the floor on which the facilities are to be laid out is superimposed by a grid of equally sized square blocks(cells). The total number of blocks in the grid is greater than or equal to the number of facilities. For example, for a layout problem with 12 facilities a grid can have dimensions of 12*1, 6*2 or 4*3. The number of blocks in rows and columns of the grid is determined by the width and the length of the actual floor.

Having established the dimensions of the grid, selected nodes are allocated to the sites in the following orders:.

a) Let RN = total number of links that

relate the first selected pair of nodes to other nodes with weights >= weight of the element(s) in the set M. At j = 1 if one of the nodes in the selected pair had link(s) only in the set S then allocate this node to a site which provides a total number of free neighbouring sites (with shared boundary) equal to that of link(s)of this node otherwise allocate selected pair in the sites which provide a total number of unoccupied neighbouring sites equal to RN.

(I) If RN > 6 (max. number of unoccupied sites that can be provided adjacent to any pair of selected nodes), then consider the sites in which their free neighbours have the maximum number of unoccupied neighbours.

(II) If there is more than one set of sites in the grid, considered in (a1) above, (due to the symmetric charactristics of the grid) then any pair of sites can be selected randomly from these sets.

b) Allocate the next node selected in the selection procedure, in an unoccupied site adjacent to the previously assigned node.

c) If the direction of allocation in step (b) is horizontal, then make the next allocation in a vertical direction and vice versa.

d) Go to step(b) and repeat the directional pattern of allocation described in (c) until the set U_j becomes an empty set.

4.3 Data Modification of Non-square Facilities

By dividing complete facilities to sub-facilities and using the a.h.v. method of assigning them to locations, the ILG technique can cope with situations where rectangular, L shaped, T shaped and larger size square shape facilities are involved. The modification to the data representing these facilities is in the following manner:.-

First, these facilities are divided to square shaped sub-facilities of equal area which can then be taken as the unit cell of the grid superimposed on the layout.

The second step is to attribute an arbitrary flow between these sub-facilities which is greater than the largest flow between any two complete facilities.

The first step is to ensure that each sub-facility can be accommodated within one cell block of the layout grid and the second step will ensure that the sub-facilities are located adjacently to form their original shape.

However, as mentioned previously, there are two circumstances where the application of the ILG is limited . The first limitation occurs with regard to the area of the non-square facilities. Assuming the area of the smallest square shape facility is one unit then the ratio of the larger non-square facilities are limited to those provided in table 4.1, otherwise due to the a.h.v. method of assignment, irregularities will appear in the generated layout.

The second limitation of the ILG is when the number of non-square facilities increase, the performance of the procedure decreases in terms of generating regular layout solution.

These limitations are not considered to be at all serious in the context of FMS layouts since machine tools, which comprise the majority of facilities, do not normally vary beyond the size and shape range shown in Table 4.1.

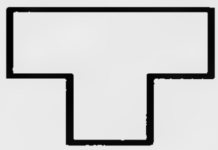
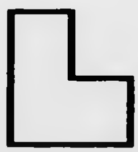
Shape of facility	Ratio of area of the faciltity / the unit area facility	Remarks
	4	———
	2	———
	4	Ratio of horizontal stroke / vertical stroke = 3/2
	3	Ratio of horizontal srtroke / vertical stroke = 1

Table 4.1 Appropriate facility shape and their area ratio to the unit area facility for ILG method.

4.4 Illustrative Examples

To illustrate the application of the ILG technique, two hypothetical manufacturing systems examples with 20 and 8 facilities are considered respectively.

It is assumed in both cases that the transport cost per unit carried per unit distance is one unit. There is no loss of generality since it is based on the consideration that the material handling systems employed are free-ranging AGVs, which will have constant operational cost.

The other two cases of (i) variable and (ii) constant (but not unity) unit cost of material transportation do not limit the applicability of the ILG method. In case (i) the variable part transportation cost between each pair of facilities can be multiplied by the volume of the parts transported and the resultant value can be considered as the present volume of the product flow. In case (ii) the fact that the parts transportation cost is constant but more than one unit, will not alter the ILG produced layout solution. This is because the effect is the same as if both sides of the objective function 4.1 are multiplied by a constant value.

4.4.1 A manufacturing system with 20 equally sized facilities

In example 1, a manufacturing system is assumed to consist of 20 facilities of the same shape (square) and size. These facilities are to be laid out on a rectangular production floor with the length/width ratio of 5/4.

The data regarding the volume of product flow have been originated by the author and are assumed to be measured in terms of unit load. This data is represented as a From-To (flow)matrix shown in Fig.4.1.

To form the link table for this example, its related F/T matrix is converted to an upper diagonal half-matrix using the relationship 4.5. This matrix is shown in Fig.4.2. The link table shown in Table 4.2 is established by the procedure described in section 4.2.1.

The basic information needed for the selection and allocation procedures of the ILG is therefore available from the link table.

At the starting step of the selection procedure, the set A_j is an empty set and the set U_j has 20 elements of 1,2,.....,20. It can be observed from the link table that the set S has only one element which is the link between facilities 10 and 13 with the weight of 44. The set M has also one element which is the link between facilities 15 and 18 with the weight of 20. The link 10 ---> 13 (or 13 --->10) belongs to the set S and both 10 and 13 are elements of U_j. Now according to the selection procedure these facilities are selected and moved to the allocation stage to be assigned to their proposed locations and at the same time their link is eliminated from the link table.

Prior to the allocation of facilities 10 and 13 the overall floor layout is superimposed by a grid of 5 cell length and 4 cell width to accommodate all 20 facilities. For convenience the cells of the grid are labelled alphabetically from left to right and from top to bottom as shown in Fig.4.3.

The values of RN_{10} and RN_{13} can be obtained by referring back to link table (these values are the total number links that facilities 10 and 13 have with other facilities in which their weights are greater than or equal to the weight of elements of the set M i.e. 20). Facility 10 has links with facilities 8,7 and 6, other than 13, with weight s of 39,28 and 20 respectively while facility 13 has links with facilities 6 and 3 with weights of 25 and 22 and linked to facilities 4 and 20 with the equal weight of 20. Therefore the maximum number of unoccupied cells required by facilities 10 and 13 in their immediate vicinity is 6. The facility 6 is counted only once in the link table since it is required by the both facilities 10 and 13.

As can be observed from Fig.4.3 and according to the allocation procedure rule a(i), the following pairs of locations can provide the above requirement for the selected facilities:-

G and H, H and I, L and M or M and N.

Due to the symmetric characteristics of the imposed grid, the selected facilities may be assigned to any of the above pairs of cells without causing any change in the value of the objective function. Here cells G and H are chosen as locations for facilities 10 and 13, but the decision as to which of these facilities should be allocated to which of locations G and H depends on the number of facility links and hence the number of available unoccupied cells. Therefore facility 13 should be located at cell H, since it requires one more free neighbour in its surrounding cells than facility 10. Location H can satisfy this requirement better than G.

As the initial assignment has been in the horizontal direction then the next selected facility has to be positioned vertically, either above or below one of the already assigned facilities. By referring back to the selection procedure and the link table, the next facility to be assigned can be determined. Facility 8 which has the strongest link with facility 10 is the candidate to be positioned in cell B in the layout. The cell B is decided upon the application of the allocation procedure.

The ILG procedures are applied to all facilities until the set U_j becomes an empty set.

The layout generated by the ILG technique is shown in Fig.4.4. The value of the objective function obtained from the ILG generated solution was 5283. This value, being computed using the rectilinear distance between facilities, obtained from the generated layout.

FROM \ TO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	10	25	5	0	0	8	10	0	5	4	0	0	5	3	4	16	10	5	0
2	5	0	3	10	15	5	6	0	3	5	0	0	9	10	7	5	7	0	4	0
3	15	2	0	5	5	7	10	5	20	4	0	10	12	25	7	0	5	4	5	5
4	5	2	0	0	8	5	4	4	7	0	10	10	5	5	0	6	0	6	0	5
5	0	7	0	6	0	4	0	0	4	10	9	0	5	0	5	10	0	0	4	6
6	0	10	5	5	4	0	3	6	6	10	15	0	15	16	0	10	4	8	0	10
7	4	5	10	6	0	5	0	0	11	4	8	0	7	5	6	0	30	9	0	0
8	8	4	6	4	0	4	0	0	0	35	6	9	0	8	5	10	0	0	8	8
9	0	0	18	4	5	6	11	4	0	7	0	6	0	9	0	10	5	0	10	0
10	5	2	8	0	5	10	24	4	7	0	4	8	14	5	0	3	0	2	10	10
11	6	0	0	15	9	6	4	5	0	14	0	15	0	13	5	10	0	12	0	3
12	0	0	8	2	0	0	0	10	10	2	7	0	6	0	10	7	0	5	12	0
13	0	0	10	15	10	10	7	0	5	30	0	10	0	15	7	0	7	0	15	5
14	0	9	15	5	5	10	3	10	9	5	5	0	0	0	8	0	7	5	0	5
15	2	10	7	0	0	0	10	10	0	4	3	8	3	2	0	10	0	10	2	7
16	11	5	5	5	12	6	4	5	8	3	28	7	5	5	0	0	0	4	10	0
17	6	3	0	0	0	4	12	5	5	0	5	0	8	7	0	5	0	8	10	5
18	8	4	4	6	0	4	9	0	0	3	8	5	0	10	10	4	7	0	5	0
19	5	0	5	5	4	0	0	2	5	6	0	16	4	0	10	8	10	35	0	42
20	0	4	5	0	4	8	0	2	0	4	7	0	15	5	7	0	5	10	0	0

Fig.4.1 From - TO (flow) matrix for example 4.4.1

FROM \ TO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	15	40	10	0	0	12	18	0	10	10	0	0	5	5	15	22	18	10	0
2		0	5	17	25	10	10	0	5	5	0	0	18	20	12	8	11	0	8	0
3			0	5	5	12	20	11	38	12	0	18	22	40	14	5	5	8	10	10
4				0	14	10	10	8	11	0	26	12	20	10	0	11	0	12	5	5
5					0	8	0	0	9	15	18	0	15	5	5	22	0	0	8	10
6						0	8	10	12	20	21	0	25	26	0	16	8	12	0	18
7							0	0	22	28	12	0	14	8	16	4	42	18	0	0
8								0	4	39	11	19	0	18	15	15	5	0	10	10
9									0	14	0	16	5	18	0	18	10	0	15	0
10										0	18	10	44	10	4	6	0	5	16	14
11											0	22	0	18	8	38	5	20	0	10
12												0	16	0	18	14	0	10	28	0
13													0	15	10	5	18	0	19	20
14														0	10	5	14	15	0	10
15															0	10	0	20	12	14
16																0	5	8	18	0
17																	0	18	15	10
18																		0	40	10
19																			0	42
20																				0

Fig.4.2 Converted full F/T matrix of example 4.4.1 to upper diagonal half matrix

(1)	40	(3)	22	(17)	18	(8)(18)	15	(2)(16)	12	(7)
(2)	25	(5)	20	(14)	18	(13)	17	(4)	15	(1)
(3)	40	(1)(14)	38	(9)	22	(13)	20	(7)	18	(12)
(4)	25	(11)	22	(13)	17	(2)	14	(5)	12	(12)(18)
(5)	25	(2)	22	(16)	18	(11)	15	(10)(13)	14	(4)
(6)	26	(14)	25	(13)	21	(11)	20	(10)	18	(20)
(7)	42	(17)	28	(10)	22	(9)	20	(3)	18	(18)
(8)	39	(10)	19	(12)	18	(1)(14)	15	(15)(16)	11	(3)(11)
(9)	38	(3)	22	(7)	18	(14)(16)	16	(12)	15	(19)
(10)	44	(13)	39	(8)	28	(7)	20	(6)	18	(11)
(11)	38	(16)	25	(4)	22	(12)	21	(6)	20	(18)
(12)	28	(19)	22	(11)	19	(8)	18	(3)(15)	16	(9)(13)
(13)	44	(10)	25	(6)	22	(3)	20	(4)(20)	19	(19)
(14)	40	(3)	26	(6)	20	(2)	18	(8)(9)(11)	15	(13)(18)
(15)	20	(18)	18	(12)	16	(7)	15	(8)	14	(3)(20)
(16)	38	(11)	22	(5)	18	(9)(19)	16	(6)	15	(1)(8)
(17)	42	(7)	22	(1)	18	(13)(18)	15	(19)	14	(14)
(18)	40	(19)	20	(11)(15)	18	(1)(7)(17)	15	(14)	12	(4)(6)
(19)	42	(20)	40	(18)	28	(12)	19	(13)	18	(16)
(20)	42	(19)	20	(13)	18	(6)	14	(10)(15)		

Table 4.2 The required link table for example 4.4.1

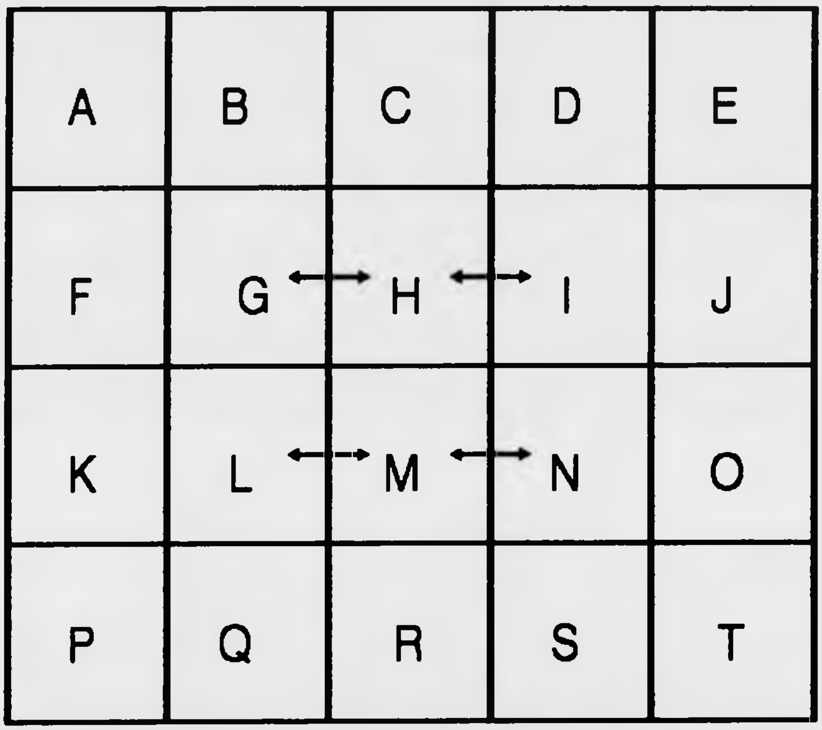


Fig.4.3 Block layout on which the facilities in example 4.4.1 should be laid out.

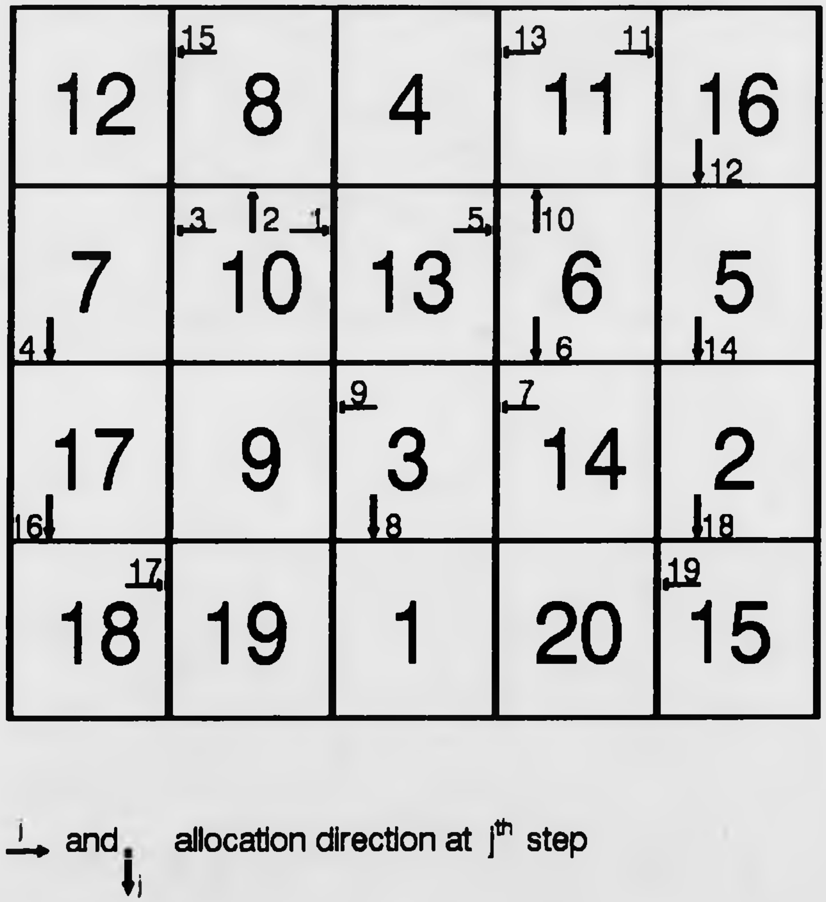


Fig.4.4 Layout solution for example 4.4.1, generated by the ILG with the total cost = 5283

4.4.2 A manufacturing system with 8 facilities of different sizes

In this example the problem is concerned with a manufacturing system comprising five square facilities of unit area, two rectangular facilities of two units area and one L-shaped of three units area, see Table 4.3. The flow matrices (full and half upper diagonal)for this example which are generated arbitrarily by the author are shown in Figs.4.5(a) and 4.5(b).

The ILG procedures are applied to this problem in the same way as in example 1, with the difference that prior to the application of the procedures, the rectangular and L shaped facilities are divided into unit square sub-facilities. These sub-facilities are artificially linked together by means of a dominant interconnection flow (of 100 unit, say) compared with the other flows. Therefore the problem is now transformed to twelve facilities of identical shape and size. The upper diagonal flow matrix for this new problem is established (provided in Fig.4.6) from which the required link table, shown in Table 4.4. is constructed.

As can be observed from the link table the set S contains seven elements of {1(a),1(b),3(a),3(b),8(a),8(b),8(c)}, but the node 8(b) has the greater number of nodes i.e.8(a) and 8(c) connected to it with the strongest weight of 100 units. Since the node 8(b) is only connected to two other nodes, according to the allocation procedure of the ILG it occupies one of the corner cells of the layout as shown in Fig 4.7. In this figure the layout solution, generated by the application of the ILG procedures is shown. The total material movement cost with this layout is 986.5 calculated using the rectilinear distance.

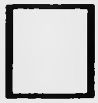
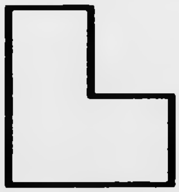
Facility number(s)	shape	area (unit square)
2, 4, 5, 6 and 7		1
1 and 3		2
8		3

Table 4.3 Geometrical specifications of the facilities in example 4.4.2

(a)

FROM \ TO	1	2	3	4	5	6	7	8
1	0	18	15	4	0	4	20	15
2	20	0	16	10	4	4	1	40
3	5	16	0	20	5	6	6	30
4	2	3	10	0	20	8	0	10
5	2	1	15	9	0	7	5	10
6	1	3	6	2	20	0	8	4
7	5	2	2	1	12	7	0	0
8	30	8	5	30	2	3	0	0

Fig.4.5(a) Flow matrix for the example in section 4.4.2

(b)

FROM \ TO	1	2	3	4	5	6	7	8
1	0	38	20	6	2	5	25	45
2		0	32	13	5	7	3	48
3			0	30	20	12	5	35
4				0	29	10	1	40
5					0	27	17	12
6						0	15	7
7							0	0
8								0

Fig.4.5(b) Upper diagonal matrix converted from matrix in Fig.4.5(a)

TO →

FROM ↓

FROM \ TO	1(a)	1(b)	2	3(a)	3(b)	4	5	6	7	8(a)	8(b)	8(c)
1(a)	0	100	38	20	20	6	2	5	25	45	0	45
1(b)		0	38	20	20	6	2	5	25	45	0	45
2			0	32	32	13	5	7	3	48	0	48
3(a)				0	100	30	20	12	5	35	0	35
3(b)					0	30	20	12	5	35	0	35
4						0	29	10	1	40	0	40
5							0	27	17	12	0	12
6								0	15	7	0	7
7									0	0	0	0
8(a)										0	100	0
8(b)											0	100
8(c)												0

Fig.4.6 Upper diagonal half-matrix for example in 4.4.2 after non-uniform facilities are divided into uniform unit size square facilities.

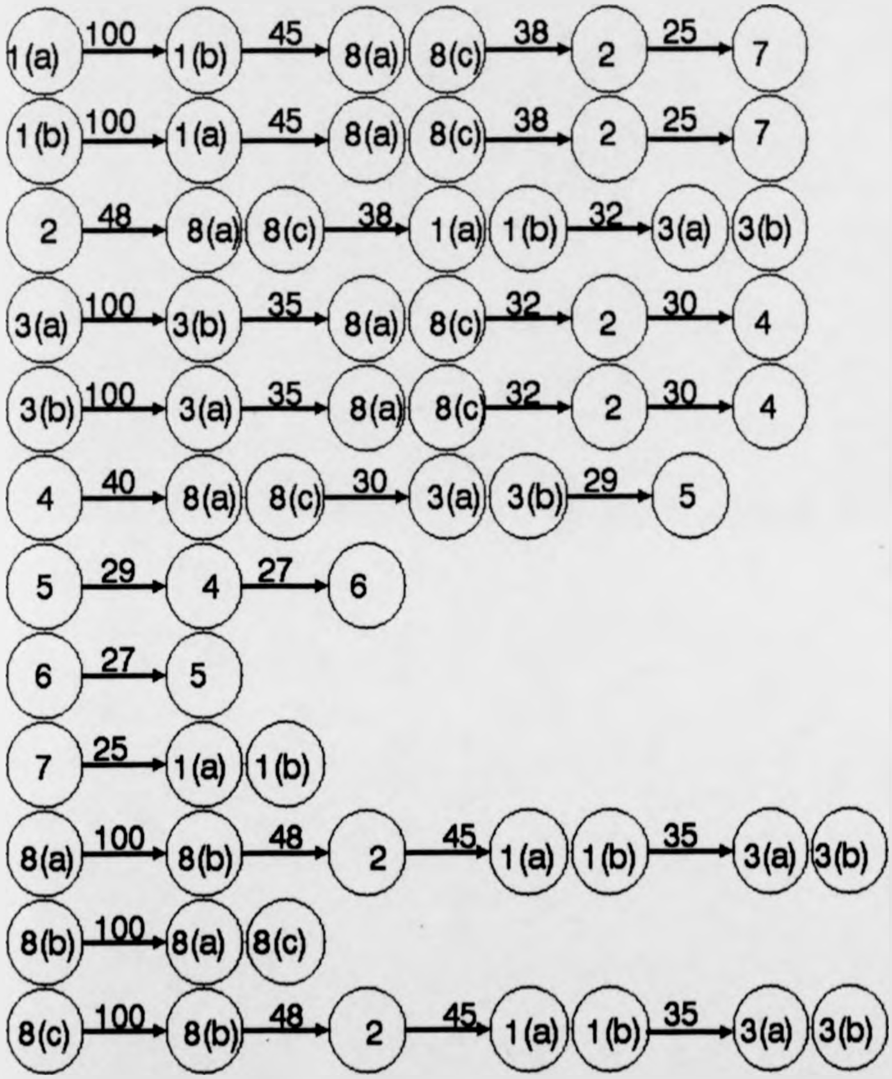


Table 4.4 The link table of material flow for example in 4.4.2.

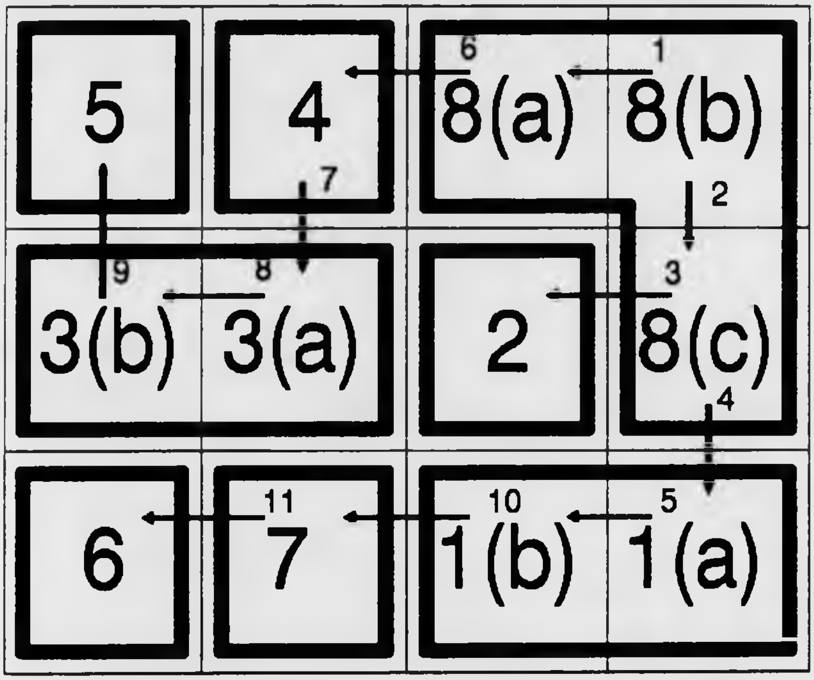


Fig.4.7 Solution layout for example in 4.4.2 generated by ILG with total cost of 986.5.

The newly proposed heuristic, ILG, described in this chapter is a construction technique for solving Static Layout Planning of facilities when formulated as a Quadratic Assignment Problem. The application of this method is not restricted by the number of facilities involved in the problem. By little modification to data presentation ILG can also produce solutions to the problems in which non-uniform facilities have to be assigned to locations. Due to the nature of the procedures, the amount of computation required by the method is significantly less than the existing methods (n instructions in each of the selection and allocation procedures).

Since in the ILG procedure adjacency of facilities with high volume of material flow between them are utilized with maximum efficiency, it is considered that the proposed method is capable of producing solutions of high quality. This consideration is tested intensively in the next chapter where solutions generated by ILG to the classical problems in the literature are compared with the solutions of other well known existing methods. The sensitivity of the ILG procedure to the characteristics of the material flow matrices is also examined in the next chapter.

CHAPTER FIVE

EVALUATION OF THE ILG PERFORMANCE

5.1 Introduction

The ILG procedures were developed to produce facility layouts which could later be utilized in a solution of the multi-period dynamic layout planning problem. Of prime importance was the speed with which initial layouts could be produced but it was also important that the layouts generated were near optimal solution in terms of minimum transport costs.

To establish precisely how well any layout method performs in solving a particular layout problem, the optimal solution has to be known. However, as has been previously explained, the only way to guarantee knowledge of the optimal solution(or solutions) is to compute the transport costs for all possible solutions. Optimal solutions are currently reported [Rosenblatt 1986] only for problems having a maximum number of 6 facilities and even then for specific sets of data. A particular merit of ILG is its ability to produce solutions to large problems and it was considered necessary to examine the relationship between problem size and performance. It was therefore only possible to do extensive comparison on the performance of ILG with other static layout methods which are claimed to give near optimal results. This was done both by comparison with results for data published in the literature and for new problems originated by the author.

The sets of problems selected from the literature for the purpose of comparison of solutions produced by the ILG methods and other recognised techniques are due to Nugent et.al.(1968).

These problems have become classical problem examples in the literature and have presented a challenge to layout design specialists. According to many researchers such as Neghabat(1972), Scriabin & Vergin(1985), Tam & Li(1991) and Houshyar & Mc.Ginnis(1991) these problems provide a comparative basis in both quality and computing time for solution methods.

Other problems were generated by the author, in which the flow data were purposely chosen to have a wide range of variation in quantity so that the performance of the ILG can be evaluated in different circumstances of flow dominance.

In order to assess the amount of improvement that can be made by an improvement procedure upon the layout solution obtained by the ILG procedure, the MICRO-CRAFT

(Microcomputer executable version of Computerized Relative Allocation of Facilities Technique) improvement procedure was applied to the ILG solution. MICRO-CRAFT is an adaptation of CRAFT, which has been developed as a program written in BASIC at the University of Central Florida, [Hosni et.al.(1988)].

CRAFT is a pairwise exchange heuristic improvement algorithm which has been known to be one of the most successful improvement algorithms in terms of solution quality,[Scriabin & Vergin(1985)] and has been widely used since it appeared in 1963.[Tomkins & Moore(1978)]

The tests presented in this chapter were all performed on an IBM,PC-AT with Intel-80286 processor equipped with maths co-processor, hence all computer processing times reported in this chapter are related to this system.

The layout solutions generated by ILG for the experimental data selected from the literature are compared with those generated by another construction method MAT (Modular Allocation Technique) together with solutions of other improvement techniques apart from CRAFT for the same material flow data.

5.2 Description of MAT procedure

MAT is a well known construction method which has been frequently referred to by facility layout investigators to as a method of producing good quality layout solutions, [Flouds(1983), Jacobs(1987) and Raoot & Rakshit(1991)].

MAT was originated by Edwards et.al.(1970), who claim that the procedure produces high quality layout solutions in terms of material flow cost. These authors state that: ".....the solution quality of MAT assignments is comparable to the quality of the solutions given by the improvement techniques ...". This claim has been supported by an experimental investigation conducted by Parker (1976), who concluded that MAT was one of the best construction methods producing high quality layout solutions. Since then no significantly better construction method has emerged and most effort has been focused on improvement techniques.

MAT produces a sub-optimal layout of facilities locations based on the loads between pairs of facilities per unit time and the distance between all pairs of locations where facilities are to be assigned. This procedure utilizes Gavett and Plyter's (1966) theorem which states that the sum of pairwise products of two sequences of real numbers is minimized if one sequence is arranged in nondecreasing order and the other in nonincreasing. Therefore in the MAT the distances between all pairs of locations are arranged as a nondecreasing sequence of real numbers and the material flows between all pairs of n facilities per unit time as a nonincreasing sequence of real numbers. Then the pairs of facilities with greatest material flow are assigned to the locations with minimum distance. The procedure is repeated in similar manner until all facilities are assigned to locations.

In the following section solutions obtained by MAT to the classical Nugent et.al. problems are compared with those of generated by ILG.

5.3 Tests and Results

5.3.1 Tests Performed on Problems Originated by Nugent et.al.

In the first set of tests, the ILG procedures were employed to solve the classical problems of Nugent et.al. These are eight problems of different sizes of: 5,6,7,8,12,15,20 and 30 departments. The plant shape for all these problems are rectangular except for those involving 5 and 7 departments which are L shape plants. All departments for all problems are square and of equal area. Distance measurement between all pairs of departments are rectangular. Flow data and plant shapes for these problems are provided in appendix(C).

The total material flow cost, using both ILG and MAT generate layouts for the above eight problems are shown in table-5.1. The actual ILG assignments are given in appendix(D). As can be observed from Table.5.1 the layout generated for the first problem using either of the techniques results in material movement cost of 25 units whereas for the remaining seven problems ILG technique produced layouts in which the material movement cost are considerably less than those obtained by applying MAT.

The next test was to compare material movement costs(M.M.Cs.)obtained by ILG for the same eight problems with the best results reported worldwide by any author. These resulrs have been obtained by use of improvement techniques. Improvement techniques almost always produce a better solution (depending upon the initial solution to be improved upon) than construction techniques but at the expense of vast numbers of computations.

It was found that the lowest M.M.C. for the first seven problems are reported by Hitchings and Cottam(1976) who have used an improvement technique known as TSP(Terminal Sampling Technique) and for the eighth problem of 30 departments Wilhelm and Ward (1987) have obtained a layout with lowest M.M.C of 3064 by applying their improvement method called Simulated Annealing Procedure (see Table-5.2).

Problem No.	Number of Facilities in the Problem	M.M.C Using ILG Generated Layout	M.M.C. Using MAT Generated Layout	% Improvement Made by ILG
1	5	25	25	0
2	6	47	55	15
3	7	74	80	7.5
4	8	116	128	9
5	12	317	337	6
6	15	606	741	18
7	20	1362	1450	6
8	30	3455	3711	7
Average				8.5

M.M.C.= Material Movement Cost on the basis of unit transport cost per unit distance travelled.

Table 5.1- Comparison of material movement costs in the layouts generated by ILG and MAT for the problems specified by Nugent et.al.

Problem No.	Number of Facilities in the Problem	M.M.C Using ILG Generated Layout	Lowest M.M.C Rrported in the Literature	% Improvement Over ILG
1	5	25	25	0
2	6	47	43	8.5
3	7	74	74	0
4	8	116	107	7.7
5	12	317	289	8.8
6	15	606	575	5.1
7	20	1362	1296	4.8
8	30	3455	3064	11.3
Average				5.7

Table 5.2 Material movement costs in layouts generated by ILG in comparison with the lowest reported Costs.

It was however noted that the average improvement made by the lowest worldwide reported costs over ILG were less than the average improvement made by ILG over MAT. This was considered to be most impressive in view of the ease and speed of obtaining results by ILG but it was clear that the performance of the ILG procedure was not as good as the very best improvement methods.

It was next considered appropriate to quantify the quality of the ILG procedure in terms of the effort required to improve upon it. Since all improvement methods require an initial solution to improve upon, the effort in terms of the number of computations required (and hence the processing time needed) depends in some way on that initial layout. Initial layouts used by most researchers investigating improvement methods are randomly selected and Nugent gives five random layouts for each of the eight problems previously described. These forty layouts, see appendix (E), together with layouts generated by ILG and MAT were presented to Microcraft as initial solutions and the number of improvement iterations, until no further improvement could be made was recorded.

As result of this investigation it was proved that, as shown in Figs.5.1 - 5.3, the layouts generated by ILG required fewer improvement iterations and hence less computation processing time to reach the final solution on which CRAFT could make no further improvement. The cumulative number of improvement iterations by CRAFT for five random initial layouts on average was over 147. The same iteration number when using MAT solutions as initial layouts was 99 whereas the ILG generated solutions needed only 39 improvement iterations for the total of the eight problems (see Fig.5.1). One considerable implication of the number of improvement iterations required with the ILG solution as the initial input to CRAFT is that although the improvement time increases exponentially as the number of facilities increases, nevertheless as shown in Figs.5.2 (a & b) the exponent of time increase is much smaller in comparison with MAT or random layouts.

Although the facilities arrangement in the final layout solution obtained by CRAFT is completely dependent on the initial layout configuration, it was found that this does not necessarily mean that for a specific problem an initial layout configuration of lower material movement cost will lead to lower cost final solution. This is contrary to the views expressed by Ligget(1981) and is discussed in chapter 7.

The major findings on the relationship between the method of selecting the initial layout and the performance in terms of the final material movement cost are shown in

Fig.5.3. This shows quite clearly that the final result does not vary significantly with the initial solution used and that no method of producing initial layouts is consistently better, in terms of final solution cost.

It may therefore be considered that since solution quality is independent of initial layout, one might as well select the initial layout produced by the method which drastically reduces the time taken by the improvement algorithm to produce the final solution. The above experimental tests showed that ILG is quite capable of providing such initial solutions.

From the results it was noted that ILG produces solutions which have a Material Movement Cost between 0 and 11% higher than the best solution produced by improvement methods. However there was no clear correlation between the percentage improvement and the number of facilities so it was not possible to predict how good was the ILG solution alone and hence whether efforts at subsequent improvements were worthwhile.

One factor which was considered to have potential influence on the performance was the material flow data itself that is presented in the From/To flow matrix. For the purpose of comparison with other methods, Nugent data was used but it was thought likely that the distribution of the data could have an influence on the results. For instance if a large number of material flows are identical, then the facility allocation criteria can become random as it is impossible to prefer the selection of one facility over another. Alternatively if material flows progressively change, the selection rules are totally unambiguous.

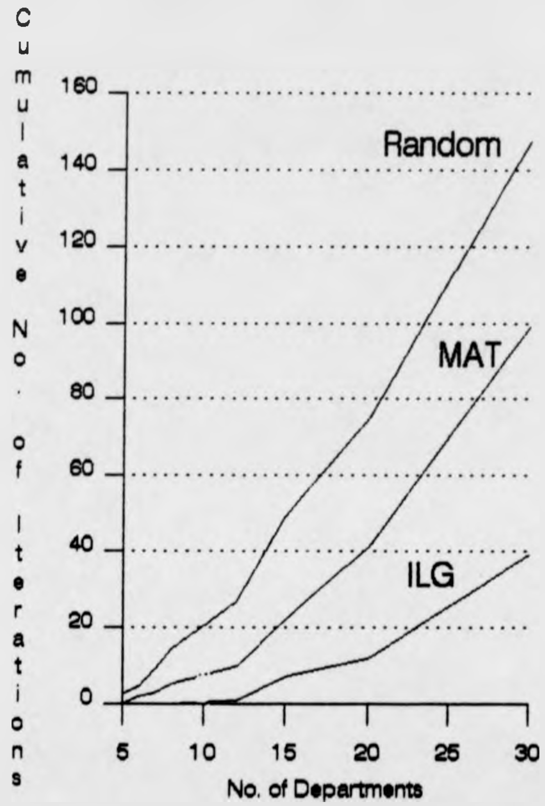


Fig.5.1 Cumulative number of CRAFT improvement iterations versus problem size n.

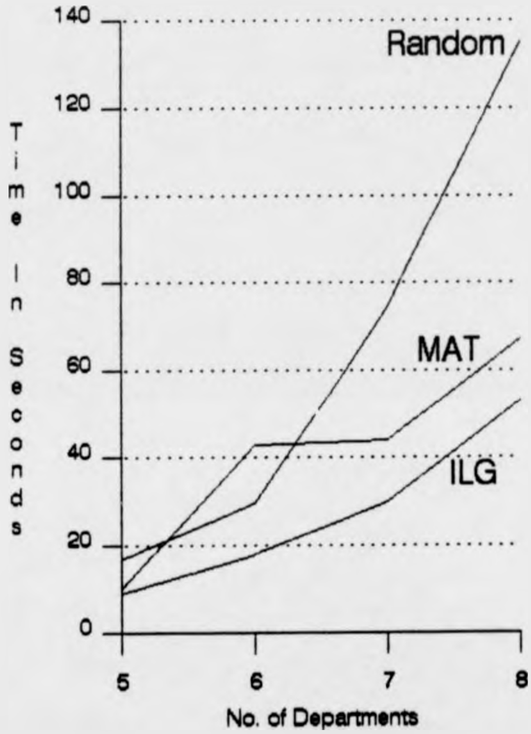


Fig.5.2(a) Time required by CRAFT to improve different initial layouts versus No.of departments.

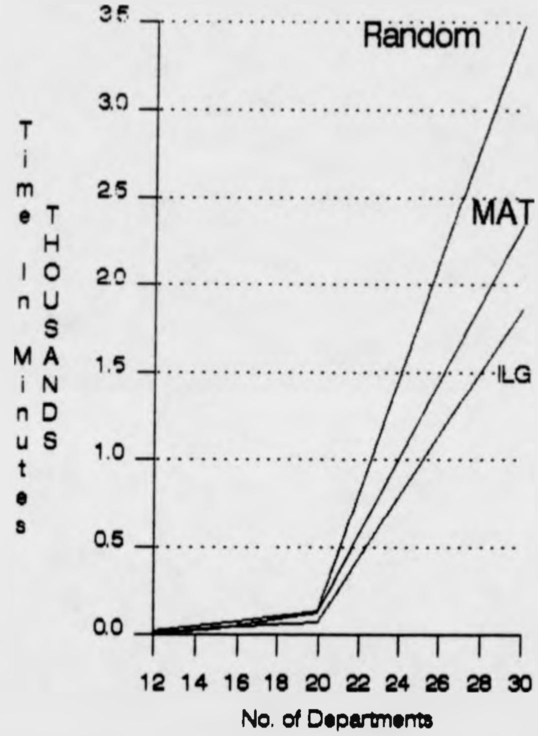


Fig.5.2(b) Time required by CRAFT to improve different initial layouts versus No. of departments.

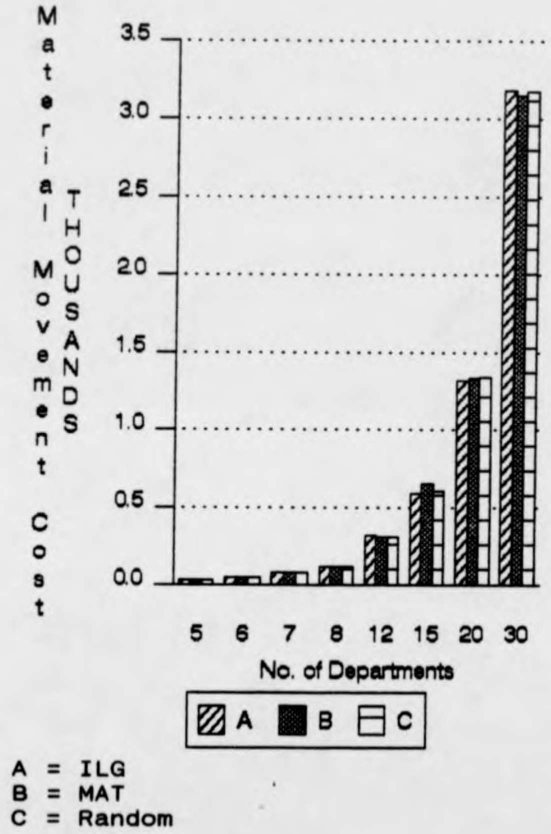


Fig.5.3 Costs of Material Movement in the Final Improved Layout by CRAFT with (A) Initial ILG Solution (B) initial MAT solution and (C) Random Initial solution.

5.3.2 Investigation into the relation between ILG performance and characteristics of the material flow matrices.

In an attempt to relate ILG performance to the From/TO matrix elements, the author initially generated five sets of flow data randomly for a hypothetical problem consisting of nine facilities and performed a correlation test between ILG performance and (i) Standard Deviation(SD) and (ii)Range of the flow data. The term performance here means the " %improvement " that ILG layout solution for the problems requires to match the final improved solution that CRAFT achieves.

Irregularities observed in the result of the performance of the ILG solutions with the variations of both the SD and Range of the considered data and shown in Figs.5.4 and 5.5 indicated that there is no correlation existing between these measurements and the ILG performance. For the purpose of further confirmation of this indication another two sets of flow matrices were created with identical Range and SD of 150 and 41.7 respectively. In the latter case the performance of ILG was 99.3% for one set of flow data and 94% for the other. The conclusion from the results obtained in these tests was that ILG performance is not related to the parameters used to characterise the flow data. Conversely it can be seen that vastly different distributions of flow data do not produce unduly large differences in the performance of ILG.

ILG is therefore relatively insensitive to the data and is applicable to problems involving a wide range of distributions of material flow.

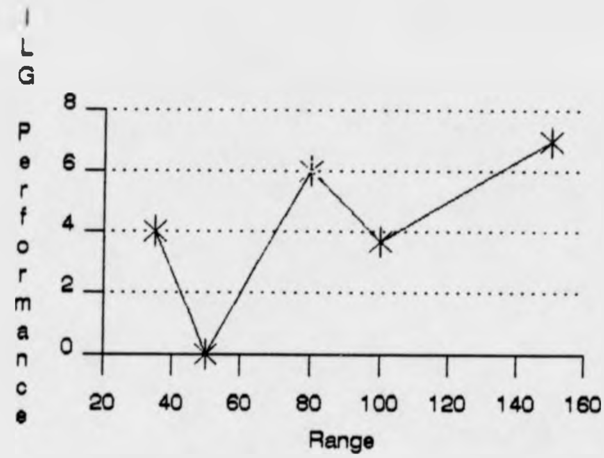


Fig 5.4 ILG performance versus flow data range.

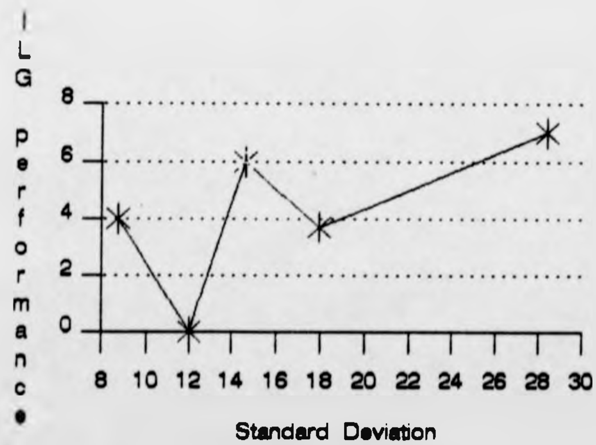


Fig 5.5 ILG performance versus flow data S.D.

CHAPTER SIX

A NEW NON-DETERMINISTIC APPROACH TO DYNAMIC LAYOUT PLANNING

6.1 Introduction

Static Layout Planning methods be can used to deal with the FMS facilities layout problem, if only a single set of material flow data corresponding to a given production period(planning horizon) is assumed. These produce good quality solutions which minimize material movement and handling cost provided that no changes occur during the production period. if significant changes do occur in the material flow, however, there exists the requirement for a strategy which enables the system to be dynamically adaptable to changes resulting from fluctuations in the market. It is necessary to consider the total planning horizon to be divided into shorter periods during which there is little or no change occurring.

A dynamic layout strategy effectively involves a sequence of static layout plans which are, based on economic considerations, suitable for each time period of a multi-period planning horizon.

The proportion of literature dealing with DLP in a manufacturing context is very small compared with that of static layout planning. Lately this subject has begun to attract the attention of researchers in this field. The two major strategies proposed in the literature due to Rosenblatt and Afentakis, are critically reviewed in this chapter, then an alternative method is suggested for the dynamic evaluation of the FMS layout in a multi-period situation. In this method the problem of uncertain future data which has not been addressed in the existing methods is also taken into account.

6.2 Existing DLP Procedures and Their Shortcomings.

6.2.1 Dynamic Programming Approach To The Layout Problem.

The dynamic programming methodology suggested by Rosenblatt, was explained previously in section 2.3.2. In this section, the aim is to indicate the main deficiencies of the method which make it inapplicable to the dynamic circumstances typically found in FMS's. The deficiencies of Rosenblatt's method are:.

* The assumption of a deterministic environment, i.e. assuming that the number of orders and quantities, arrival and due dates for the different products are known and remain unchanged for a specified number of time intervals into the future.

* The assumption that the planning horizon is finite

and data outside this horizon is ignored.

* The assumption of fixed time intervals in which evaluation of facilities layouts is performed.

These three basic assumptions on which the DLP procedure is developed may not be valid for FMS since one of the prime objectives is to have a manufacturing system that is capable of responding to a volatile market in terms of product design and production mix. It is quite reasonable to assume that the details of material flow between facilities can be predicted for a short period of time ahead, but cannot be accurately forecast for a relatively long time into the future. Therefore it is evident that as the number of time periods considered at the dynamic layout design stage increases, the reliability of the data in later periods declines and the reliance that is placed on this less reliable data should diminish.

The second assumption that the planning horizon is finite and limited to a specified number of time intervals into the future is, in part, a recognition of the fact that forecasts are inevitably inaccurate. By eliminating consideration of orders or product changes too far into the future, the risk of making extensive layout changes in preparation for something that may not materialise is avoided. However it also overlooks long term strategic and data outside this horizon is ignored.

* The assumption of fixed time intervals in which evaluation of facilities layouts is performed.

These three basic assumptions on which the DLP procedure is developed may not be valid for FMS since one of the prime objectives is to have a manufacturing system that is capable of responding to a volatile market in terms of product design and production mix. It is quite reasonable to assume that the details of material flow between facilities can be predicted for a short period of time ahead, but cannot be accurately forecast for a relatively long time into the future. Therefore it is evident that as the number of time periods considered at the dynamic layout design stage increases, the reliability of the data in later periods declines and the reliance that is placed on this less reliable data should diminish.

The second assumption that the planning horizon is finite and limited to a specified number of time intervals into the future is, in part, a recognition of the fact that forecasts are inevitably inaccurate. By eliminating consideration of orders or product changes too far into the future, the risk of making extensive layout changes in preparation for something that may not materialise is avoided. However it also overlooks long term strategic changes that can be predicted with a very high level of confidence. The opportunity to gradually move towards a radical revision of layout rather than be forced to initiate it within a very short time scale is lost.

The third assumption concerning the constancy of time intervals between which layouts remain unchanged cannot be upheld if it is accepted that a deterministic market environment is not valid. The fact that the data changes means that the time intervals must change so that decisions can be made to establish whether the layout should be altered in response to the market. The faster the data changes, the more frequent must be the re-calculations to decide whether a new layout is warranted and so the shorter the time interval for which data must be supplied.

Although, as is correctly pointed out by Rosenblatt, focusing on the DLP problem involves the solution of a series of static problems, this in itself does not necessarily imply that the sequence of static problems should be confined to and solved as a series of equal and constant length time periods.

Rosenblatt, acknowledging the weakness of the assumptions in his model states," However in a dynamic environment, things may change and orders may either be cancelled or added. Assuming that data are usually available for n periods, then after the first period, additional data for the coming n periods may become available. Based on these new data, the "From-To" matrices are updated and different layouts may be recommended for periods 2,3,.....n,n+1".

The above author while accepting that the data does vary in changing market conditions, only concentrates on updating the layout at fixed time periods. To enhance the applicability of his model, he recommends the consideration of incorporating "changing cost" or "nervousness cost" into the dynamic programming formulation.

Rosenblatt claims that:. " Two types of nervousness in layouts may occur. One is when a change in layout takes place in a period where it has not been scheduled before, or when a previously suggested shift in layout in a given period is cancelled. Another type of nervousness is when a different change in layout is desired for a period for which initially a change in layout was scheduled."

The idea of incorporating nervousness cost in dynamic programming was originated by Carlson et.al.(1979 and 1984) for dynamic lot-sizing that was suggested by Wagner and Within(1958), as a treatment for dealing with nervousness of Material Requirement Planning (MRP) systems.

Carlson et.al. define the nervousness cost as the cost of shifting from scheduled setups and indicate that nervousness resulting from schedule changes takes two forms. These are either lot size changes for periods in which setups are already scheduled or setups are required in those periods in which they were not previously scheduled. These authors then propose a modification to the Wagner and Within model of dynamic lot-sizing. In principle the Wagner and Within model is an algorithm for the dynamic version of the economic lot size problem. In this model the possibility of demands for a single item, inventory holding charges and set up costs are allowed to vary over N periods. The algorithm determines a minimum total cost inventory management scheme which satisfies known demand in every single period. This model suffers from two shortcomings:.(i) Optimization of the scheduling is attempted at each time period independent of other time periods. Therefore the effect of decisions taken at each time period are not reflected in other planning periods. (ii) The model assumes that demand data predicted at the start of the multi-period planning horizon remains unchanged over the duration of all periods within the finite planning horizon.

These assumptions make the solution produced by the model quite sensitive to changes in the future demand. To alleviate this sensitivity, Carlson et.al.(1979), have then modified the model by introducing the idea of incorporating "effective" setup costs. In their algorithm the idea is to increase the "effective" set up cost in those periods for which no set up was previously scheduled, and decrease the "effective" set up cost for periods having scheduled setups.

Rosenblatt in turn proposes the above treatment be adopted for the dynamic layout planning problem, i.e.periodically up-dating the layout arrangement while considering the nervousness aspect in layout in a similar manner to that used in lot-sizing.

Although the above recommendation relaxes the restrictive assumption of a deterministic environment, there still remain other major disadvantages in Rosenblatt's method, these are:.

* Dynamic lot-sizing can in many cases be disastrous for a system where nervousness is present i.e. when effective set-up costs are decreased or increased they may even amplify the nervousness. [Steel(1975)] This is analogous to an underdamped system which easily goes out of control if a small disturbance is applied and this could equally apply to dynamic layout planning. Introduction of changing cost at one time period can result in

undesirable layout design in the next period. Hence the overall layout strategy for all periods in the planning horizon could be affected adversely.

* Periodic revision of facility layouts can only be an acceptable procedure when data regarding product mix can be predicted with reasonable accuracy. In practice this can only be done for a relatively short time in the future. Therefore if the length of time periods are equally short there arises the problem of compatibility between this time and the re-arrangement implementation lead time which may be quite long if provision of sevices(power,air,data networks etc.) is required.

6.2.1.1 Computational Feasibility of Dynamic Programming

Apart from disadvantages outlined in the previous section, the computational feasibility of the application of dynamic programming is also very questionable.

Even assuming that all variable parameters of nervousness have been accounted for, and hence a set of confirmed From-To data has been established, for an FMS with n facilities over a duration of T time periods the number of all possible layouts for this FMS in any single time period is n!. The number of all possible layout combinations that can be considered for optimal layout configuration in the planning horizon is $(n!)^T$.

In order to illustrate the magnitude of the computational problem, an FMS with a moderate number of 15 facilities (e.g. the system supplied by Kearney and Trecker [O'Leary (1982)]), is considered as an example. It is assumed that this system is set up to produce different components for five periods (this is finite production horizon example) with periodical variation in product design and production volume. To obtain the objective function of minimized material movement cost including machine shifting cost, 3.8 E+60 different layouts have to be evaluated if a guaranteed optimal solution is to be found. Obviously this total procedure can be computationally prohibitive in most practical situations.

To overcome the computational problem of DLP, Rosenblatt suggests that by using Sweeney and Tatham's theorem (see appendix (B)) it is possible to evaluate a much smaller proportion of all possible n! layouts in each time period. This smaller proportion corresponds to the R_t best ranked layout solutions in each period in terms of material movement cost.i.e. R_1 is the optimal, R_2 is the second best layout solution and so on.

However, using Sweeney and Tatham's theorem in order to determine the number of R_t best solutions requires two values of the upper and lower bound. These two values can be regarded as Z^{inf} for lower bound and Z^{UB} for upper bound where:.

$$Z^{inf} = \sum_{t=1}^{T} Z_{t1} \qquad 6.1$$

where:

T = number of time periods

Z_{t1} = minimum cost of material movement in each period

and

$$Z^{UB} = Z^{inf} + \sum_{T=2}^{T} (SC)_T \qquad 6.2$$

$(SC)_T$ = machine movement cost at period T.

Also to find the values of the R_t best solutions in each period, the static optimum layout problem has to be solved in that period with the addition of the constraints identified in section 2.1. The implication of this for finding M of the best R_t solutions is that the total number of layout evaluations of a system containing n facilities over T time periods will be E where:.

$$E = T * M * (n!) + (M)^T - T * \sum_{M=1}^{M} (M - 1) \qquad 6.3$$

However, the summation term and $(M)^T$ in 6.3 are so small relative to the first term that both can be ignored in practice.

Referring to the previous example of a system containing 15 facilities and considering only the 10 best static layout solutions for 5 time periods, by applying the dynamic programming technique suggested by Rosenblatt, to obtain the best sequence of layouts in a dynamic situation, the number of layout evaluations will amount to:

$$10 * (15!) - \sum_{M=1}^{10} (M - 1) + 10^{\wedge 5}$$

$$\simeq 1.31 \text{ E+13}$$

Even assuming each layout evaluation to be only one instruction in CPU terms then a mini-computer or a powerful workstation with a processing speed of 10-mips (million instructions per second), which presently costs of the order of £10K, will require about 16 days to solve the problem.

From the above example and considering the following points it becomes evident that the proposed dynamic programming method is not currently computationally feasible even for systems with a moderate number of facilities.

* A lower bound value is required to use Sweeney and Tatham's theorem for assessment of the R_t best solution. To find the lower bound, the static layout problem has to be solved optimally.

* From the above point, to find the R_t best solution it is required first to obtain the optimum static solution for each period. For systems with a relatively large number of facilities (e.g. n>20) unless a complete enumeration procedure is conducted, the optimal solution may not be easily obtained. Therefore as the SLP problem is formulated as a QAP and the latter belongs to the set of NP-complete problems so does the problem of finding the R_t best solution. Hence the computation involved in finding the R_t best solution increases

exponentially as the number of facilities in the system increases.

* In some cases the value of the R_t best solution may correspond to several different layouts resulting in complication in sequential layout arrangement of dynamic layout planning.

* The purpose of finding the R_t best solution is to reduce the number of facility layouts considered for the dynamic programming procedure. This means that arrangements resulting in higher material movement cost than those in the R_t best are eliminated in the dynamic programming procedure. However taking into account the machine shifting costs there is no guarantee that the long-term best solution will be composed of a sequence of configurations derived only from the R_t best layouts in each period. For example if it was decided to consider only the best four layouts at each period, there is a possibility that any other layout, such as the fifth best, could be optimal in the following period, resulting in zero machine shifting cost from the previous period. This could easily yield a lower cumulative material and machine movement cost in the two periods together

than any other combination of the four best layouts in the same two periods.

* Finally, in many cases the value of K in Sweeney and Tatham's theorem, i.e $Z^{UB} - Z^{inf}$, can be greater than the summation of the cost all machine movements. The implication of this is that no layout configuration can be eliminated from the dynamic programming procedure.

6.2.2 Simulation Approach To The Dynamic Layout Planning Of FMSs.

In a more recent investigation by researchers in dynamic layout planning, the impact of changes in the attributes such as part mix, volume and design of product, on the long term layout strategy have been examined non-analytically.

Researchers such as Afentakis et.al.(1990) have utilized a discrete time simulation model. In their approach, they have divided the planning horizon into a number of time periods of equal length. The above authors have also assumed that variation in the product design and volume takes place at the beginning of each time period. The philosophy of this approach, outlined earlier in section 2.3.2 is based on(i) periodical rearrangement of facilities and(ii) re-layout contemplation according to a level of percentage change in product related variables, namely, volume, new design and part routing.

Since the percentage change in the From-To matrix is difficult to quantify for the purpose of re-layout analysis, the above authors have selected the three mentioned "measures of interest" as criteria for determining at what point a re-layout should be contemplated.

As a critical factor, it has to be emphasized that the measure of optimality (or near optimality) of any layout is strongly dependent on the data in the related From-To matrix.

It is quite possible that changes in some of the measures of interest may or may not affect the structure of the From-To matrix. Therefore, for example, a small change (less than 10%) in the flow volume could lead to a different layout with reduced material movement cost in which case re-layout analysis is required. Conversely, there may occur a case where introduction of new parts (more than 10%) would not change the From-To matrix structure, due to the compensation from similar parts departing from system. In this case the layout has to remain the same, making the re-layout analysis unnecessary.

Apart from the above criticism, the following remarks also make the approach utilized by Afentakis et.al. open to question:

* The results obtained by simulation to the static layout problem and hence dynamic layout problem are limited only to the specific system and conditions that are simulated. A new model complete with all its operating rules has to be constructed to obtain results from a different layout.

* The approach is time consuming and only applicable to flexible manufacturing systems containing a small number of facilities(e.g. 5 or 7 as reported by Afentakis). As these authors state :"A related issue is developing methods to determine optimal or near optimal layouts quickly. ......Computational requirements grow very rapidly as the number of machines increases. Thus the development of heuristics to employ for large scale problem is another fruitful area for further research."

Therefore despite the fact that this approach aims to reduce the need for computation to a minimum by establishing when it is likely that a new layout might be of some benefit and only then determining alternatives, it is still too computationally intensive to be of use for anything but small scale problems at present.

It is clear that neither of the existing approaches is suitable for large layouts but it is also obvious that the penalties arising from poor layout in small manufacturing systems cannot be too costly and probably will not justify the expense of developing and running the necessary computer program. Therefore it was considered necessary to develop a heuristic method that was computationally very efficient so that there was no practical constraint on the size of problem that could be handled by a small, low cost computer system.

6.3 A New Approach To Dynamic Layout Planning of Facilities For FMSs.

In the literature on dynamic planning of facility layout, mathematical models and simulation procedures have been proposed as decision aids for the planning of facilities over time. In the major sources on this subject [Rosenblatt(1986), Afentakis et.al. (1990)] significant attention is given to obtaining the optimal solutions either for a finite planning horizon or under deterministic conditions or both. However as discussed previously, a so-called optimal layout is only optimal if the data used for its determination happens to correspond to the material flow that actually occurs within a given time interval. In the case of FMS's where full advantage is taken of the flexibility provided, this is considered highly unlikely.

The objective in the new approach to the FMS dynamic layout planning is development of a layout strategy for an infinite planning horizon, more responsive to dynamic situations regarding the product data and less susceptible to variations in the material flow.

This new method aims to produce the most economic sequence of layout configurations for a continuous set of consecutive time periods with a computational efficiency that allows the practical solution of large problems.

The mathematical model developed in this approach is based on the following considerations:.

(i) The planning horizon is infinite. This means that the FMS for which a layout design is desired, will operate indefinitely. Therefore assumption of an artificially fixed planning horizon is avoided.

(ii) The planning horizon is divided into time periods of unequal span. The length of the individual time periods are only established when changes occur in the elements of the From-To matrices representing the volume of material flow between facilities. Hence, facilities re-arrangement analysis is performed only at times when the data in the From-To matrices change.

(iii) The influence of both accurate current material flow data and less reliable future data is acknowledged in the layout design.

(iv) The dynamic layout strategy is composed of a series of static layouts designed for each variable time period.

There are two main reasons behind the above considerations.

1. To allow the layouts to be generated in a rolling manner without ignoring the fact that any major future change can influence the present layout decision.

2. By dividing the planning horizon into consecutive time periods the layout decision process can be confined into finite but variable planning periods. This can be an appropriate decision making policy for an infinite planning horizon because (i)since material flow data for future periods are obtained in the form of forecasts, they are subject to uncertainty. Hence as the length or number of time periods increases so does the data unreliability, and accordingly their influence on the present layout decision should diminish. Therefore the model does not allow material flow data forecast for some considerable

time in the future to have significant influence on the present layout. (ii) Decisions regarding the facilities layout must of necessity be based on limited information about the future.

When a flexible manufacturing system is set up to operate for an unknown life time, then an optimal (or near optimal) sequence of layout decisions would depend in principle on data from an infinite number of future periods. In other words, a multi-period dynamic layout planning procedure requires material flow data forecasts for the whole of the system life time (assuming perfectly reliable data forecasts), in order to determine the desired layout sequence.

This is impossible, so to make the proposed methodology capable of practically solving the dynamic layout planning problem, the limitation of future information has to be realised.

The proposed method produces dynamic layout designs in a rolling manner. The layout designs are produced as a result of a sequence of layout decisions determined by successive solutions of finite, multi-period models.

In summary, the proposed method is as follows:

Solve the multi-period model and implement the decisions for the first period, in which future data has also been reflected. Then update the model only when a change occurs in the From-To flow matrix, so that the information gathered in the interim is reflected in the model. Implement re-layout only if it is economic to do so and continue to update the From/To flow matrix in order to determine when the next re-layout is justified.

6.3.1 Formulation of DLP Problem

In Static Layout Planning (SLP) the influence of the layout on production cost is generally considered to be the material handling cost which is a function of handling distance and the number of products moved along each route.

In the dynamic context, however, the cost of re-layout, if required from one period to the next, has also to be reflected in the total production cost.

Considering the influence of future data and the degree of reliability of their forecast values on the design of the present layout, then the cumulative material movement and facilities re-arrangement cost at each period within the planning horizon can be formulated as the following equation:

$$M_t = \sum_{t=1}^{T} C_{(t-1,t)} + \sum_{t=1}^{T} L_t(a_t)_{ij} \qquad 6.4$$

where

$$(a_t)_{ij} = \sum_{t=1}^{T} \beta_t * [(P_t)_{ij} * (a_t^*)_{ij}] \quad i,j=1,2,\ldots,n \qquad 6.5$$

and

M_t = the cumulative cost of material movement and facilities re-arrangement up to time T.

$L_t(a_t)_{ij}$ = material movement cost using layout L generated from flow data $(a_t)_{ij}$.

$C_{t-1,t}$ = facilities shifting cost from time t-1 to time t.

$(a_t^*)_{ij}$ = material flow between facilities i and j forecast at time t.

P_t = probability associated with $(a_t^*)_{ij}$.

β_t = reliability factor attributed to the flow matrix at time t.

Let, for the sake of convenience, S_t represent the second summation term in equation 6.4. The parameter $(P_t)_{ij}$ in S_t is the probability that the predicted material flow between facilities i and j will be equal to the corresponding forecast value $(a_t^*)_{ij}$ at time t. The purpose of including this parameter in the model is to enable the system layout policy to accommodate the future flow data without over-reacting to the data as probability of the data being correct becomes greater . By introducing this parameter all individual links i.e. flow between all pairs of facilities in the system, will have an influence in the dynamic layout design. Where there is a greater confidence in the market for a specific product, then a larger value can be attributed to the probability parameter associated with material flow of that product. In other words as the level of confidence in the market of a product tends to 100% the corresponding probability parameter tends to 1, conversely as the level of confidence declines so does the value of parameter P_t.

The second parameter, the reliability factor β_t corresponds to the whole of F/T matrix and acts as a filter in the system in order to reduce the effect of less certain forecast data on the long term layout policy to a desirable level. The implication of this is that more reliable current flow data will have greater role in planning the configuration of the immediate layout.

Both P_t and β_t parameters in S_t are assumed to be determined by market research largely on the basis of historical data.

Both parameters are determined in accordance with the length and number of time periods. The value of parameter β_t decreases as the number of time periods for which orders are predicted increases. For example, β_t can be represented by a linear or non-linear negative exponential function of time with decreasing values proportional to the increase in the length of time.

6.3.2 Establishment of time periods.

To establish the length of time periods in an infinite horizon, initially this horizon should be divided into a number of finite horizons which contain a number of time intervals. These time intervals are determined to be when a change is predicted to occur in the structure of the From-To flow matrix. Even a change in a single element of the F/T matrix will provoke consideration as to the placement of time interval boundaries. Determination of the number of time intervals in any finite horizon is dependent on the values of both parameters in S_t. Upon application of these parameters in relationship 6.5 the structure of the flow matrix $(a_t)_{ij}$ in 6.4 is decided. Therefore as the values of the two parameters reduce significantly as the further into the future data is considered then the elements of the flow matrix $(a_t)_{ij}$ become so small that they can be ignored in the dynamic layout planning model. At this point the number of time intervals and hence time span of a finite horizon is determined.

The number and duration of time periods, between which re-layout should be performed, can in turn be decided by using the relationship 6.4. in the following manner:.

Having established the static layout solutions for all time intervals concerned, at each time period a comparison can be made between the material movement cost in the following time interval while maintaining the existing layout configuration, and the total cost of facilities re-layout and material movement cost resulting from the new suitable layout for the following time interval. If it was economically justified to change the layout then a time period is determined and re-layout performed, otherwise the existing layout remains unaltered and the above comparison is made for the following time intervals until a layout re-arrangement is required. The mechanism of the procedure is further demonstrated by means of an example presented in the next section.

A point of great importance in terms of data processing time to reach a solution is how the static layout corresponding to S_t, can be selected. This depends on the number of facilities involved in the system. If the number of layout evaluations, calculated using the equation 6.3 is such that excessive computational problems do not arise, then the optimal layout approach may result in better long term layout policy, though, this is not guaranteed. Otherwise, a heuristic approach such as ILG or ILG improved by CRAFT, has to be utilised to establish the static layouts for each time period.

Because of future data amalgamation into the present material flow data and the possibility of changes or additions to the future information, it cannot be anticipated whether an optimal policy will be superior to a good solution producing heuristic.

To examine the efficiency of the proposed method, a test was performed by the author on the problem originated by Rosenblatt(1986). The solution to the problem and results are given in the next section.

6.3.3 A Numerical Example

6.3.3.1 The Representative Problem

The data in this example is due to Rosenblatt and is considered for the purpose of comparing the results obtained by the application of two different procedures, i.e.the optimum procedure and the proposed method by the author.

The original problem is representative of a plant comprising six departments. A planning horizon with five time periods for which material flow is forecast is assumed. However to describe the mechanism of the newly proposed alternative non-deterministic dynamic method the author has considered the following modifications:,

(i) time periods used by Rosenblatt are regarded as time intervals of variable duration, at each of which the structure of F/T matrices has changed. Time periods are established only after the requirement for re-layout becomes evident,

(ii) an arbitrary relationship of:

$$\beta_t = t^{-(t-1)} \qquad 6.6$$

where t is the number of time intervals was assumed for the reliability parameter. Two reasons were considered to justify the above function for the parameter β_t,(1) to make the value of this factor decrease exponentially proportional to the increase of number of time intervals so to reduce the influence of less certain future data and (2) to account for the flow data as far as the fifth time interval in the model for the purpose of comparison with the solution using dynamic programming with optimal static solutions provided by Rosenblatt. Hence the reliability factors for the first five time intervals, using the relationship 6.6 above are those given in Table 6.1. At each time interval the flow data from no more than five time periods needs to be considered due to the fact that the application of the flow matrix reliability factor makes the elements of the fifth period matrix tend to zero or become so insignificant that it cannot possibly affect the design of the layout for the current interval,

(iii) the number of time intervals has been extended to 10, by using the same flow data in the initial five time intervals after the fifth interval, so that five sets of F/T data can be considered at each time interval.

(iv) the elements of F/T matrices in all ten time intervals are obtained using $P_t * a_t^*$.

t	ß
1	1
2	1/2
3	1/9
4	1/64
5	1/625

Table 6.1-Reliability factors for the first five intervals, at each interval of the problem using relationship 6.6

The problem, therefore, can be re-stated as follows: Given the forecast material flow data and their related probability and reliability factors, in a finite horizon during which 10 significant changes occur in the forecast flow data, it is desired to determine time periods when different layouts are required based on economic considerations. The sequence of layouts proposed in these time periods must be such that the total cost attributed to material handling and shifting costs associated with layout changes is minimised over the total planning horizon.

6.3.3.2 Problem Solution

The flow data between different departments for the various time intervals, when change occurs in the flow data, are provided in Table 6.1. In this table the row vector s_i represents the cost associated with shifting departments to another location between time intervals. It is assumed that all elements of forecast flow matrices (which represent the links between related pairs of facilities) for all time intervals have been multiplied by their corresponding probability factor. Given this data, the problem is to find the best possible layout sequence defined above within the fixed planning horizon, in this case.

According to the proposed method, the first step in this multi-period DLP problem is to up-date material flow matrices as far ahead as the time interval at which the flow matrix tends to a zero matrix.

The updated From-To matrices, after consideration of probability and reliability factors for the first five intervals are shown in Table 6.3. By the same method the updated From-To matrices are obtained for the remaining four intervals are provided in appendix (F).

The next step is to form the matrix a_{ij}(i & j=1,2,....n)

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The next step is to form the matrix a_{ij}(i & j=1,2,....n) of equation 6.5 which represents both certain current and less reliable forecast flow data. Therefore at each time interval material flow data are revised to obtain the above matrix and this in turn is used to generate the facility layout at each time interval.

In Table 6.4 the revised flow matrices for the first five intervals, using the relationship 6.5 to reflect forecast flow data, are presented.

In the subsequent step static layouts are generated. The ILG method was used to generate these layouts based on the flow data given in Table6.4 and are provided in Table 6.5.

Having established the static layouts for the flow data concerned in different time intervals, the sequence of static layouts and the time periods after which re-layout is required have to be decided in order to determine the dynamic layout arrangement for the finite multi-period problem. To achieve the multi-period policy, economic considerations of facility shifting cost has to be contemplated. At the beginning of each time interval the cost of material movement in the existing facilities layout designed for the flow data in the previous interval is compared with the total material movement and facility shifting cost in the layout suitable for the new set of flow data in the current interval. The current layout has to be re-arranged when there is a reduction in the total cost, otherwise the system operates under the existing facility layout conditions.

The summary of the solution policy, using the newly proposed method is given in Table 6.6. It can be observed from this table that it is more cost effective to retain the facility layout generated using the ILG method, for the first time interval until the end of the third time interval. However a layout re-arrangement at the beginning of the fourth time interval proves to be more economical with the saving of 744 cost units. At the fifth time interval the gain obtained by re-arranging the layout designed for the fourth interval to that of appropriate for the flow data in the fifth interval is 17 units. (In cases where unanticipated minor costs involved in the layout re-arrangements are not accounted for then the trade-off between small gains and prevention of the re-layout problem and hence accepting minor costs may be contemplated).

Therefore for this example there are three time periods of $T_1 = t_1 + t_2 + t_3$, $T_2 = t_4$ and $T_3 = t_5$ in the finite horizon of this problem (with fixed duration of $t_1 + t_2 + t_3 + t_4 + t_5$) at which re-arrangement of facilities are required.

The solutions for the problem obtained by both optimal procedure (provided by Rosenblatt and shown in Table 6.7) and the proposed non-deterministic dynamic layout planning method are compared in Table 6.8 which shows that in the proposed method less time periods are required, and the total cost is increased by only about 3%.

To further investigate the performance of the proposed method, the author performed another test on the problem by utilizing CRAFT to improve the static layout solutions generated by ILG in all the five time intervals and study their impact on the dynamic layout planning policy. The results of this improved version shown in Table 6.9 suggested that the final solution can only be improved by less than 0.33%.

To facility:

		1	2	3	4	5	6
From	1	0	63	605	551	116	136
facility:	2	63	0	635	941	50	191
	3	104	71	0	569	136	55
t=1	4	65	193	662	0	77	90
	5	162	174	607	591	0	179
	6	156	13	667	611	175	0

		1	2	3	4	5	6
	1	0	175	804	904	56	176
	2	63	0	743	936	45	177
	3	168	85	0	918	138	134
t=2	4	51	94	962	0	173	39
	5	97	104	730	634	0	144
	6	95	115	983	597	24	0

		1	2	3	4	5	6
	1	0	90	77	553	769	139
	2	168	0	114	653	525	185
	3	32	35	0	664	898	87
t=3	4	27	166	42	0	960	179
	5	185	56	44	926	0	104
	6	72	128	173	634	687	0

		1	2	3	4	5	6
	1	0	112	15	199	665	649
	2	153	0	116	173	912	671
	3	10	28	0	182	855	542
t=4	4	29	69	15	0	552	751
	5	198	71	42	24	0	758
	6	62	109	170	90	973	0

		1	2	3	4	5	6
	1	0	663	23	128	119	50
	2	820	0	5	98	141	66
	3	822	650	0	137	78	91
t=5	4	826	570	149	0	93	151
	5	915	515	53	35	0	177
	6	614	729	178	10	99	0

Continued....

		1	2	3	4	5	6
	1	0	63	605	551	116	136
	2	63	0	635	941	50	191
	3	104	71	0	569	136	55
t=6	4	65	193	662	0	77	90
	5	162	174	607	591	0	179
	6	156	13	667	611	175	0

		1	2	3	4	5	6
	1	0	175	804	904	56	176
	2	63	0	743	936	45	177
	3	168	85	0	918	138	134
t=7	4	51	94	962	0	173	39
	5	97	104	730	634	0	144
	6	95	115	983	597	24	0

		1	2	3	4	5	6
	1	0	90	77	553	769	139
	2	168	0	114	653	525	185
	3	32	35	0	664	898	87
t=8	4	27	166	42	0	960	179
	5	185	56	44	926	0	104
	6	72	128	173	634	687	0

		1	2	3	4	5	6
	1	0	112	15	199	665	649
	2	153	0	116	173	912	671
	3	10	28	0	182	855	542
t=9	4	29	69	15	0	552	751
	5	198	71	42	24	0	758
	6	62	109	170	90	973	0

		1	2	3	4	5	6
	1	0	663	23	128	119	50
	2	820	0	5	98	141	66
	3	822	650	0	137	78	91
t=10	4	826	570	149	0	93	151
	5	915	515	53	35	0	177
	6	614	729	178	10	99	0

s_i =(887 964 213 367 289 477)

Table 6.2 - Material flow data and machine shifting costs

		To facility:					
From		1	2	3	4	5	6
facility:	1	0	63	605	551	116	136
	2	63	0	635	941	50	191
	3	104	71	0	569	136	55
t=1	4	65	193	622	0	77	90
	5	162	174	607	591	0	179
	6	156	13	667	611	175	0
		1	2	3	4	5	6
	1	0	88	402	452	28	88
	2	31	0	372	468	24	89
	3	84	42	0	459	69	67
t=2	4	25	47	481	0	87	19
	5	49	52	365	317	0	72
	6	48	58	492	299	12	0
		1	2	3	4	5	6
	1	0	10	9	61	85	15
	2	19	0	13	73	58	21
	3	4	4	0	78	100	10
t=3	4	3	18	5	0	107	20
	5	21	6	5	103	0	12
	6	8	14	19	70	76	0
		1	2	3	4	5	6
	1	0	2	0	3	10	10
	2	2	0	2	3	14	10
	3	0	0	0	3	13	18
t=4	4	0	1	0	0	9	12
	5	3	1	1	0	0	12
	6	1	2	3	1	15	0
		1	2	3	4	5	6
	1	0	1	0	0	0	0
	2	1	0	0	0	0	0
	3	1	1	0	0	0	0
t=5	4	1	1	0	0	0	0
	5	1	1	0	0	0	0
	6	1	1	0	0	0	0

Table 6.3- Up-dated flow matrices in time intervals 1 to 5 with consideration of the Pt and ßt factors

		To facility					
		1	2	3	4	5	6
From	1	0	164	1016	1067	339	249
facility	2	116	0	1022	1485	146	311
	3	193	118	0	1106	318	140
t=1	4	94	260	1108	0	280	141
	5	236	234	978	1011	0	275
	6	214	88	1181	981	278	0
		1	2	3	4	5	6
	1	0	242	846	1206	517	319
	2	177	0	814	1286	411	346
	3	198	116	0	1273	683	239
t=2	4	81	194	988	0	715	214
	5	226	148	732	1102	0	283
	6	148	202	1093	975	474	0
		1	2	3	4	5	6
	1	0	221	98	677	1117	472
	2	332	0	209	767	998	531
	3	130	122	0	780	1337	369
t=3	4	134	267	94	0	1247	573
	5	383	152	78	952	0	506
	6	173	264	290	691	1188	0
		1	2	3	4	5	6
	1	0	454	110	339	740	692
	2	571	0	202	343	991	728
	3	436	362	0	329	912	596
t=4	4	450	376	174	0	613	838
	5	676	350	147	119	0	869
	6	387	477	348	173	1048	0
		1	2	3	4	5	6
	1	0	715	416	513	196	141
	2	862	0	408	683	180	186
	3	394	696	0	570	176	136
t=5	4	865	680	565	0	167	204
	5	1010	615	439	415	0	286
	6	702	751	624	392	203	0

Table 6.4- Revised flow matrices for the first five time intervals

time interval t	facility layout L_t		
1	2	4	1
	6	3	5
2	2	4	5
	1	3	6
3	2	4	3
	6	5	1
4	2	6	4
	1	5	3
5	5	1	4
	6	2	3

Table 6.5 Facility layouts generated by ILG for the first five time intervals.

t.i.	f.l.	m.m.c	m.m.s.c	m.m.c.c.l	t.c.
1	2 4 1 6 3 5	12964	_____	12964	12964
2	2 4 5 1 3 6	14961	16614	14853	27817
3	2 4 3 6 5 1	13684	15073	14962	42779
4	2 6 4 1 5 3	13188	15421	16165	58200
5	5 1 4 6 2 3	12819	15436	15453	73636

t.i. = time interval,
f.l. = facility layout,
m.m.c. = material movement cost in the layout generated by ILG,
m.m.c.s. = total material movement and facility shifting cost,
m.m.c.c.l.= material movement cost with the current layout,
t.c. = m.m.c.s. over the finite horizon.

Table 6.6 Dynamic layout policy and the related material movement and facility shifting cost over multi-period finite horizon utilizing the ILG method to generate the static layouts.

Time interval	Layout		
1	2	4	6
	1	3	5
2	2	4	6
	1	3	5
3	2	4	6
	1	5	3
4	2	6	4
	1	5	3
5	2	1	4
	6	5	3
total cost	71187		

Table- 6.7 Optimal layout solution for the problem.

	Optimal layout policy	Proposed method
No. of time periods	4	3
No.of facilities moved over finite horizon	6	8
Cumulative material and facility movement cost	71187	73636

Table 6.8 Summarized comparison of optimal policy and the proposed method solution to the problem.

t.i.	f.l.	m.m.c	m.m.s.c	m.m.c.c.l	t.c.
1	2 4 5 6 3 1	12910	_____	12910	12910
2	2 4 5 6 3 1	14883	0	14883	27793
3	2 4 6 1 5 3	13172	15038	14746	42539
4	2 6 4 1 5 3	13188	15421	16991	57960
5	6 2 4 5 1 3	13020	15637	15453	73413

t.i., f.l., m.m.c., m.m.c.s., m.m.c.c.l. and t.c. as in Table-6.6

Table-6.9 Dynamic layout policy and the related material movement and facility shifting cost over multi-period finite horizon utilizing the ILG+CRAFT method to generate the static layouts.

The results obtained show that dynamic layout in rolling manner utilizing the relationship given in equation 6.4, produces a layout decision policy comparable with the optimal policy.

Although, in the above problem, the total material movement and facilities shifting cost showed a 3% increase compared with the optimal policy, the computational requirements of the procedure are a fraction of that of the optimal policy and was initially performed manually with the aid of a non-programmable calculator.

The method is therefore shown to be valid by comparison with the only published set of solutions. Comparison is not possible with larger problems because no other method is reported which can generate solutions in an acceptable computation time. The proposed method is therefore unique and the claim for its validity rests on the sound assumptions and tested principles described in this thesis.

CHAPTER SEVEN

DISCUSSION

7.1 Introduction

This research has been shown to make contributions both in the area of static layout planning and in the area of dynamic layout planning. This chapter discusses the results obtained by the proposed new methods in each area.

In the first section, the new construction technique referred to as the Initial Layout Generator (ILG) is discussed in the context of its performance compared with other methods of static layout planning reported in the literature. In the second section the assumption of non-deterministic data for layout evaluation is discussed together with the economic criteria for establishing when a new layout becomes economically viable.

7.2 Evaluation of ILG in generating solutions for the Static Layout Problems.

Exhaustive tests followed by critical examination of the ILG procedure by the author revealed the need for consideration of three main areas:

1) ILG quality
2) ILG speed
3) ILG applicability

7.2.1 ILG Quality

(a) In the first set of tests reported in charter five, in fourteen cases out of forty trials, ILG produced solutions to Nugent's problems with a range of 0.3% to 10% lower material flow cost compared with the mean of solutions produced by CRAFT from initial random solutions, see Table 7.1.

This clearly indicates the competitiveness of the ILG method in comparison with improvement techniques of which CRAFT is generally acknowledge as one of the best. This is in spite of comments by several authors who have stated that improvement methods must always be considered superior to construction techniques in producing near optimal layout solutions. [Hanan et.al.(1976), Scriabin and Virgin(1985)]

It was however recognised that in the remaining 26 cases, CRAFT produced a better solution than the ILG method, although the average percentage improvement made by CRAFT in terms of material movement cost was only 3.6%. Overall, for Nugent's problems the ILG method gave a solution less than 1% worse than CRAFT starting from initial random solutions in terms of material movement cost. It must therefore be concluded that if solution quality is the <u>sole</u> criterion and if only <u>one</u> layout planning method could be used, then the ILG method is not the best choice. However if quality is still the sole criterion but a combination of layout methods is possible, then for Nugent's problems the ILG solution improved by CRAFT gave, on average, a 1.2% lower material movement cost than the mean of several random solutions improved by CRAFT, (see appendix(G)).

Therefore it is concluded that to obtain the solution which on average is closest to the optimal without resorting to computing all possible solutions, the best choice is to use the ILG method followed by an improvement technique like CRAFT.

(b) From the comparison between results of random initial layouts improved by CRAFT and ILG solutions improved by CRAFT (appendix G), despite the conclusion drawn above that the average cost of those originating from ILG being lower, there were 15 cases where CRAFT produces a lower cost solution from initial random layout than from the ILG solution. These are shown in table 7.2.

These results therefore prove that it cannot be guaranteed that starting from a better initial layout will yield a better final solution following the use of an improvement method. Claims such as those made by Hanan et.al.(1976) and Scriabin and Virgin (1985) both of which state that a construction method followed by an improvement method produces better solutions than improvement methods alone must be disputed. However although it is not true in all cases it is shown by these results to be true on average.

(c) In view of the fact that the ILG method sometimes produced results that were better than CRAFT and sometimes worse, an attempt was made to correlate this with the data in order to establish whether it was possible to predict solution quality. No correlation was found with either the number of facilities or with the distribution of data in the From/To matrices. On reflection it is perhaps not surprising that no correlation was found since it is necessary to reduce a whole matrix of flow data to a single number. The numbers used in this case, i.e. mean, range and standard deviation, take no account of the position of the data in the matrix and so much of the information is lost. Nevertheless it was shown that the ILG method was not sensitive to large variations in flow characteristics with regard to distribution of quantities within the matrix and so it is a robust method.

(d) The underlying reason for the ILG method producing good solutions is that its allocation procedure is forward looking. Assignments are not simply made on the basis of the next best position, but instead provision is made to enable subsequent facility placement to have as great a

No of Depts	Rand Initial Soln. No.	Initial Mater. Flow Cost	Final CRAFT Soln. Cost	No. of Iterations From Initial to Final Solution.	ILG Soln. Cost	ILG Advan. Over Rand. + CRAFT in %
5	1	33	29	2	25	10
	2	29	29	0		
	3	36	26	4		
	4	34	29	2		
	5	41	26	4		
7	1	87	78	3	74	7
	2	120	78	3		
	3	108	78	7		
	4	114	84	3		
	5	101	79	6		
8	1	136	120	3	116	3
12	3	437	328	17	317	3
15	2	806	608	22	606	0.3
20	5	1661	1386	22	1362	2

Table 7.1 Nugent's problems for which ILG outperforms CRAFT in terms of both quality and computation time.

No. of Depts.	Rand. Initial Solution No.	Inial Mat. Flow Cost	Final CRAFT Cost	No. of Its From Initial Solution	ILG + CRAFT Cost	No. of Its From ILG To CRAFT Final
6	2	55	43	2	47	0
	3	54	46	1		
	4	58	46	3		
	5	58	46	5		
8	2	161	112	6	116	0
	3	145	110	5		
	4	160	112	4		
	5	144	109	7		
12	1	392	306	17	315	1
	2	392	302	11		
	4	425	295	11		
	5	373	296	8		
30	1	4030	3128	71	3184	27
	2	3879	3150	69		
	4	3824	3176	65		

Table 7.2 Nugent's problems for which CRAFTproduced better final solution starting with a poorer random initial solution.

chance as possible of allowing adjacent location of facilities with high material flow between them. In this sense the philosophy of ILG is similar to that of dynamic layout planning in that it is the overall performance of the system that is important and not optimum location of a limited number of facilities or optimum layout for a limited period of time.

7.2.2 ILG Speed

(a) In almost all construction techniques the decision process of selecting a facility and assigning it to a location is made in either 2-dimensional or 3-dimensional ways.[Liggett (1981)]

In 2-dimensional assignment, a facility is fixed to a location at each k^{th} assignment stage and the remaining (n-k+1) possible assignments are evaluated whereas in 3-dimensional methods all $(n-k+1)^2$ facility-location combinations are evaluated [Heider (1973)]. As mentioned in chapter four this iterative evaluation procedure is not embedded in the ILG procedures resulting in only n assignments in the allocation procedure. This results in a dramatic reduction in solution time which is a necessity if a layout solution is sought for manufacturing systems with a relatively large number of facilities.

(b) The facility layout problem has been formulated as a quadratic assignment problem. The latter belongs to the set of NP-Complete problems. The implication of this is that the amount of computation required to solve large scale problems increases exponentially as the number of facilities involved in the problem increases. Even heuristic methods developed to date require expensive computer systems(mainframes) to solve large scale problems.

The efficiency of ILG makes it the only heuristic among the existing methods that can handle large size problems in a short time with less costly computer systems i.e micro-computers.

7.2.3 ILG Applicability

(a) Because of the alternating vertical/horizontal (or horizontal/vertical) method of facilities assignment in allocation procedure of the ILG and depending on the structure of the material flow matrix, it is sometimes possible that the allocation procedure may be curtailed before the assignment of all facilities is completed. For example consider ILG applied to generate a layout solution for a system consisting of six facilities with material flow links shown in Table 7.3. These facilities have to be assigned to appropriate locations in a plant such as shown in Fig.7.1 in a way that material movement cost is a minimum.

According to ILG procedures, facilities 1,4,5 and 6 are selected and assigned to locations B,A,F and D respectively in a manner illustrated in Fig.7.2. As can be seen from this figure facility number 6 is assigned to D rather than to location F.

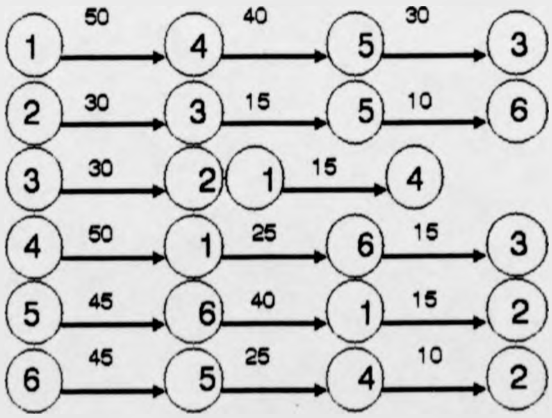

Table 7.3 The link table for the hypothetical example of a manufacturing system with six facilities.

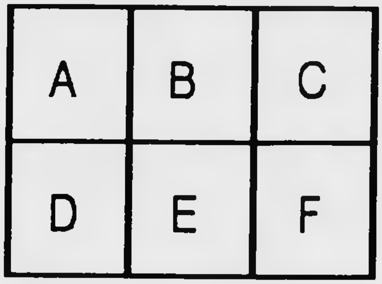

Fig.7.1 Plant shape considered for the hypothetical example

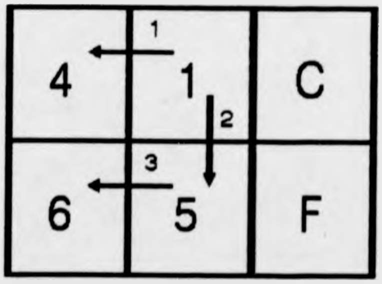

Fig.7.2. Assignment of facilities to locations according to the ILG procedure.

This is due to the priority given by ILG to situations when the two neighbours of an empty location are occupied by facilities which have the strongest link with the candidate facility. Under this condition the empty location should be occupied by the candidate facility, otherwise an available location with maximum number of free neighbours is selected. At assignment stage 3, allocation of the candidate facility i.e.facility number 6, should be in horizontal direction (since at stage 2 the direction was vertical) for which two locations of D and F are available. In normal circumstances this facility would have been assigned to location F because this location has the maximum number of free neighbours but since both facilities 4 and 5 have their strongest link with the facility No.6, this facility must be assigned to location D. At this stage the allocation procedure of ILG is curtailed in the sense that alternating manner of allocation cannot proceed because no vertical assignment can be made. To cope with these circumstances ILG can be modified so that the allocation procedure re-commences with assignment of a candidate facility to an unoccupied location neighbouring an occupied location containing a facility which has the strongest link with the candidate facility. For the above example the allocation procedure restarts with assigning facility 3 to location C and then facility 2 to location F, as shown in Fig.7.3.

(b) As described in chapter four the ILG method can also handle problems containing non-square facilities. By dividing non-square facilities into unit square sub-facilities and by modifying the link table to represent these sub-facilities as independent facilities, ILG can

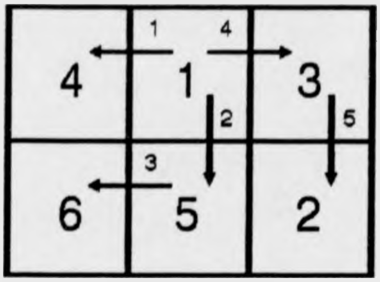

Fig.7.3 Complete assignment of facilities to locations after modification of the allocation procedure.

produce solutions comparable to those generated by improvement methods such as CRAFT. However in cases where a relatively large number of irregular shaped facilities are involved, the application of ILG may not be as straight-forward as the case of all square facilities. In this case the ILG procedure may have to be repeated a number of times in order to complete the assignment of all facilities in a manner similar to that explained in section 7.2.3 (a).

7.3 Differences Observed in the Solution to the Problems in the Literature

Minor differences were observed between final solutions reported by Nugent et.at. for their eight classical problems and those of produced by implementation of Micro-CRAFT, see appendix (H). These differences are assumed to be due to variation in coding of different versions of CRAFT.

7.4 Discussion of the Proposed DLP Method

7.4.1 Benefits of Coping with Non-deterministic and Up-dated Data

The assumption of a non-deterministic environment regarding material flow data in the proposed dynamic method provides a realistic approach to the layout planning problem in a infinite planning horizon with uncertain material flow data. Continuous up-dating of flow data is another feature of the proposed procedure by which the method is able to monitor continuously variations of the flow data and absorb them without over-reacting to the changes.

7.4.2 Consideration of "Time value of money" in solution of multi-period layout problem.

In multi-period layout planning situations, as time intervals between layout changes increase, then the discounted value of money and its impact on, for example, facility shifting cost, may influence re-layout strategy. The concept of discounted value of money can be introduced to the non-deterministic dynamic layout strategy proposed in chapter six by including the rate of time value of money. Therefore to take the time value of money into account, equation 6.4 can be modified to the following:

$$M_t = \sum_{t=1}^{T} C_{(t-1,t)} * (1 + r_t) + \sum_{t=1}^{T} L_t \ (a_t)_{ij}$$

where

r_t = rate of discounted money value.

7.4.3 Sensitivity of the proposed dynamic method to the flow matrix reliability and flow probability factors.

The proposed dynamic layout method acknowledges that all material flow data that is used for decision making purposes has an element of uncertainty associated with it.

In static layout planning where flow data is aggregated into a single time period and is assumed to be fixed, it is likely that forecasts of individual movements in the flow matrix will be reasonably accurate. However when the flow is highly variable and forecasts need to be made for events occurring at different times in the future, it is not considered safe to make this assumptions.

Two factors have been introduced to ensure that decisions are not dependent on dubious data but also that decisions are influenced by data which is considered sound. A probability value is associated with the best estimate of individual material flows arising from an order being placed on the manufacturing system. This probability is not essentially time dependent but reflects the likelyhood that an order will materialise at a particular time. As that time approaches, the probability will tend to move towards either 0 or 1 depending on whether the order does or does not appear in the flow matrix. The proposed dynamic method is sensitive to this probability only if it is associated with a large material flow and in such cases it is likely that market research is able to estimate the probability with some precision.

The flow matrix reliability factor accounts for the inability to forecast accurately the further into the future one predicts. Very short term forecasts are likely to be highly accurate but the rate of decline of accuracy, or reliability of the forecast, depends on the nature of the business, volatility of the market, product innovation etc. As an example, in Fig.7.2 two trends of reliability factor are illustrated. Trend A represents a market where it is very difficult to predict orders and therefore future flow data is made less influenced than case B where greater reliability is attributed to the forecast. However, in both cases the reliability attributed to forecasts made of events in the long term is relatively small. The reliability factor must be determined from historical data which reflects how well it has been possible to make accurate forecasts in the past, but the sensitivity of layout decisions to this factor are unlikely to be great provided that the magnitude of the factor decreases rapidly with time.

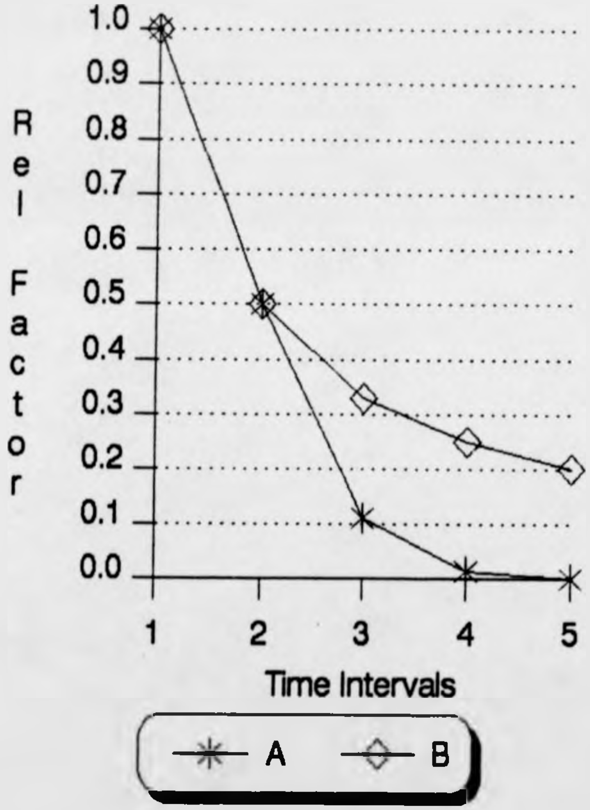

Fig.7.4 Two different trends of Reliability Factors

CHAPTER EIGHT

CONCLUSION

Flexibility inherent in the elements of flexible manufacturing systems does not undermine the importance of the layout of facilities.

As variations in product mix and design occur over time the layout should be adapted to suit the new requirements if manufacturing costs are to be minimized. As soon as a significant change occurs it is necessary to establish whether changes in the layout are justified, and if so to what configuration it should be altered.

In this thesis a new and promising approach has been suggested to the dynamic layout planning (DLP) problem which satisfies the above and which provides the following advantages over existing methods:

* The solution to the DLP problem incorporates a new, very rapid solution procedure to SLP problems known as the initial layout generator(ILG). The use of the ILG method

permits a very large number of static problems to be solved in a short time. This permits objective decisions to be made concerning <u>when</u> a re-layout is justified by continuously monitoring the predicted flow data and does not constrain decision making to occur at fixed time intervals.

* The highly computationally efficient ILG method allows very large scale problems (>30 facilities) to be solved with ease. Solution to 30 facility problems have been produced by hand in approximately 60 minutes using only a non-programmable calculator.

* The proposed dynamic layout planning procedure is a non-deterministic approach in which future material flow is considered not to be accurately known. By means of introducing two parameters representing flow matrix reliability and material flow probability, the influence of forecast data is taken into account in design of the current layout.

* The procedure can deal with an infinite planning horizon so that policy decisions made far into the future but with high reliability can prevent short sighted decisions being made.

* The results of the tests performed by the author on the data provided in the literature showed that the proposed non-deterministic dynamic procedure can produce solutions as near as 3% of the optimal solution.

* The concept of an 'optimal' solution when using

forecast values whose accuracy are uncertain, is questionable. A technique which can respond as soon as definite changes appear in the data is considered to be more useful.

Although the objective of the research was to develop an improved dynamic layout planning method, the new static layout planning method known as ILG is considered to be a substantial contribution in its right. Properties of the ILG procedure are:-

* It produces solutions using far fewer computations than any other procedure known to the author and is therefore a very fast method.

* The quality of solutions produced are better than any other construction algorithms known to the author and only marginally less good than one of the best improvement algorithms (CRAFT)- but are obtained in a fraction of the time.

* The quality of solutions is not noticeably dependent on the distribution of data in the material flow matrices.

* It can deal with layouts that are rectangular or L shaped and can handle facilities that are square, rectangular, T or L shaped within certain bounds.

Furthermore the use of ILG showed that the improvement technique, CRAFT, does not always produce better final solution with a better initial solution.

* Improvement procedures do not always necessarily generate better solutions than construction techniques.

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APPENDIX (A)

WIMMERT'S METHOD

Wimmert's method of facilities layout is quantitative technique. In this method minimized distance * volume of materials handling between facility locations is the criteria.

There are three basic assumptions made in Wimmert's method: (1) individual areas are interchangeable, (2) the distance between two locations is independent of the direction of movement, e.g. distance from location i to location j is equal to the distance from location j to location i, and (3) cost is directly proportional to equivalent distance.

To use the method first a distance matrix, say D, and a load matrix, say L, should be established. Based on these D and L matrices, a load-distance matrix can be constructed. In order to perform problem solution operations on this matrix, it is necessary that paths between locations ij be used as column headings arranged in nondescending order, left to right, and that loads handled between locations ij be the row headings in nonascending order, top to bottom.

In order to arrive at a solution, it is necessary to start at the northeast corner cell of the load-distance matrix, eliminating the northeast corner location assignment and all other locations dependent upon the northeast corner cell. Next the cells on the minor diagonal lying closest to the northeast corner and all dependent facility location combinations are eliminated. This manner of elimination is repeated until there remains only a single cell in one or more of the matrix rows and columns. Then it remains necessary to determine compatible locations. Collecting the facility location combinations, feasible assignments can be made using the single remaining column and row cells.

APPENDIX (B)

SWEENEY AND TATHAM'S THEOREM

Let v_{tr} denote the value of the r^{th} best static configuration in period t, and

$$v^{inf} = \sum_{t=1}^{T} v_{t1} \quad \text{(T represents the entire planning horizon)}$$

= a lower bound on the value of the optimal multi-period solution

v^* = upper bound corresponding to any feasible solution to the multiperiod problem

Theorem. Let $K = v^* - v^{inf}$. Also let R_t be such that:

$$v_{t,R_t} - v_{t,1} < K$$

and

$$v_{t,R_t+1} - v_{t,1} > K.$$

In period $\bar{t}$, no static solution with value $v_{\bar{t}r}$ may become part of an optimal multiperiod solution if $r > R_{\bar{t}}$.

Proof. Suppose $r > R_{\bar{t}}$. The value of the best multi-period solution containing the r^{th} best configuration in year $\bar{t}$ is bounded below by $\sum_{t \neq \bar{t}} v_{t1} + v_{\bar{t}r}$. Now,

$$\sum_{t \neq \bar{t}} v_{t1} + v_{\bar{t}r} = \sum_{t=1}^{T} v_{t1} + v_{\bar{t}r} - v_{\bar{t}1} > v^{inf} + K = v^*.$$

APPENDIX (C)

MATERIAL FLOW DATA AND PLANT SHAPES FOR NUGENT'S PROBLEMS

Since the flow distance data are symmetrical($F_{ij}=F_{ji}$, $D_{ij}=D_{ji}$, for all i,j) for all Nugent's problems the data are compactly presented in pages C-2 to C-4 of this appendix in the following form:

	1	2	3	.....	n
1	—	D_{12}	D_{13}		D_{1n}
2	F_{21}	—	D_{23}		D_{2n}
3	F_{31}	F_{32}	—		
.	.	.			
.	.	.			
.	.	.			
n	F_{n1}	F_{n2}			

n = No. of departments.

Plant shapes presented in page C-5, are numbered in accordance with Nugent et.al. convention, given in appendix(E).

n = 5

	1	2	3	4	5
1	—	1	1	2	3
2	5	—	2	1	2
3	2	3	—	1	2
4	4	0	0	—	1
5	1	2	0	5	—

n = 6

	1	2	3	4	5	6
1	—	1	2	1	2	3
2	5	—	1	2	1	2
3	2	3	—	3	2	1
4	4	0	0	—	1	2
5	1	2	0	5	—	1
6	0	2	0	2	10	—

n = 7

	1	2	3	4	5	6	7
1	—	1	2	3	2	3	4
2	5	—	1	2	1	2	3
3	2	3	—	1	2	1	2
4	4	0	1	—	3	2	1
5	1	2	0	5	—	1	2
6	0	2	2	2	10	—	1
7	0	2	5	2	0	5	—

n = 8

	1	2	3	4	5	6	7	8
1	—	1	2	3	1	2	3	4
2	5	—	1	2	2	1	2	3
3	2	3	—	1	3	2	1	2
4	4	0	0	—	4	3	2	1
5	1	2	0	5	—	1	2	3
6	0	2	0	2	10	—	1	2
7	0	2	0	2	0	5	—	1
8	6	0	5	10	0	1	10	—

n = 12

	1	2	3	4	5	6	7	8	9	10	11	12
1	—	1	2	3	1	2	3	4	2	3	4	5
2	5	—	1	2	2	1	2	3	3	2	3	4
3	2	3	—	1	3	2	1	2	4	3	2	3
4	4	0	0	—	4	3	2	1	5	4	3	2
5	1	2	0	5	—	1	2	3	1	2	3	4
6	0	2	0	2	10	—	1	2	2	1	2	3
7	0	2	0	2	0	5	—	1	3	2	1	2
8	6	0	5	10	0	1	10	—	4	3	2	1
9	2	4	5	0	0	1	5	0	—	1	2	3
10	1	5	2	0	5	5	2	0	0	—	1	2
11	1	0	2	5	1	4	3	5	10	5	—	1
12	1	0	2	5	1	0	3	0	10	0	2	—

$n = 15$

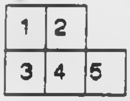
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	—	1	2	3	4	1	2	3	4	5	2	3	4	5	6
2	10	—	1	2	3	2	1	2	3	4	3	2	3	4	5
3	0	1	—	1	2	3	2	1	2	3	4	3	2	3	4
4	5	3	10	—	1	4	3	2	1	2	5	4	3	2	3
5	1	2	2	1	—	5	4	3	2	1	6	5	4	3	2
6	0	2	0	1	3	—	1	2	3	4	1	2	3	4	5
7	1	2	2	5	5	2	—	1	2	3	2	1	2	3	4
8	2	3	5	0	5	2	6	—	1	2	3	2	1	2	3
9	2	2	4	0	5	1	0	5	—	1	4	3	2	1	2
10	2	0	5	2	1	5	1	2	0	—	5	4	3	2	1
11	2	2	2	1	0	0	5	10	10	0	—	1	2	3	4
12	0	0	2	0	3	0	5	0	5	4	5	—	1	2	3
13	4	10	5	2	0	2	5	5	10	0	0	3	—	1	2
14	0	5	5	5	5	5	1	0	0	0	5	3	10	—	1
15	0	0	5	0	5	10	0	0	2	5	0	0	2	4	—

$n = 20$

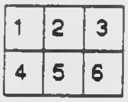
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	—	1	2	3	4	1	2	3	4	5	2	3	4	5	6	3	4	5	6	7
2	0	—	1	2	3	2	1	2	3	4	3	2	3	4	5	4	3	4	5	6
3	5	3	—	1	2	3	2	1	2	3	4	3	2	3	4	5	4	3	4	5
4	0	10	2	—	1	4	3	2	1	2	5	4	3	2	3	6	5	4	3	4
5	5	5	0	1	—	5	4	3	2	1	6	5	4	3	2	7	6	5	4	3
6	2	1	5	0	5	—	1	2	3	4	1	2	3	4	5	2	3	4	5	6
7	10	5	2	5	6	5	—	1	2	3	2	1	2	3	4	3	2	3	4	5
8	3	1	4	2	5	2	0	—	1	2	3	2	1	2	3	4	3	2	3	4
9	1	2	4	1	2	1	0	1	—	1	4	3	2	1	2	5	4	3	2	3
10	5	4	5	0	5	6	0	1	2	—	5	4	3	2	1	6	5	4	3	2
11	5	2	0	10	2	0	5	10	0	5	—	1	2	3	4	1	2	3	4	5
12	5	5	0	2	0	0	10	10	3	5	5	—	1	2	3	2	1	2	3	4
13	0	0	0	2	5	10	2	2	5	0	2	2	—	1	2	3	2	1	2	3
14	0	10	5	0	1	0	2	0	5	5	5	10	2	—	1	4	3	2	1	2
15	5	10	1	2	1	2	5	10	0	1	1	5	2	5	—	5	4	3	2	1
16	4	3	0	1	1	0	1	2	5	0	10	0	1	5	3	—	1	2	3	4
17	4	0	0	5	5	1	2	5	0	0	0	1	0	1	0	0	—	1	2	3
18	0	5	5	2	2	0	1	2	0	5	2	1	0	5	5	0	5	—	1	2
19	0	10	0	5	5	1	0	2	0	5	2	2	0	5	10	2	2	1	—	1
20	1	5	0	5	1	5	10	10	2	2	5	5	5	0	10	0	0	1	6	—

n = 30

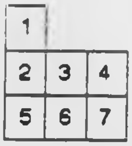
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	—	1	2	3	4	5	1	2	3	4	5	6	2	3	4	5	6	7	3	4	5	6	7	8	4	5	6	7	8	9
2	3	—	1	2	3	4	2	1	2	3	4	5	3	2	3	4	5	6	4	3	4	5	6	7	5	4	5	6	7	8
3	2	4	—	1	2	3	3	2	1	2	3	4	4	3	2	3	4	5	5	4	3	4	5	6	6	5	4	5	6	7
4	0	0	3	—	1	2	4	3	2	1	2	3	5	4	3	2	3	4	6	5	4	3	4	5	7	6	5	4	5	6
5	0	10	4	0	—	1	5	4	3	2	1	2	6	5	4	3	2	3	7	6	5	4	3	4	8	7	6	5	4	5
6	2	4	0	0	5	—	6	5	4	3	2	1	7	6	5	4	3	2	8	7	6	5	4	3	9	8	7	6	5	4
7	10	0	5	0	2	1	—	1	2	3	4	5	1	2	3	4	5	6	2	3	4	5	6	7	3	4	5	6	7	8
8	5	0	5	2	0	2	10	—	1	2	3	4	2	1	2	3	4	5	3	2	3	4	5	6	4	3	4	5	6	7
9	0	2	5	2	0	2	10	1	—	1	2	3	3	2	1	2	3	4	4	3	2	3	4	5	5	4	3	4	5	6
10	5	2	1	0	0	1	5	3	10	—	1	2	4	3	2	1	2	3	5	4	3	2	3	4	6	5	4	3	4	5
11	2	1	4	6	0	4	10	5	2	5	—	1	5	4	3	2	1	2	6	5	4	3	2	3	7	6	5	4	3	4
12	5	0	1	0	2	10	10	0	1	5	0	—	6	5	4	3	2	1	7	6	5	4	3	2	8	7	6	5	4	3
13	0	5	0	2	0	10	6	0	5	6	0	5	—	1	2	3	4	5	1	2	3	4	5	6	2	3	4	5	6	7
14	0	0	4	5	0	2	0	0	2	0	1	5	2	—	1	2	3	4	2	1	2	3	4	5	3	2	3	4	5	6
15	2	0	0	2	0	5	0	2	0	1	2	2	0	2	—	1	2	3	3	2	1	2	3	4	4	3	2	3	4	5
16	0	0	4	5	0	5	10	4	3	5	1	0	4	1	4	—	1	2	4	3	2	1	2	3	5	4	3	2	3	4
17	5	0	0	1	2	0	2	5	0	5	0	0	2	0	5	0	—	1	5	4	3	2	1	2	6	5	4	3	2	3
18	6	2	6	1	1	5	1	2	2	0	2	0	2	5	1	3	2	—	6	5	4	3	2	1	7	6	5	4	3	2
19	3	0	3	1	0	0	10	10	0	5	0	0	1	3	0	0	2	5	—	1	2	3	4	5	1	2	3	4	5	6
20	0	1	2	1	0	0	1	6	0	2	0	2	0	10	1	2	0	1	0	—	1	2	3	4	2	1	2	3	4	5
21	1	6	5	2	2	0	5	0	4	3	0	0	6	0	0	2	0	2	5	5	—	1	2	3	3	2	1	2	3	4
22	10	1	5	2	0	10	5	5	0	5	6	4	2	0	5	0	0	10	5	2	4	—	1	2	4	3	2	1	2	3
23	0	0	2	4	5	0	2	5	5	0	6	5	1	4	0	2	6	10	1	1	0	5	—	1	5	4	3	2	1	2
24	10	1	1	0	1	0	3	2	2	5	0	10	5	2	2	0	5	4	0	3	1	0	0	—	6	5	4	3	2	1
25	2	2	0	2	0	0	5	5	0	2	4	1	5	0	0	5	3	0	5	1	0	4	4	5	—	1	2	3	4	5
26	1	2	0	0	2	4	0	0	5	10	5	0	0	0	0	0	5	0	2	5	0	4	4	5	1	—	1	2	3	4
27	1	5	3	2	1	0	2	5	2	10	3	0	0	4	5	5	0	5	1	6	0	5	1	0	0	0	—	1	2	3
28	1	1	1	2	0	10	0	5	2	1	2	0	1	2	1	2	0	0	2	5	5	0	0	1	10	0	0	—	1	2
29	0	10	0	5	2	1	1	0	5	5	2	0	5	5	1	5	5	0	10	5	0	2	2	0	1	0	0	2	—	1
30	1	5	2	5	1	1	3	2	2	2	10	1	5	5	0	10	1	0	10	3	0	5	2	0	0	0	10	2	2	—



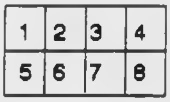
Five-Department Plant



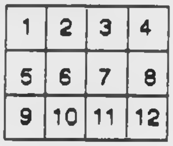
Six-Department Plant



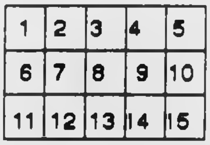
Seven-Department Plant



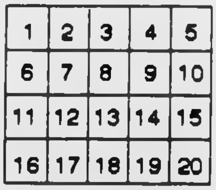
Eight-Department Plant



Twelve-Department Plant



Fifteen-Department Plant



Twenty-Department Plant

Thirty-Department Plant

APPENDIX (D)

ILG SOLUTION ASSIGNMENTS TO THE NUGENT'S PROBLEMS

The numbers in the ILG solution column represent the number of departments assigned to locations shown in page C-5 of appendix (C).

Problem No.	No. of Depts.	ILG Solution Assignment					
1	5	4	1				
		5	2	3			
2	6	5	4	3			
		6	1	2			
3	7	3					
		7	2	1			
		6	5	4			
4	8	1	8	4	3		
		2	7	6	5		
5	12	2	3	11	9		
		1	8	4	12		
		10	7	6	5		
6	15	10	6	14	5	12	
		3	15	13	9	11	
		4	1	2	7	8	
7	20	9	18	19	5	17	
		3	14	2	15	4	
		6	10	12	8	11	
		13	1	7	20	16	
8	30	21	9	27	2	5	25
		13	10	8	29	16	4
		6	12	7	19	30	11
		22	24	1	18	23	17
		28	26	20	3	14	15

APPENDIX (E)

INITIAL SOLUTIONS FOR NUGENT'S PROBLEMS

The Department numbers given in this appendix indicate the assignment of departments to locations. The numbers are given in accordance with Nugent and in the order of locations 1,2,....,n. Location numbers follow the sequence of left to right, top to bottom.

Problem No.	No. of Dept.s	Random Initial Solutions
1	5	1. 1,2,3,4,5. 2. 2,1,3,4,5. 3. 1,4,5,2,3. 4. 1,3,2,5,4. 5. 5,3,1,4,2.
2	6	1. 1,2,3,4,5,6. 2. 2,1,3,4,6,5. 3. 6,2,5,3,1,4. 4. 4,5,3,1,2,6. 5. 1,2,5,3,6,4.
3	7	1. 1,2,3,4,5,6,7. 2. 5,4,7,2,3,1,6. 3. 5,1,3,4,2,7,6. 4. 2,7,1,5,6,4,3. 5. 4,2,3,7,5,6,1.
4	8	1. 1,2,3,4,5,6,7,8. 2. 2,4,6,8,1,7,5,3. 3. 4,1,6,7,3,8,5,2. 4. 5,6,3,1,8,7,2,4. 5. 3,8,1,6,2,7,5,4.

Problem No.	No. of Dept.s	Random Initial Solutions
5	12	1. 2,12,10,7,9,4, 3,8,1,6,5,11. 2. 2,7,3,6,12,9 8,5,10,4,1,11. 3. 8,11,5,3,2,4 12,10,9,1,6,7. 4. 5,11,2,1,4,10 12,6,9,3,8,7. 5. 1,5,3,9,4,8 7,12,11,10,6,2.
6	15	1. 1,11,8,9,10, 15,3,13,14,4, 6,2,7,5,12. 2. 12,14,10,13,8, 1,9,7,4,5, 2,6,11,3,15. 3. 1,4,6,15,11, 13,8,14,10,12, 7,3,9,2,5. 4. 9,1,3,7,2, 13,14,12,4,8, 5,11,6,15,10. 5. 6,14,12,9,2, 5,11,15,4,10, 3,13,7,8,1.
7	20	1. 1,2,3,4,5, 6,7,8,9,10, 11,12,13,14,15, 16,17,18,19,20. 2. 18,13,19,7,4, 15,1,20,11,3, 16,14,5,2,12, 10,6,9,8,17.

Problem No.	No. of Dept.s	Random Initial Solutions
7	20	3. 6,10,1,16,20, 13,8,17,18,14, 3,19,15,9,5, 2,7,12,11,4.
		4. 13,14,18,3,4, 8,17,9,7,16, 10,6,20,11,15, 19,2,12,5,1.
		5. 4,5,15,20,12, 10,9,8,1,7, 19,11,16,13,2, 3,17,18,6,14.
8	30	1. 1,2,3,4,5,6, 7,8,9,10,11,12, 13,14,15,16,17,18, 19,20,21,22,23,24, 25,26,27,28,29,30.
		2. 15,25,4,8,22,21, 11,26,10,13,16,12, 14,29,20,24,18,3, 23,17,1,28,27,6, 9,19,30,7,5,2.
		3. 28,5,1,8,3,11, 24,7,22,12,20,18, 14,29,16,13,19,26, 27,21,4,15,25,2, 9,10,6,30,23,17.
		4. 11,28,25,1,15,26, 9,21,4,23,8,22, 5,29,19,17,10,3, 27,14,20,30,12,18, 2,6,13,16,7,24.
		5. 13,20,22,24,19,17, 18,16,23,21,10,14, 8,12,7,27,25,9, 4,30,28,26,5,11, 2,1,6,15,29,3.

APPENDIX (F)

UPDATED FROM - TO FLOW MATRICES OF THE REMAINING FOUR TIME INTERVALS OF THE EXAMPLE PROBLEM IN CHAPTER SIX.

	From	1	2	3	4	5	6
To	1	0	175	804	904	56	176
	2	63	0	743	936	45	177
	3	168	85	0	918	138	134
t_2	4	51	94	962	0	173	39
	5	97	104	730	634	0	144
	6	95	115	983	597	24	0

		1	2	3	4	5	6
	1	0	45	39	277	385	70
	2	84	0	57	327	263	93
	3	16	18	0	332	449	44
t_3	4	14	83	21	0	480	90
	5	93	28	22	463	0	52
	6	36	64	87	367	344	0

		1	2	3	4	5	6
	1	0	12	2	22	74	72
	2	17	0	13	19	101	75
	3	1	3	0	20	95	60
t_4	4	3	8	2	0	61	83
	5	22	8	5	3	0	84
	6	7	12	19	10	104	0

		1	2	3	4	5	6
	1	0	10	0	2	2	1
	2	13	0	0	2	2	1
	3	13	10	0	2	1	1
t_5	4	13	9	2	0	1	2
	5	14	8	1	1	0	3
	6	10	11	3	0	2	0

		1	2	3	4	5	6
	1	0	0	1	1	0	0
	2	0	0	1	2	0	0
	3	0	0	0	1	0	0
t_6	4	0	0	1	0	0	0
	5	0	0	1	1	0	0
	6	0	0	1	1	0	0

	From	1	2	3	4	5	6
To	1	0	90	77	553	769	139
	2	168	0	114	653	525	185
	3	32	35	0	664	898	87
t_3	4	27	166	42	0	960	179
	5	185	56	44	926	0	104
	6	72	128	173	634	687	0

		1	2	3	4	5	6
	1	0	56	8	100	333	325
	2	72	0	83	87	456	336
	3	5	14	0	91	428	271
t_4	4	15	35	8	0	276	376
	5	94	36	21	12	0	379
	6	31	55	85	45	478	0

		1	2	3	4	5	6
	1	0	74	3	14	13	6
	2	91	0	1	11	16	7
	3	91	72	0	15	9	10
t_5	4	91	63	21	0	0	17
	5	102	57	6	4	0	20
	6	68	81	20	1	11	0

		1	2	3	4	5	6
	1	0	1	9	9	2	2
	2	1	0	10	15	1	3
	3	2	1	0	9	2	1
t_6	4	1	3	10	0	1	1
	5	2	3	9	9	0	3
	6	2	0	10	10	3	0

		1	2	3	4	5	6
	1	0	0	1	1	0	0
	2	0	0	1	1	0	0
	3	0	0	0	1	0	0
t_7	4	0	0	2	0	0	0
	5	0	0	1	1	0	0
	6	0	0	2	1	0	0

To \ From		1	2	3	4	5	6
t_4	1	0	112	15	199	665	649
	2	153	0	116	173	912	671
	3	10	28	0	182	855	542
	4	29	69	15	0	552	751
	5	198	71	42	24	0	758
	6	62	109	170	90	973	0

		1	2	3	4	5	6
t_5	1	0	332	12	64	60	25
	2	410	0	3	49	71	33
	3	411	325	0	69	39	46
	4	413	285	75	0	47	76
	5	458	258	27	18	0	89
	6	307	365	89	5	55	0

		1	2	3	4	5	6
t_6	1	0	7	67	61	13	15
	2	7	0	71	105	6	21
	3	12	8	0	63	15	6
	4	7	21	69	0	9	10
	5	18	19	67	66	0	20
	6	17	1	74	68	19	0

		1	2	3	4	5	6
t_7	1	0	3	13	14	1	3
	2	1	0	12	15	1	3
	3	3	1	0	14	2	2
	4	1	1	15	0	3	1
	5	2	2	11	10	0	2
	6	1	2	15	9	0	0

		1	2	3	4	5	6
t_8	1	0	0	0	1	1	0
	2	0	0	0	1	1	0
	3	0	0	0	1	1	0
	4	0	0	0	0	2	0
	5	0	0	0	1	0	0
	6	0	0	0	1	1	0

	To \ From	1	2	3	4	5	6
	1	0	663	23	128	119	50
	2	820	0	5	98	141	66
	3	822	650	0	137	78	91
t_5	4	826	570	149	0	93	151
	5	915	515	53	35	0	177
	6	614	729	178	10	99	0

		1	2	3	4	5	6
	1	0	32	303	276	58	68
	2	32	0	318	471	25	96
	3	52	36	0	285	68	28
t_6	4	33	97	311	0	39	45
	5	81	87	304	296	0	90
	6	76	7	334	306	88	0

		1	2	3	4	5	6
	1	0	19	89	100	6	20
	2	7	0	83	104	5	20
	3	19	9	0	102	15	15
t_7	4	6	10	107	0	19	4
	5	11	12	81	70	0	16
	6	11	13	109	66	3	0

		1	2	3	4	5	6
	1	0	1	1	9	12	2
	2	3	0	2	10	8	3
	3	1	1	0	10	14	1
t_8	4	0	3	1	0	15	3
	5	3	1	1	14	0	2
	6	1	2	3	10	11	0

		1	2	3	4	5	6
	1	0	0	0	0	1	1
	2	0	0	0	0	1	1
	3	0	0	0	0	1	1
t_9	4	0	0	0	0	1	1
	5	0	0	0	0	0	1
	6	0	0	0	0	2	0

APPENDIX (G)

COMPARISON OF MATERIL FLOW COSTS RESULTING FROM SOLUTIONS PRODUCED BY CRAFT STARTING WITH RANDOM AND ILG GENERATED INITIAL LAYOUTS

I.R.S = Initial Random Solution
I.R.L.C = Initial Random Layout Cost

	No. of Depts.	I.R.S. No.	I.R.L.C	Final CRAFT Cost	ILG Cost	ILG+CRAFT Cost
	5	1	33	29	25	25
		2	29	29		
		3	36	26		
		4	34	29		
		5	41	26		
Average Cost				27.8		
% Improvement by ILG over average cost					10	10
	6	1	43	43	47	47
		2	55	43		
		3	54	46		
		4	58	46		
		5	58	46		
Average Cost				44.8		
% Improvement by ILG over average cost					-4.6	-4.6

	No. of Depts.	I.R.S. No.	I.R.L.C	Final CRAFT Cost	ILG Cost	ILG+CRAFT Cost
	7	1	87	78	74	74
		2	120	78		
		3	108	78		
		4	114	84		
		5	101	79		
Average Cost				79.4		
% Improvement by ILG over average cost					6.8	6.8
	8	1	136	120	116	116
		2	161	112		
		3	145	110		
		4	160	112		
		5	144	109		
Average Cost				112.6		
% Improvement by ILG over average cost					-2.9	-2.9

	No. of Depts.	I.R.S. No.	I.R.L.C	Final CRAFT Cost	ILG Cost	ILG+CRAFT Cost
	12	1	392	306	317	315
		2	392	302		
		3	437	328		
		4	425	295		
		5	373	296		
Average Cost				305.4		
% Improvement by ILG over average cost					-3.6	-3
	15	1	724	590	606	583
		2	806	608		
		3	798	593		
		4	805	605		
		5	813	604		
Average Cost				600		
% Improvement by ILG over average cost					-1	2.8

	No. of Depts.	I.R.S. No.	I.R.L.C	Final CRAFT Cost	ILG Cost	ILG+CRAFT Cost
	20	1	1722	1319	1362	1317
		2	1651	1326		
		3	1770	1334		
		4	1728	1344		
		5	1661	1386		
Average Cost				1341.8		
% Improvement by ILG over average cost					-1.5	1.1
	30	1	4030	3128	3455	3184
		2	3879	3150		
		3	4086	3209		
		4	3824	3176		
		5	4112	3192		
Average Cost				3171		
% Improvement by ILG over average cost					-8.2	-0.4

APPENDIX (H)

DIFFERENCES OBSERVED IN RANDOM SOLUTION COSTS TO THE NUGENT'S PROBLEM REPORTED IN THE LITERATURE AND OBTAINED BY MICRO-CRAFT

Number of departments	Starting random solution	Reported cost	Observed Cost
5	3	25	26
6	4	43	46
7	1	79	78
	3	74	78
	5	83	79
8	1	119	120
	2	107	112
	3	124	110
	4	110	112
	5	107	109
12	1	298	306
	2	308	302
	3	291	328
	5	289	296
15	1	628	590
	2	588	608
	3	591	593
	4	640	605
	5	583	604
20	1	1334	1319
	2	1354	1326
	3	1351	1334
	4	1324	1344
	5	1332	1386
30	1	3161	3128
	2	3169	3150
	3	3197	3209
	4	3273	3176
	5	3148	3192

TITLE: A NON-DETERMINISTIC APPROACH TO DYNAMIC LAYOUT PLANNING OF FLEXIBLE MANUFACTURING SYSTEMS.

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