UNIDIRECTIONAL LOOP NEWTORK LAYOUT PROBLEM IN FLEXIBLE MANUFACTARING SYSTEMS

A THESIS
SUBMITTED TO THE DEPARTMENT OF INDUSTRIAL
ENGINEERING
AND THE INSTITUTE OF ENGINEERING AND SCIENCES
OF BILKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

By
Canan Bilen
August, 1993

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Barbaros C. Tansel

Assoc. Prof. Barbaros Tansel (Advisor)

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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Prof. Mehmet Baray
Director of the Institute

ABSTRACT

UNIDIRECTIONAL LOOP NETWORK LAYOUT PROBLEM IN FLEXIBLE MANUFACTURING SYSTEMS

Canan Bilen
M.S. in Industrial Engineering
Advisor: Assoc. Prof. Barbaros Tansel
August, 1993

Unidirectional Loop Networks are the most common architecture in FMSs. This is partly due to lower implementation costs of unidirectional loop networks. But mainly it is the higher flexibility unidirectional loop networks provide that makes then more common.

In this thesis we are interested in the arrangement of machines in a unidirectional loop network. Our objective is to determine an assignment of machines yielding the minimum cost defined as the sum of products of the parts moving between machines and the distances moved. We give our formulation of the problem and propose two heuristics; Positional Move Heuristic and Positional Move-Pairwise Interchange Heuristic. The computational effectiveness of these heuristics is compared with other existing heuristics from the literature.

Keywords: Flexible Manufacturing Systems, Unidirectional Loop Network Layout Problem

ÖZET

ESNEK ÜRETİM SİSTEMLERİNDE TEK YÖNLÜ DÖNGÜ SERİM MAKİNA YERLEŞTİRME PROBLEMİ

Canan Bilen
Endüstri Mühendisliği, Yüksek Lisans
Danışman: Doç. Dr. Barbaros Tansel
Ağustos, 1993

Tek Yönlü Döngü Serim Esnek Üretim Sistemlerinde en yaygın yapıdır. Bu, uygulama maliyetlerinin düşük olmasına bağlanabilir. Fakat Tek Yönlü Döngü Serimlerinin yaygın olmasının asıl sebebi, bu serimlerin sağladığı yüksek esnekliktir.

Bu tez çalışmasında Tek Yönlü Döngü Serimlerinde makina yerleştirme problemi ele alınmıştır. Yerleştirme yapılırken, makinalar arası parça akımı çarpı katedilen mesafelerin toplamı olarak tanımladığımız maliyetin en düşük düzeyde tutulması hedeflenmiştir. Problemin formulasyonu tezde verilmiştir. Tek Yönlü Döngü Serimlerinde Makina Yerleştirme Probleminin çözümü için iki sezgisel yöntem önerilmiştir; Pozisyonal Hareket ve Pozisyonal Hareket-Çiftler Arası Değişim Sezgisel Yöntemleri. Bu sezgisel yöntemlerin sayısal başarısı literatürde mevcut diğer sezgisel yöntemlerle karşılaştırılmıştır.

Anahtar Sözcükler: Esnek Üretim Sistemleri, Tek Yönlü Döngü Serimleri

To those few who really know me...

ACKNOWLEDGEMENTS

This thesis would not have met with success without the generous support of my advisor, Assoc. Prof. Barbaros Tansel. I would like to thank him for his motivating and challenging assistance.

In addition my gratitude is warmly extended to Lütfiye Yener, for her devoted friendship.

Chapter 1

Introduction

Design of the physical layout of any system, especially of Flexible Manufacturing Systems (FMSs), is of particular importance. Layout related costs are not only observed during the implementation but also during the operation of the system. Expensive hardware used and the flexibility is what makes the design of the layout in an FMS environment a major undertaking.

Typically, the type of automated material handling device used determines the layout structure in FMSs. Basically five layout types are reported in FMS layout literature: unidirectional loop network layout, circular machine layout, single row machine layout, double row machine layout, and the cluster machine layout.

Unidirectional loop networks are the most common architecture in FMSs. This is partly due to lower implementation costs of unidirectional loop networks. But mainly it is the higher flexibility unidirectional loop networks provide that makes them more common.

In this thesis we are interested in the arrangement of machines in a unidirectional loop network. Our objective is to determine an assignment of machines yielding the minimum cost defined as the sum of product of the number of parts moving between machines and the distances moved. We give our formulation of the problem. Our assumptions are primarily based on the research results on unidirectional loop network problem.

We propose two heuristics: Positional Move Heuristic and Positional Move-Pairswise Interchange Heuristic for the problem.

The organization of the thesis is as follows:

- Chapter 2 gives a general literature review about the flexible manufacturing systems layout. Basic properties of the flexible manufacturing systems are discussed. The existing literature is reviewed under the topics, Quadratic Assignment Problem and the FMS Layout Problem, Graph Theoretic Modelling Approaches, Special FMS Layout Structures, Queing Aspects of the Layout Decisions, FMS Layout Problem and the Intelligent Heuristics, Dynamic Aspects of the FMS Layout Decisions
- Chapter 3 gives existing research results on the Unidirectional Loop Network Layout Problem under the topics equidistance layouts, nonequidistance conserved flow layouts, and nonequidistance nonconserved flow layouts.
- Chapter 4 gives the statement and the formulation of the problem. Assumptions underlying the formulation are presented. Proposed heuristic procedures are described. Other developed heuristics from the literature are discussed.
- Chapter 5 discusses the computational results of the proposed heuristics.
- Chapter 6 concludes the thesis and discusses the contribution of our proposed heuristic.

Chapter 2

FMS Layout Problem

Recent Research Results

2.1 Flexible Manufacturing Systems

We will give a concise review of Flexible Manufacturing Systems. For more information refer to Groover 1980, O'Grady and Menon 1986, Huang and Chen 1986, Nisanci 1985, and Warnecke 1985.

A Flexible Manufacturing System (FMS) is an automated manufacturing system consisting of a group of processing stations connected together by an automated material handling system (MHS). It operates as an integrated system under a central computer control. FMSs are equipped with rather sophisticated flexible machine tools which are capable of processing a sequence of different part types with negligible tool change times.

The parts are loaded and unloaded at a central location in the FMS. Pallets are used to transfer parts between machines. Once a part is loaded on the handling sytem it is automatically routed to the particular machines required for its processing. For each different part type, the routing may be different, and the operations required at each machine may be different too. The coordination of the parts, handling, and processing activities are accomplished under the command of a central computer.

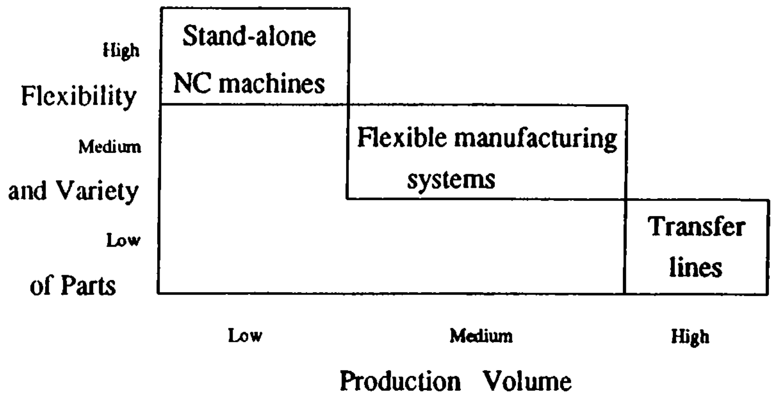

Figure 2.1. Application characteristics of the FMSs

Transfer lines have been traditionally used for machining a single product in high quantities. In a transfer line, machines are arranged in a straight line flow pattern and parts are automatically transferred from machine to machine in a sequence. Transfer lines are very efficient when producing parts in large volumes at high output rates. The highly mechanized lines are inflexible and cannot tolerate variations in part type design. A change over in part type design requires the line to be shut down and retooled. On the other hand, stand-alone NC (Numerical Control) machines are ideally suited for variations in work part configurations. Numerically controlled machine tools are appropriate for jobshop and small batch manufacturing because they can be conveniently reprogrammed to deal with product changeovers and part design changes. In terms of manufacturing efficiency and productivity, a gap exists between the high production rate transfer lines and the higly flexible NC machines. FMSs are designed to fill this gap. Production of mid range, mid variety parts, with the efficiency of mass production and the flexibility of jobshops is what FMSs provide.

2.2 FMS Layout Problem

The layout problem of interest in this thesis is concerned with the selection of the locations for M stations from M (or more) candidate alternative locations in order to satisfy the throughput requirements of the system.

Design problems have been strategically critical in any system operation. Optimal design of the physical layout is one of the most important issues that must be resolved in early stages of the system design. Cost consequences of the decisions related to the layout of the machines can be observed not only during the implementation but also during the operation of the system. Layout of a system affects:

- required initial investment,
- amount of in process inventory,
- production lead time,
- production rate,
- material handling costs,
- complexity of the operational control algorithms.

Tompkins and White 1984 emphasized the importance of layout decisions for effective material handling by pointing out that 20 to 50 percent of the total operating expenses in manufacturing are attributed to material handling and layout related costs.

According to Kouvelis, Kiran, and Chiang 1991 and Kouvelis, Chiang and Kiran 1992 FMS layout is more complicated and more important than the layout of conventional manufacturing systems for the following reasons:

- Alternative (flexible) routing: In an FMS environment machines are able to perform different operations when properly tooled. Tool change times are negligible. Material handling system allows part movement between any pair of machines while bypassing some machines. These characteristics of the FMS generate a large set of alternative manufacturing routes for each part produced, which adds complexity to the manufacturing environment.
- Expensive hardware used for material handling processing and handling: Implementation of FMSs require huge capital investments. Advanced MHSs (Material Handling Systems) used are expensive not only in terms

of acquisition but also operating costs. Hence, any subutilization caused through inefficient layout designs impose significant cost penalties.

- FMS stations are tightly linked: In FMSs parts are stored at local buffers when waiting for processing. These buffers have limited capacity, usually 1 to 2 parts. This limitation increases machine interdepencies, requiring better layout designs.

- Topological constraints on the arrangement of the machines: In FMSs different material handling systems favor different architectures. This puts an additional complexity on the FMS layout since machine location determination and material handling system selection must be done simultaneously.

- High uncertainty and fluctuations in the quantities of parts to be produced: FMSs are designed to handle changes both in the type and the volume of parts produced. Design of the FMS layout should also consider possible future launches of new part types and changes in the volumes of the parts produced.

Cost elements that are relevant to the FMS layout decisions can be divided into following parts:

- Locational Cost: Fixed cost associated with assigning a particular machine to a candidate location.

- Material Handling Cost: A weighted sum of the travelling distances of different part types in the system, with weights being the estimated flows between pairs of machines.

- Work In Process (WIP) Cost: The cost of maintaining a certain population of part types in the manufacturing system in order to achieve a desirable throughput rate. Costs of pallets and fixtures used for transportation of the parts should also be included.

2.3 Recent Research Results

A review of papers related or applicable to FMS layout problems will be given next. Research results are classified into the following topics:

- The Quadratic Assignment Problem and FMS Layout Problem
- Graph Theoretic Modelling Approaches to FMS Layout Problem
- Special FMS Layout Structures
- Queuing Aspects of FMS Layout Decisions
- FMS Layout Problem and Intelligent Heuristics
- Dynamic Aspects of FMS Layout Decisions
- Robustness Approach to FMS Layout Problem
- FMS Layout Problem Related Topics

2.3.1 The Quadratic Assignment Problem and FMS Layout

In general, the layout problem for conventional manufacturing systems has been formulated as a quadratic assignment problem (QAP).

Koopmans and Beckman 1957 were the first to model the problem of locating plants with material flow between them. They modeled the the problem as a QAP. The name was so given because the objective of QAP is a second degree function of the variables and the constraints are linear fuctions of the variables.

Gilmore 1963 and Lawler 1963 developed optimal procedures to solve the QAP formulations under the objective of minimizing the total material handling costs. Due to computational complexity of QAP, these optimal procedures are efficient for small sized problems.

Sarin and Wilhelm 1984 showed that the QAP is NP-Complete. This led researchers to concentrate on heuristic algorithms for solving QAPs. Surveys of approximate algorithms for QAP can be found in Burkard and Stratman 1978, Nugent, Vollman, and Ruml 1968, and of exact algorithms in Burkard 1984 and Pierce and Crowstone 1971.

There exist some special cases of QAPs which are polynomially solvable (Christofides and Gerrard 1976). Polynomially solvable cases of FMS layout problems are presented in Bozer and Rim 1989, Kiran and Karabati 1988, Kouvelis and Kiran 1989, and Kouvelis and Kim 1992. These papers will be rewieved further in Chapter3.

Heragu and Kusiak 1988 and Kusiak and Heragu 1987 raise questions regarding the applicability of the QAP formulations for FMS implementations. In FMSs, machines are generally not equal sized. Since the clearence between machines tends to be constant, distance between locations depends on the sequence of the machines. This violates the assumption in QAP formulations; that is candidate location distances are independent of station sequence. For such cases, the appropriate formulation of the FMS layout problem is a quadratic set covering problem (QSP). A discussion of QSP and FMS layout problem can be found in Kusiak and Heragu 1987.

2.3.2 Graph Theoretic Modelling Approaches

Afentakis 1986 developed a graph theoretic formulation of the static FMS layout problem. He classifies the problem as NP-Complete, and proposes heuristic algorithms.

The formulation (as discussed in Kouvelis 1992) relies on the following assumptions:

- unidirectional material handling system (MHS) with bypassing of certain machines permitted,
- an operation can be performed only on a particular machine.

The author models the MHS using the notion of a layout graph $L(M,T)$, where the node set M represents the set of machines, and the arc set T represents the material handling system links. If the part mix and the routing problem have been solved, and operations have been assigned to workstations, then one can proceed to the definition of a part transition graph $G_i(M, E_i)$, where E_i = set of arcs with $(j, k) \in E_i$ if part i must go from workstation j to workstation k. There is a weight associated with each link $(j, k) \in E_i$ which represents the number of parts moving along link (j, k). Call $G(M, E)$ the graph obtained by superpositioning of the part transition graphs for all parts, after removing all but one arc from each set of parallel arcs. Then, the graph theoretic formulation of the FMS layout problem is:

Find the layout graph L with the following properties:

- the graph L has the same nodes as G,
- if $(i, j) \in G$, then there is exactly one path from i to j in L,
- the sum of the weights associated with links (i, j) is minimized.

2.3.3 Special FMS Layout Structures

Analysis of existing FMSs show that the layout is determined by the type of material handling system being used. Heragu and Kusiak 1988 and Afentakis 1986 report the specific layout types that are implemented in an FMS environment. These are:

- unidirectional loop network layout,
- circular machine layout,
- linear single row machine layout,
- linear double row machine layout, and
- cluster machine layout.

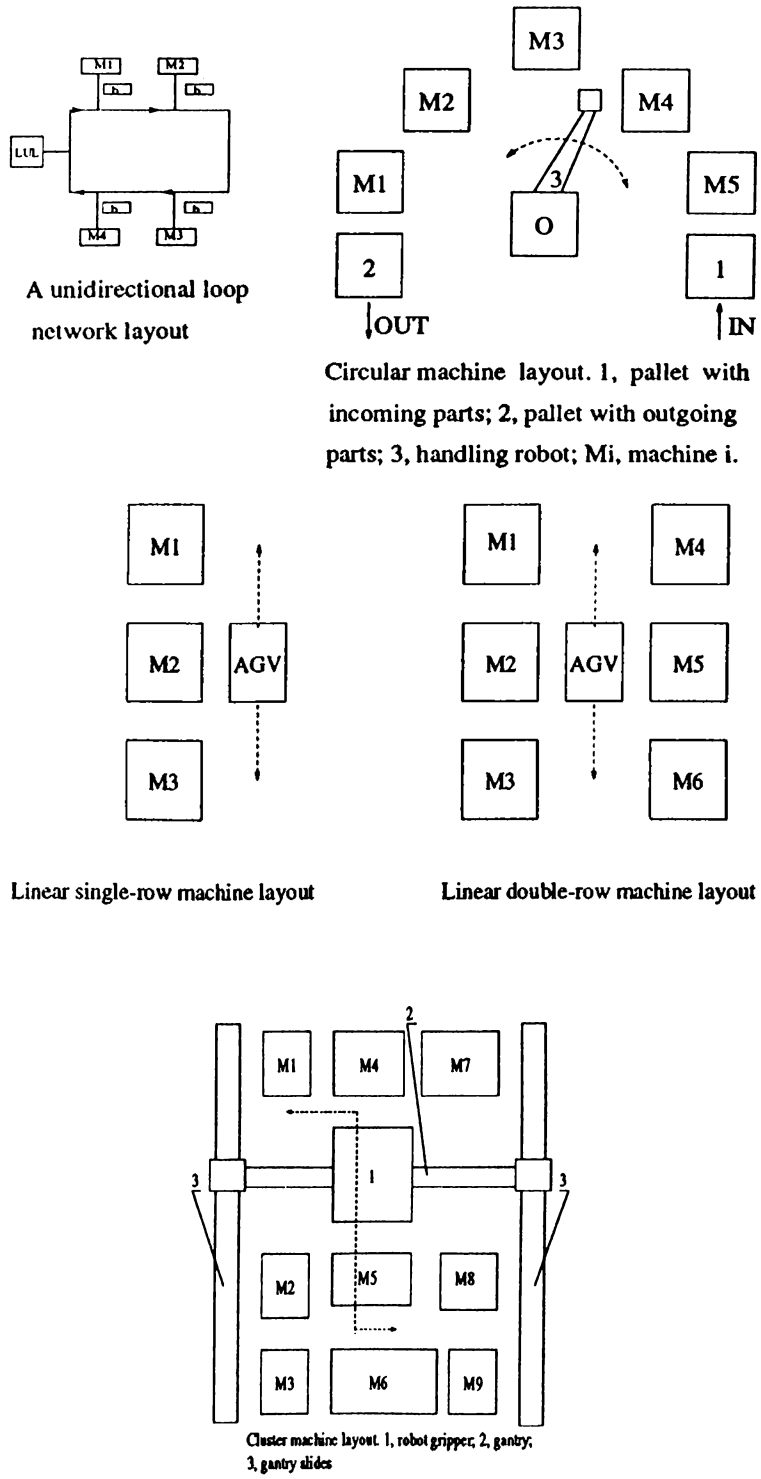

Figure 2.2. Machine Layout Configurations in FMSs

Each of the above layout types is more appropriate for a specific MHS device. The unidirectional loop network layout is suited for unicyclic conveyors, while the circular machine layout is usually served by a handling robot. Automatic guided vehicles (AGVs) serve efficiently the single row and the double row machine layouts. Due to space limitations, cluster machine layouts are served by gantry robots.

Recently researchers focused on developing solution methods for these specific layout types.

Unidirectional loop network layouts (ULNLs) have been investigated by; Kiran and Karabati 1988, Kouvelis and Kim 1992, and Bozer and Rim 1989. We defer our discussion on ULNLs to Chapter3.

Sarker et. al. 1990 consider the backtracking problem for a generalized flow line (GFL). A GFL is a serial line in which a job does not neces sarily visit all of the stations in the line. According to its sequence of operations, a job may begin production at any machine and complete process ing at any machine downstream. When the sequence of operation for a given job does not specify a machine located downstream of its current location, th e job has to travel to the left in order to complete the required operation. This reverse travel is termed backtracking, and locating the workstations along a line to minimize the flow of materials in the backward direction is called the backtracking problem. The problem is formulated as a QAP. Depth-first insertion heuristic (DIH) is introduced for its solution. The objective of the heuristic is to search for an assignment that minimizes the total backtracking steps, so the procedure relocates machine(s) to reduce backtracking. For a given assignment, total backtracking distance incurred by all jobs in going from one machine to all other possible machines are obtained from the backtracking matrix. Location of the machine with the largest such distance is changed to all other possible locations. For each possible case the backtracking distance is computed. If any of the new generated assignments result in a lower backtracking distance, then location of the stations are changed according to that assignment. The procedure is continued until an improvement can not be accomplished.

Heragu and Kusiak 1988 give a way to calculate the frequency of trips between two machines from the volume of each part to be carried from one machine to another station, total number of different part types to be carried, and the number of units of a part that can be carried in a single trip. They argue that travel time is a better measure of closeness for an FMS than the travel distance and use the adjusted flow matrix for assigning machines to locations. Adjusted flow matrix is obtained by multiplying the frequency of trips for machine pairs with the time required to travel between these machines. Two heuristics are presented to determine the machine layout. The first heuristic works like a maximum spanning tree algorithm. It generates the sequence in which machines are placed in the layout. The actual layout depends on the material handling devices, the required clearence between the machines and their orientation. The heuristic is for the circular machine layout if a handling robot is used for material handling, and for the single row machine layout if AGVs are used for material handling. This heuristic provides optimal results when the number of machines is less than four. The second heuristic, called the triangle assignment algorithm, is for the arrangement of machines in linear double row and cluster machine layout s. Triangle assignment algorithm consists of two phases. In the first phase of the algorithm triangles with the maximum sum of adjusted flow values in the ir corresponding edges are generated. In the second phase machines are assigned to locations according to the generated triangles in the first phase. Authors report that the developed heuristics require a very low CPU time when compared with other algorithms, initial solutions are not required and that the CPU time requirement for equal and unequal sized machines is almost the same. They point out that in an FMS environment part mixes are subject to changes resulting in an inaccurate flow data. In such cases it is not worthwhile to use methods that produce good solutions in a significantly high computation time.

Heragu 1992 developed models for the single row layout and the multi row layout. The first model, referred to as ABSMODEL for the single row layout problem, assumes that machines are to be arranged along a straight line and to be oriented in only one given direction. Machines can have square or rectangular shapes. The shape and dimensions of the building in which the machines are to be located are not considered. The objective of the formulation is to minimize the total cost involved in making the required trips between the machines. This model can be converted into linear mixed integer and nonlinear models. For the multi row layout problem two formulations are presented. One formulation is for the equal area machines and the other formulation is for unequal area machines. In fact, equal area multi row machine layouts can be formulated as QAP.

Sarin and Wilhelm 1984 presents mathematical programming models for analysis and design of circular layouts for robotic systems. The problems addressed include, determining an optimal set of tasks assigned to a single robot and an appropriate layout of the stations, specification of the number and type of the robots required, and finally organizing a set of robot cells into an efficient system configuration.

2.3.4 Queueing Aspects of Layout Decisions

QAP based formulations, which are static in nature, ignore interactions between the layout decisions and queuing performance measures of an FMS. The significance of such interactions have been demonstrated in Solberg and Nof 1980. CAN-Q model, a central server closed queing network model, is used to explore important factors affecting layout decisions. Four different layout configurations are considered: product layout, cart line, conveyor loop, and process layout. The computational results showed that flow control issues, including the interplay of processing requirements, travel times, part mix and process selection, can yield circumstances favoring any of the four layouts.

2.3.5 FMS Layout Problem and Intelligent Heuristics

Research has also been done in applying new methodological approaches like Simulated Annealing and Tabu Search, which are developed for combinatorial optimization problems.

Simulated Annealing (SA) is an algorithmic approach for the solution of optimization problems. SA, coined from the analogy between statistical mechanics and combinatorial optimization, is a useful method to solve many traditional optimization problems. The research literature on QAPs indicates that the use of Simulated Annealing heuristic algorithm is an efficient way to solve the machine layout problems.

Kouvelis, Chiang, and Fitzsimmos 1992 introduce the layout problem with zoning constraints. Zoning constraints exist when particular machines favored to be located next to each other or when certain machines need not be in close proximity. This problem can not be formulated as a general QAP, since the assumption that any machine can be located at any of the available sites is violated. For this case, a modification of the QAP is developed called Restricted Quadratic Assignment Problem (RQAP). In the formulation, an appropriate cost function is minimized while not violating the zoning constraints. Specialized implementations of the SA procedure to handle the machine layout problem with a general class of zoning constraints have been developed. The first SA algorithm developed by the authors is the compulsion method. This method accounts for the presence of zoning constraints mostly during the search for a new layout in the neighborhood of the original configuration. The second algorithm, the penalty method, accounts for the presence of zoning constraints in the objective function through the use of appropriate penalty terms.

Kouvelis, Kurawarwala, and Robredo 1991 developed an apropriate adaptation of the tabu search heuristic, called the Robust Tabu Search (RTS) procedure, for finding robust layouts for both single and multiple period layout problems. RTS can find many robust layouts even for large size problems, more than 20 machines, in a reasonable computation time.

2.3.6 Dynamic Aspects of Layout Decisions

In situations where product attributes change frequently and these products related changes require process related changes, layout issues need to be adressed in a dynamic structure.

Montreuil and Laforge 1992 discuss three cases for the layout problem:

- If the cost of a relayout is negligible then specific treatment of layout dynamics is not necessary. Layout should be designed according to the near future requirements.
- If relayout costs are prohibitive then treatment of layout dynamics is not necessary. One simply needs to aggregate the requirement sets for all expected futures into a single aggregate requirement set based upon

which the permanent layout is to be designed.

- In all other intermediate steps, i.e. relayout costs are neither totally negligible nor totally prohibitive, then layout dynamics should be considered.

For the last case authors have introduced a dynamic layout design model. The model considers the probabilistic nature of the future requirement sets. The designer is allowed to input a scenario tree of probable futures. For each future, the designer specifies shape requirements for various cells, the intercell interactions, as well as the linearized costs for displacing cells from their location in the previous future to their location in this future. The designer is further required to propose a design skeleton for each possible future. The model generates a layout for each possible future. The resulting layout tree minimizes an objective combining the intercell interaction cost in each future and the interfuture relayout cost. This linear programming model can be solved optimally in a few minutes for medium sized problems. The model when implemented in an interactive layout design environment, permits the designer to investigate multiple design skeletons and scenario trees during a design work session, thus allowing for the generation of a number of robust layouts.

2.3.7 Robustness Approach to FMS Layout Problems

Kouvelis, Kurawarwala, and Gutierrez 1992, inroduce the concept of layout robustness. Robustness of a layout is an indication of flexibility in handling demand changes and is measured by the number of times the layout has a total material handling cost within a prespecified percentage of the optimal solution under different demand scenarios. With such an approach, the designer will select a layout that has the highest frequency of being closest to the optimal under any demand scenario. Being within a few percentage of the optimal is perceived as satisfactory for the layout designer given the level of inaccuracy of the available data during the design phase. For single period layout problems, simple modifications of B&B procedures for the QAP formulations are used to generate the list of robust layouts. For the multi period dynamic layout designs, it is more challenging to generate the sequence of robust layouts. A systematic approach is suggested, which is efficient for medium sized problems.

For multiperiod layouts monuments, machines which are difficult to relocate, are considered.

2.3.8 FMS Related Research

Millen, Solomon, and Afentakis 1992 consider the impact of the number of Load/Unload(LUL) stations in automated manufactucturing systems with unidirectional closed loop material handling equipment. Comparison of material handling costs for two cases, single LUL station, and each procesing station with a LUL station showed that providing flexibility in part entry/exit functions reduce material handling movement. Co and Araar 1988 introduce a procedure for configuring machines into manufacturing cells, and assignning the cells to process specific sets of jobs, for group technology (GT) cells.

Chhajed, Montreuil, and Lowe 1992 formulated the problem of determining optimal flow network for manufacturing systems given the location of stations.

In Chapter3 Unidirectional Loop Network Problem will be studied in depth.

Chapter 3

ULN Layout Problem

Recent Research Results

3.1 Unidirectional Loop Networks

In a unidirectional loop network (ULN) layout, machines are arranged in a loop. All machines are connected by a path passing through each exactly once. Materials are transported in only one direction, e.g. in clockwise direction. These layouts are often served by loop conveyors, tow lines, overhead monorail systems, or wire paths of unidirectional AGVs.

The most commonly used operational strategy for such systems is that parts enter and exit the system at the Load/Unload (LUL) workstation, it proceeds to the next one on its route by moving on the unicyclic material handling network. If the workstation is occupied, the part is stored in a local buffer, waiting for the workstation to become free.

According to Afentakis 1989 ULN layouts are preferred to other configurations due to their relatively lower initial investment costs, since they contain the minimum number of required material links to connect all workstations and possess higher material handling flexibility.

Such configurations are able to satisfy all material handling requirements for the part types scheduled for manufacturing in the system, as there is at least one directed path connecting any pair of workstations. With these layouts future introduction of new part types and process changes are easily accommodated.

Afentakis 1989 state that ULN layouts are extensively implemented due to the wide use of efficient unicylic material handling networks.

Of the 53 FMS in Japan, surveyed by Jaikumar and Wassenhove 1989, ULNLs are the most common architecture.

These systems also have lower operational complexity. According to Gaskins and Tanchoco 1987, bidirectional material handling paths require more sophistiated control and higher installation costs.

3.2 ULN Layout Problem

The Unidirectional Loop Network Layout Problem (ULNLP), is generally formulated as a Quadratic Assignment Problem (QAP), where the objective is to assign each machine to one of the candidate locations, such that an appropriate objective function is minimized.

In formulating the ULNLP two types of objective functions have been used in the literature:

1. Minimizing the total part flows times distances per unit time (Bozer and Rim 1989, Kiran and Karabati 1988, and Kiran, Unal, and Karabati 1992).
2. Minimizing the total number of parts that cross the LUL station per unit time (Afentakis 1989 and Kouvelis and Kim 1992).

Let $W = (w_{ij})$ be the part flow matrix, where $w_{ij} \geq 0$ represents the number of parts moved from machine i to machine j in a given period of time, for $i = 1, \ldots, n, j = 1, \ldots, n$, and $w_{ii} = 0$ for all i.

Let $D = (d_{lk})$ be the location distance matrix, where $d_{lk} > 0$ is the clockwise distance from location l to k, for $l = 1, \ldots, n, j = 1, \ldots, n$ and $d_{ll} = 0$ for all l. One of the most important properties of the ULNLP is that, for any pair of locations l and k, the distance from location l to k and the distance from location k to l sum up to the total loop length, c. That is, $d_{lk} + d_{kl} = c$. Such a matrix is called a circular matrix. Properties of the distance matrix can be summarized as follows:

1. $d_{lk} = 0$ if $l = k$
2. $d_{lk} \leq d_{lr} + d_{rk}$ for distinct $l, r, k = 1, \ldots, n$
3. $d_{lk} + d_{kl} = c$ for distinct $k, l = 1, \ldots, n$
4. $d_{lk} \neq d_{kl}$ if $d_{lk} \neq \frac{1}{2}c$

Define a machine assignment vector $\alpha = (\alpha(1), \ldots, \alpha(n))$, which denotes a layout of n machines, where $\alpha(i)$ denotes the location occupied by machine i.

Then the ULNLP can be stated as that of finding an assignment vector α over the set Π, the set of all permutations of integers $1, \ldots, n$, which minimizes the objective function.

Then under the first objective function, minimizing the total part flows times distances, the ULNL is:

$$\min_{\alpha \in \Pi} Z(\alpha) = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} d_{\alpha(i)\alpha(j)}.$$

Let

$$l(\alpha(i), \alpha(j)) = \begin{cases} 1, & \text{if } \alpha(i) > \alpha(j) \\ 0, & \text{otherwise} \end{cases}$$

be an indicator function. This indicator function will be used to count the number of parts passing through the LUL station. If the location of machine i, denoted by $\alpha(i)$, is greater than the location $\alpha(j)$ of machine j, the parts going from machine i to machine j will pass through the LUL station. In such a case the indicator function will take a value 1 and such parts will be counted.

Then under the second objective function, minimizing the number of parts passing through LUL station, ULNLP is:

$$\min_{\alpha \in \Pi} Z(\alpha) = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} l(\alpha(i), \alpha(j)).$$

In fact, minimization of the total material handling cost, which is sum of flows times distances, is equivalent to the minimization of the number of parts passing through LUL station. Any part entering the sytem will complete an integer number of cycles around the loop as the parts enter and exit the system from the LUL station. Then given α, the product of part flows and distances is:

$$c \left(\sum_{i=1}^{n} w_{0i} + \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} l(\alpha(i), \alpha(j)) \right)$$

where,

w_{0i} = part flow from the LUL station, denoted by 0, to machine i,
c = length of the loop.

The first summation gives the total number of parts to be processed in the system, which is independent of the layout decision. So the first term can be removed from the objective function. Consequently, the two objective functions turn out to be equivalent.

Research Results on the ULNLP can be divided into two parts:

1. Equal Spaced Unidirectional Loop Networks
2. Non-Equal Spaced Unidirectional Loop Networks. Two subclasses arise:
   (a) Conserved Flow Non-Equal Spaced Unidirectional Loop Networks

(b) Non-Conserved Flow Non-Equal Spaced Unidirectional Loop Networks

3. Special Cases of Unidirectional Loop Networks

3.2.1 Equal Spaced Unidirectional Loop Networks

In such layouts, locations are equally spaced around the loop. Generally it is assumed that adjacent locations are unit length apart so that the circumference length of the loop is n (number of locations).

Bozer and Rim 1989 presented an LP relaxation for ULNLP with equal spaced locations. The objective function they consider is the total part flow between machines times the distances.

Their formulation of the problem is as follows:

LP:

$$
\begin{array}{lll}
min \sum_i \sum_{j \neq i} w_{ij} dij & & \\
st & & \\
\sum_{j \neq i} d_{ij} = \frac{n(n-1)}{2} & \text{for all } i & (1) \\
\sum_{i \neq j} d_{ij} = \frac{n(n-1)}{2} & \text{for all } j & (2) \\
d_{ij} + d_{ji} = n & \text{for all distinct } i,j & (3) \\
d_{ij} + d_{jk} \leq d_{ik} + n & \text{for all distinct } i,j,k & (4) \\
d_{ij} + d_{jk} \geq d_{ik} & \text{for all distinct } i,j,k & (5) \\
d_{ij} \geq 0 & \text{for all distinct } i,j & (6)
\end{array}
$$

Constraints (1), (2) and (3) define the properties of the circular distance matrix. Regardless of the sequence of machines, the distances from station i to all other stations and the distance from all other stations to station i add to the same constant:

$$\sum_{j \neq i} d_{ij} = 1 + 2 + \ldots + (n-1) = \frac{n(n-1)}{2}.$$

Since $D = (d_{ij})$ is circular we have

$$d_{ij} + d_{ji} = n.$$

Constraints (4) and (5) are used for precedence relationship of any three machines around the loop. Starting at machine i, either j precedes k ($d_{ij}+d_{jk} = d_{ik}$) or k precedes j ($d_{ij} + d_{jk} = d_{ik} + n$). Then

$$d_{ij} + d_{jk} = (d_{ik} \ OR \ d_{ik} + n).$$

For the LP relaxation,

$$d_{ik} \leq d_{ij} + d_{jk} \leq d_{ik} + n$$

is used.

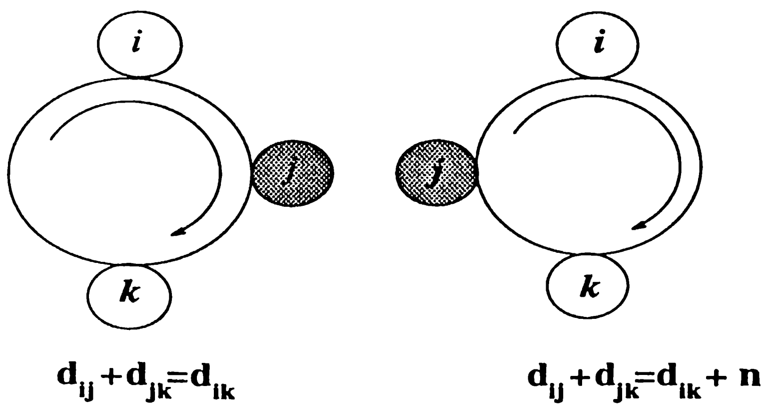

Figure 3.1. Precedence relationships of three machines

Bozer and Rim 1989 arguably proved that LP optimally solves the Equal Spaced ULNLP. Whether or not the proof is correct is yet to be verified.

3.2.2 Conserved Flow Non-Equal Spaced Unidirectional Loop Networks

Part flow is said to be conserved at station k if the total flow entering station k is equal to the total flow leaving station k ($\sum_{i=1}^{n} w_{ik} = \sum_{j=1}^{n} w_{kj}$). A part flow matrix is called a conserved flow matrix if flow is conserved at each machine. (In chapter 4 we will refer to this property as "balanced".)

Flow conservation may not be satisfied at some stations if there are more than one LUL station in the system, or defective parts are moved manually or scrabbed at some of the machines.

Bozer and Rim 1989 and Kiran, Unal and Karabati 1992 showed that when the flow matrix is conserved, distances between adjacent machines do not affect the problem solution. The sequence of stations completely determines the objective function value, regardless of the spacing between locations of machines.

Let $R(i) = \sum_{k=1}^{n} w_{ki}$ be the total inflow of machine i, and $C(i) = \sum_{k=1}^{n} w_{ik}$ be the total outflow of machine i. Consider moving machine i a small distance, $\delta \geq 0$, along the circumference. Objective function value will increase by $\delta R(i)$ units while decreasing by $\delta C(i)$. Since flow is conserved, $R(i) = C(i)$, the above increase and decrease will cancel out each other and the objective function value will not change. The same argument holds if machine i is moved counterclockwise. This result holds for any $\delta > 0$, as long as machine i remains between the two machines j and k that are immediate predecessor and successors of i in the sequence.

Consequently any formulation for the equal spaced ULNL (e.g. of Bozer and Rim 1989) can be used in finding the sequence of the machines for Conserved Flow Non-Equal ULNLPs.

Define a location assignment vector $\beta = (\beta(1), \ldots, \alpha(n))$, which denotes a layout of n machines, where $\beta(i)$ denotes the machine index that is assigned to location i. Observe that, $\alpha(i) = j \iff \beta(j) = i$.

Using the location assignment vector Kiran, Unal, and Karabati 1992 formulated the ULNLP as an equivalent QAP as follows:

$$\min_{\beta\in\Pi} Z(\beta) = \sum_{i=1}^{n}\sum_{i=1}^{n} w_{\beta(i)\beta(j)}d_{ij}.$$

Using the result of conservation of flow at each machine as mentioned above, they developed an integer programming model IP;

IP:

$$\begin{array}{lll}
min \sum_{i=1}^{n} \sum_{j=1, j\neq i}^{n} w_{ij} dij & & \\
st & & \\
\sum_{i=1}^{n} p_{ij} = 1 & \text{for all } j & (1) \\
\sum_{j=1}^{n} p_{ij} = 1 & \text{for all } i & (2) \\
d_{ij} + d_{ji} = 1 & \text{for all distinct } i,j & (3) \\
d_{ij} \leq d_{ik} + d_{kj} + p_{kj} - 1 & \text{for all distinct } i,j,k & (4) \\
d_{ij} \geq 0 & \text{for all distinct } i,j & (5) \\
p_{ij} \in \{0,1\} & \text{for all distinct } i,j & (6)
\end{array}$$

where,

$$p_{ij} = \begin{cases} 1, & \text{if station } j \text{ is immedietly following station } i, \\ 0, & \text{otherwise.} \end{cases}$$

In this formulation, distances are normalized by the cycle length. Therefore the loop lenght is 1 and d_{ij}'s take values between 0 and 1. Constraints (1) and (2) ensure that any machine will have exactly one predecessor and one successor. Constraints (3) and (4) define the properties of the circular distance matrix. Contraint (4) is for the presedence relationships.

Kiran, Unal, and Karabati 1992 report that integer solutions are obtained from IP in all their test problems when the integrality contraints are relaxed.

3.2.3 Non-Conserved Flow Non-Equal Spaced Unidirectional Loop Networks

When the candidate locations are not equally spaced around the loop network and the flow is not conserved at one or more of the machines, the ULNLP is formulated as a QAP. For such cases researchers concentrated on developing heuristic procedures or lower bounds for the problem.

Bozer and Rim 1989 developed a tighter lower bound by modifying the well known Gilmore-Lawler bound. They took adventage of the circularity of the distance matrix.

Kiran and Karabati 1988 introduced an exact solution algorithm with a B&B structure similar to that of Gilmore 1963 and Lawler 1963. Computations of the lower and upper bounds are presented.

If there is a large number of buffer spaces interacting independently with loop network, then these buffer spaces should be treated as separate stations. In such cases, the number of stations increases and the B&B algorithm will not be efficient. Kiran and Karabati 1988 developed a polynomial approximation algorithm based on filtered beam search technique.

Kouvelis and Kim 1992 inroduced Dominance Rules for identifying optimal solutions for the ULNLP. Accordingly,

- In an optimal solution, a machine i that has only incoming flows (from other machines) will be located at the last candidate location, i.e. $\alpha(i)^* = n$ for an optimal machine assignment vector α^*. If there are $k(k < n)$ machines having the same property, they will be located at the last k-candidate locations, and their relative positions do not affect the optimal objective function value.
- In an optimal solution, a machine i that has only outcoming flows (to other machines) will be located at the first candidate location, i.e. $\alpha(i)^* = (1)$ for an optimal machine assignment vector α^*. If there are $k(k < n)$ machines having the same property, they will be located at the first k-candidate locations, and their relative positions do not affect the optimal objective function value.

Kouvelis and Kim 1992 developed three heuristic procedures, KK-1, KK-2, and KK-3, for the problem.The heuristics are supported by the dominance rules presented. In chapter 4 we will describe these heuristics. Also they have developed an optimal B&B algorithm.

3.2.4 Special Cases of Unidirectional Loop Networks

Bozer and Rim 1989 proved that if the flow matrix is symetric, that is to say $w_{ij} = w_{ji}$ for all i, j, interchanging machines i and j does not change the objectice function value. Hence, any layout is optimal when the flow matrix is symmetric.

Kiran and Karabati 1988 report a polynomially solvable special case of the problem; when the parts are transported to a LUL station after every operation. Then if l denotes the LUL station

$w_{ij} = 0$ for all i, j, where $i \neq l$ and $j \neq l$.

They make the following modification to the solution method given in Christofides and Gerrard 1976 as follows:

Initially a vector consisting of the differences between the LUL station and the machines is formed. After reordering the flows in a non-increasing order, k'th machine is assigned to the k'th location after the location of the LUL station. A different assignment vector is obtained for each possible location of the LUL station. An optimum solution is found by comparing the resulting assignment vectors. The total time requirement of this algorithm is bounded by $O(n^2 logn)$.

In developing our formulation in Chapter 3, for the ULNLP, we mainly rely on the existing research results presented in this chapter.

Chapter 4

Problem Statement

In chapter 3, recent research results regarding the unidirectional loop network layout problem are presented. In this chapter we give our formulation of the problem. Two heuristic procedures, Positional Move Heuristic and Positional Move-Pairwise Interchange Heuristic, will be proposed for the problem. In addition, heuristic procedures of Kouvelis and Kim 1992, and the well known pairwise interchange algorithm will be discussed.

4.1 Problem Formulation

The ULNL problem we consider can be stated formally as follows:

Given machines 0, 1, ..., n, with machine 0 being the Load/Unload (LUL) station, candidate positions labelled 0, 1, ..., n and pairwise nonsymmetric part flows between machines, what is the assignment of the machines to candidate positions that yields the minimum cost defined by the sum of partflows times distances between the machines.

We condider a unidirectional loop network layout in an FMS environment. Machines are to be assigned to candidate locations around the loop. The material movement is unicyclic, and it is in the clockwise direction.

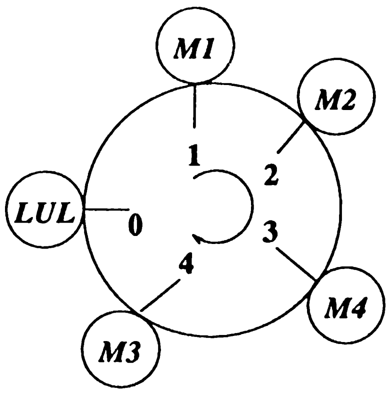

Figure 4.1. A unidirectional network with four machines

In an FMS environment, machines are capable of processing different part types simultaneously. There will be different part types to be produced in the loop network.

Let $P = \{1, \ldots, \bar{p}\}$ be the set of different part types to be processed in the loop system in a given time period. Each of the different part types may require different routes for their processing. With a route we mean the sequence in which a part visits the machines in the loop. This sequence is given by the process plan, I_p, for a particular part type $p \in P$. For example, if part type 2 needs to be processed by three machines in the order, machine 3, machine 1, and machine 2, then $I_2 = (3, 1, 2)$.

For a clear understanding of the problem formulation, the following definitions are provided:

Definition: The total number of parts moved from machine i to machine j is called the *part flow* from i to j.

Generally, an automated manufacturing system is balanced since no manual interruption is permitted so that any part entering the system will surely exit the system.

Definition: If the total part flow from one machine to all other machines is equal to the total part flow from other machines to that machine, that machine is said to satisfy the balance equation or flow conservation. The system is said to be *balanced* if every machine satisfies the flow conservation.

Before passing to our formulation of the problem, assumptions underlying the formulation will be given.

4.1.1 Assumptions:

1. The location of the LUL station is fixed at position 0.
2. System is balanced.
3. Adjacent locations are unit distance apart(since the system is balanced the distance between machines is of no importance as stated in chapter 3).
4. Process plans and the number of units to be produced for each part type are given, so that pairwise part flows between machine pairs can be calculated.
5. Parts enter and exit the system at the LUL station.

4.1.2 Notation:

- N : set of indices of machines ($N = \{1, \ldots, n\}$)
- p: part type $p(p \in P = \{1, \ldots, \bar{p}\})$
- I_p : process plan (subsequence in N with repetitions allowed) for part type p
- n_{ij}^p : number of times i, j appear consecutively (in that order) in I_p, equivalently, number of moves made from machine i to machine j by part type p
- v_p : number of units of part type p to be produced per time period
- w_{ij} : number of parts moving from machine i to j per period
- d_{lk} : distance from location l to k
- Π : set of all permutations of integers $1, \ldots, n$

- α : machine assignment vector ($\alpha \in \Pi$)

Part flow of part type p from machine i to j is given by;

$$v_p n_{ij}^p.$$

Then part flow from i to j is determined by using the following formula:

$$w_{ij} = \sum_{p \in P} v_p n_{ij}^p, \quad i, j \in N.$$

The distance metric, d_{lk} has the following properties;

1. $d_{lk} = 0$ if $l = k$,
2. $d_{lk} \neq d_{kl}$ in general,
3. $d_{lk} + d_{kl} = n + 1$ (length of the loop).

Due to assumption 3, and unit spacing between adjacent locations, the distance from locations l to k, d_{lk} is determined by:

$$d_{lk} = \begin{cases} k - l & \text{if } k > l \\ n + 1 - l + k & \text{if } k < l \\ 0 & \text{if k = l} \end{cases}$$

A machine assignment vector is a permutation of the integers 1, 2, ..., n, denoted by $\alpha = (\alpha(1), \ldots, \alpha(n))$, where $\alpha(i)$ gives the location of machine i.

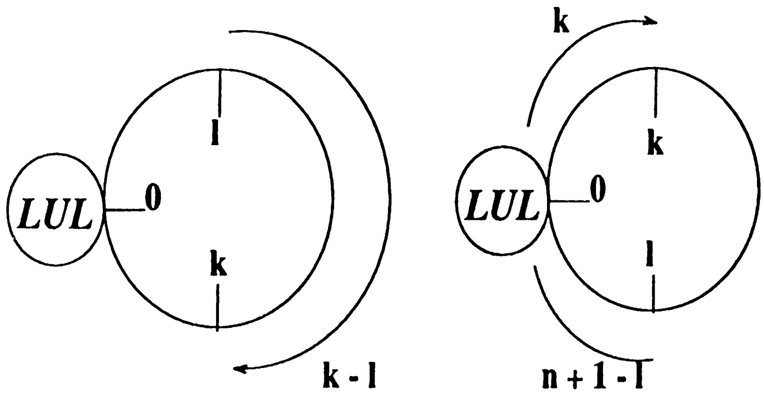

Figure 4.2. Determination of the distance from location l to k

4.1.3 The Model

ULNLP:

$$\min_{\alpha \in \Pi} \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} d_{\alpha(i)\alpha(j)} + \sum_{i=1}^{n} w_{0i} d_{0\alpha(i)} + \sum_{i=1}^{n} w_{i0} d_{\alpha(i)0}.$$

The first term in the above formula gives the sum of pairwise part flows between the machines, the second (third) term is the part flow from (to) LUL station to (from) machine i.

Observe that, $d_{0\alpha(i)}$ is simply $\alpha(i)$, and $d_{\alpha(i)0}$ is $n + 1 - \alpha(i)$.

Equivalently,

ULNLP:

$$\min_{\alpha \in \Pi} Z(\alpha) = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} d_{\alpha(i)\alpha(j)} + \sum_{i=1}^{n} c_{i\alpha(i)}$$

where,

$$c_{i\alpha(i)} = w_{0i}\alpha(i) + w_{i0}(n + 1 - \alpha(i)).$$

Then the ULNL problem can be stated as that of finding an assignment vector α that minimizes the expression $Z(\alpha)$:

ULNLP:

$$\min_{\alpha \in \Pi} Z(\alpha)$$

Our formulation for the unidirectional loop network problem is nothing but a special case of the QAP. The special structure results from the stated properties of the distance matrix. As QAP is NP-Complete, exact solutions for large sized problems cannot be handled. Whether or not the special distance matrix may lead to efficient exact methods is an open question. We propose two heuristics for the problem.

4.1.4 Positional Move Heuristic

In this section we present a heuristic which we call the positional move heuristic for the solution of the ULNLP.

Given an arbitrary assignment vector, we try to improve the solution by making positional moves. By an improvement in the objective function value we mean the difference between the objective function value of the current assignment vector and the assignment vector resulting from the positional move is positive. Formally;

Let α be a given assignment vector and $Z(\alpha)$ be the resulting objective function value. Let $\grave{\alpha}$ be the obtained assignment vector after the positional move with the objective function value $Z(\grave{\alpha})$. Then an improvement is obtained if

$$Z(\alpha) - Z(\grave{\alpha}) \ > \ 0.$$

A positional move is made by taking a machine from its current position to one of the other canditate positions, and shifting all affected machines by one position down in counter clockwise direction. The affected machines are those that occupy the positions between the old and new positions of the moved machine. If the new ordering of the machines result in an improvement in the

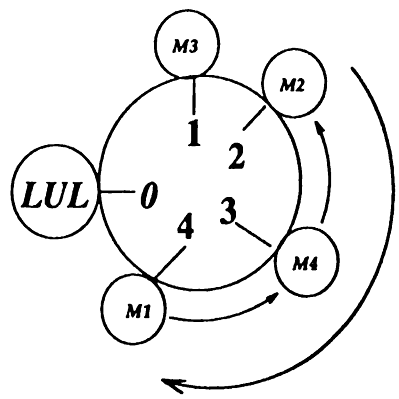

Figure 4.3. Illustration of a positional move

value of the objective function, the ordering of the machines is changed to that of the new generated ordering.

In the generation of the best possible assignment vector we make use of an nxn matrix, which we call PM. Rows of the PM matrix correspond to machines, and the columns correspond to positions. The (i, j) entry of the PM matrix gives the $Z(\alpha) - Z(\grave{\alpha})$ value that resulted from i'th machine to j'th location. Largest positive entry in the PM matrix will give us the maximum improvement assignment. This procedure will be repeated until no more improvement is accomplished. That is to say, until all the entries in the PM matrix is negative or zero.

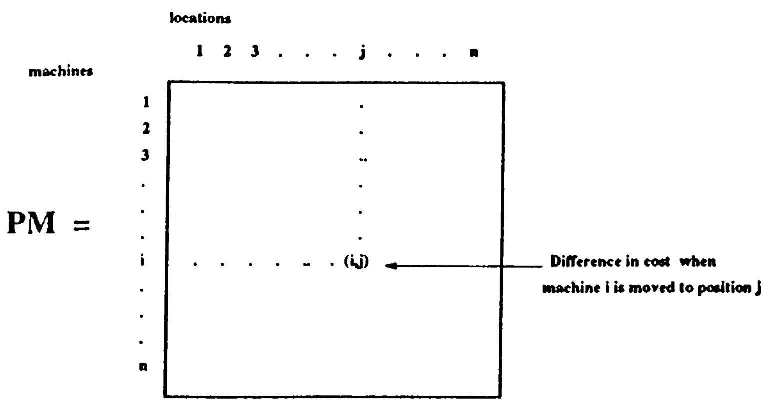

Figure 4.4. The PM matrix

For computational easiness we derive a simplified expression for $Z(\alpha) - Z(\grave{\alpha})$:

The definitions of $Z(\alpha)$ and $Z(\grave{\alpha})$ imply

$$Z(\alpha) - Z(\grave{\alpha}) = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(d_{\alpha(i)\alpha(j)} - d_{\grave{\alpha}(i)\grave{\alpha}(j)}).$$

Let

$$\Delta_{ij} = (d_{\alpha(i)\alpha(j)} - d_{\grave{\alpha}(i)\grave{\alpha}(j)}),$$

then,

$$Z(\alpha) - Z(\grave{\alpha}) = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\Delta_{ij}.$$

Consider moving machine p to location q by a positional move. Then there are two cases:

1. $\alpha(p) < q$: Machine p is moved clockwise, i.e. Machine p is moved to a position with a larger index than its current position index.

2. $\alpha(p) > q$: Machine p is moved counter clockwise i.e. Machine p is moved to a position with a smaller index than its current position index.

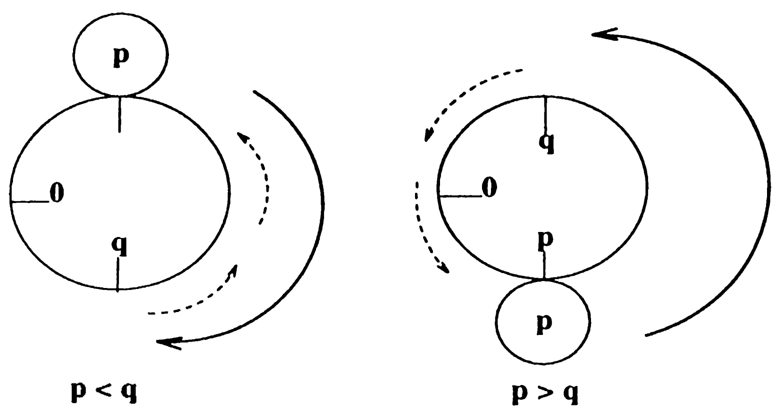

Figure 4.5. Different structures of the positional move

Define;

p = machine index which is to be moved.

I = the set of indices of machines whose positions are moved one unit block down due to movement of machine p. These are the set of affected machines.

$\bar{I}$ = the set of indices of machines whose positions remain unchanged when machine p is moved.

x = the unique machine index in I (if it exist) whose position is moved by 2 units; i.e. the machine which is initially at position 1, moved to position n.

Let the initial position of machine p be $\alpha(p)$ and let machine p be moved to location q. i.e. $\alpha(p) = p$ and $\alpha(\dot{p}) = q$.

- Case 1: $\alpha(p) < q$:

  It can be observed that,

$$\Delta_{ij} = \begin{cases} 0 & i \in I, j \in I \\ -1 & i \in I, j \in \bar{I} \\ 1 & i \in \bar{I}, j \in I \\ 0 & i \in \bar{I}, j \in \bar{I} \end{cases}$$

$$\Delta_{pj} = \begin{cases} -(n - |\bar{I}|) & j \in I \\ |I| & j \in \bar{I} \end{cases}$$

$$\Delta_{ip} = \begin{cases} (n - |\bar{I}|) & i \in I \\ -|I| & i \in \bar{I} \end{cases}$$

  Using above calculations we get:

$$Z(\alpha) - Z(\dot{\alpha}) = -\sum_{i \in I}\sum_{j \in \bar{I}} w_{ij} + \sum_{i \in \bar{I}}\sum_{j \in I} w_{ij} + n(\sum_{i \in I} w_{ip} - \sum_{i \in I} w_{pi}).$$

- Case 2: $\alpha(p) > q$:

  Similiarly,

$$\Delta_{ij} = \begin{cases} 0 & i \in I, j \in I \\ -1 & i \in I, j \in \bar{I} \\ 1 & i \in \bar{I}, j \in I \\ 0 & i \in \bar{I}, j \in \bar{I} \end{cases}$$

and

$$\Delta_{pj} = \begin{cases} -|\bar{I}| & j \in I \\ n - |I| & j \in \bar{I} \end{cases}$$

$$\Delta_{ip} = \begin{cases} |\bar{I}| & i \in I \\ -(n - |I|) & i \in \bar{I} \end{cases}$$

$$\Delta_{xj} = \begin{cases} -1 & j \in I \\ -2 & j \in \bar{I} \end{cases}$$

$$\Delta_{ix} = \begin{cases} 1 & i \in I \\ 2 & j \in \bar{I} \end{cases}$$

$$\Delta_{px} = 1 - |\bar{I}|$$

$$\Delta_{xp} = |\bar{I}| - 1$$

and,

$$\begin{aligned} Z(\alpha) - Z(\grave{\alpha}) &= -\sum_{i \in I}\sum_{j \in I} w_{ij} + \sum_{i \in I}\sum_{j \in I} w_{ij} + n(\sum_{i \in I} w_{pi} - \sum_{i \in I} w_{ip}) \\ &- \sum_{i \in I \cup p} w_{xi} + \sum_{i \in I \cup p} w_{ix} + 2(\sum_{i \in I} w_{ix} - \sum_{i \in I} w_{xi}). \end{aligned}$$

4.1.5 The Algorithm:

Positional Move Heuristic

Inputs to the algorithm are a partflow matrix, $W = (w_{ij})$ and a initial machine assignment vector, α.

- Step1. Initialize an nxn matrix $\grave{W}$ by setting $\grave{W} = W$, where $W = (w_{ij})$ is the part flow matrix.

- Step2. Initialize an $nx1$ vector $\grave{\alpha}$ by setting $\grave{\alpha} = \alpha$, where α is an arbitrary machine assignment vector. Move machine i to location j for all i, j, by positional move. Calculate $Z(\alpha) - Z(\grave{\alpha})$.

- Step3. Generate the PM matrix. Change $\grave{\alpha}$ according to maximum improvement satisfying assignment vector.

- Step4. Repeat Step 3 until all the entries in the PM matrix are nonpositive.

The following example demonstrates how the heuristic works:

Example:

Consider a ULNLP with n=4 machines and the following workflow matrix W:

$$W = \begin{bmatrix} 0 & 3 & 5 & 4 \\ 4 & 0 & 2 & 5 \\ 2 & 4 & 0 & 3 \\ 6 & 4 & 2 & 0 \end{bmatrix}$$

and an initial assignment vector $\alpha = (3, 4, 1, 2)$.

Initially machine 1 is at position 3, machine 2 at position 4, machine 3 at position 1 and machine 4 at position 2. That is,

$$\begin{aligned} \alpha(1) &= 3 \\ \alpha(2) &= 4 \\ \alpha(3) &= 1 \\ \alpha(4) &= 2 \end{aligned}$$

- Assume moving machine 4 to position 4: Initial position of machine 4 is 2. We will move machine 4 to position 4. Since the position of machine 2 is occupied by machine 4, it will move one position in the counter clock wise direction and will occupy position number 3. In position number

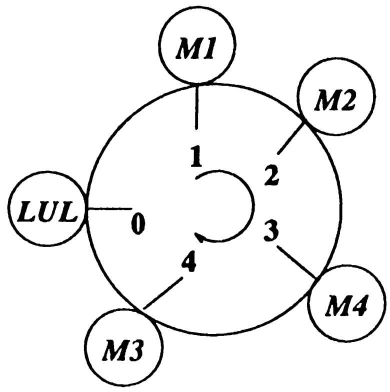

Figure 4.6. example

3, machine 1 was located, similarly machine 1 will move in the counter-clockwise direction and occupy position 2. Position 2 was empty due to movement of machine 4 to location 4. As all the machines are located at one of the positions, positional movement terminates. This movement results in the assignment vector, $\grave{\alpha} = (2,3,1,4)$. Formally;

$$
\begin{aligned}
\grave{\alpha}(1) &= 2 \\
\grave{\alpha}(2) &= 3 \\
\grave{\alpha}(3) &= 1 \\
\grave{\alpha}(4) &= 4
\end{aligned}
$$

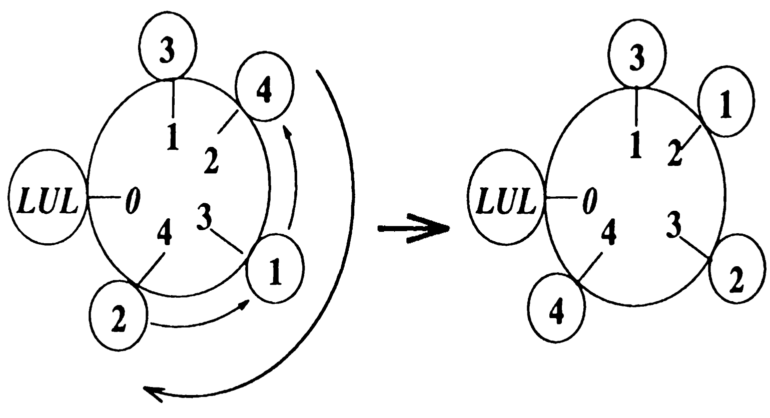

Figure 4.7. Machine 4 moved to position4

Next step is to calculate the difference in the objective function value due to movement of machine 4 to position 4. Since, $\alpha(4) = 2 < \grave{\alpha}(4) = 4$ we will use the first formula.

Both from the figure and the assignment vector α, set of machines whose positions changed one unit can be determined; $I = \{2, 1\}$. Machine 3 remained at its initial position; $\bar{I} = \{3\}$. Since positional movement occurred due to machine 4 we have $p = 4$. Using the formula 1 we find;

$$\begin{aligned} Z(\alpha) - Z(\grave{\alpha}) &= -w_{23} - w_{13} + w_{32} + w_{31} + 4(w_{24} + w_{14} - w_{42} - w_{41}) \\ &= -5. \end{aligned}$$

We obtained a negative value indicating that the new assignment of the machines cause a worse objective function value.

- Assume moving machine 4 to location 1: When we move machine 4 to position 1, machine number 3 will move in the counterclockwise two units and occupy position 4. Initially position 4 was occupied by machine 2, so machine 2 will move 1 unit. New position of machine 2 is now position 3. Accordingly machine 1 will move 1 unit and occupy position 2. This will terminate the movement of the machines along the loop. Then the resulting assignment vector is, $\grave{\alpha} = (4, 3, 2, 1)$

$$\begin{aligned} \grave{\alpha}(1) &= 4 \\ \grave{\alpha}(2) &= 3 \\ \grave{\alpha}(3) &= 2 \\ \grave{\alpha}(4) &= 1 \end{aligned}$$

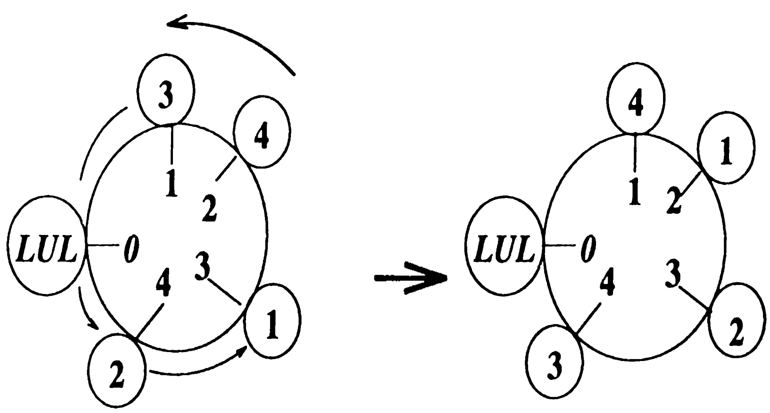

Figure 4.8. Machine 4 moved to position1

Since $\alpha(4) = 2 > \grave{\alpha}(4) = 1$ we will use second formula; Machine 1 and 2 are moved one unit; $I = \{1, 2\}$. All the machines are moved from their initial positions so $\bar{I}$ is empty. Machine 3 was at the first position initially and moved to the last position after the positional move, so x=3. From formula 2 we get;

$$\begin{aligned} Z(\alpha) - Z(\grave{\alpha}) &= -w_{31} - w_{32} + w_{13} + w_{23} + w_{43} - w_{34} \\ &= 0. \end{aligned}$$

Moving machine 4 to position 1 did not produce an improvement, either.

For the purpose of developing efficient heuristic procedures, which give near optimal solutions we will also use the procedure of the well known pairwise interchange heuristic. Below the algorithm of the pairwise interchange heuristic is given.

Pairwise Interchange Heuristic:

- Step1. Initialize an nxn matrix $\grave{W}$ by setting $\grave{W} = W$, where $W = (w_{ij})$ is the part flow matrix.
- Step2. Initialize an $nx1$ vector $\grave{\alpha}$ by setting $\grave{\alpha} = \alpha$, where α is an arbitrary machine assignment vector.
- Step3. Change positions of machine i and j. Calculate $Z(\alpha) - Z(\grave{\alpha})$.
- Step4. Generate the PS matrix. Change $\grave{\alpha}$ according to maximum improvement satisfying assignment vector.
- Step5. Repeat Step 3 until all the entries in the PS matrix are nonnegative.

The operation of the pairwise interchange heuristic is like the Positional Move Heuristic. Given an initial assignment of the machines, positions of the machines are swapped one pair at a time. Initial assignment is changed with an assignment of machines providing the maximum improvement in the objective function value. This improvement is determined from the PS matrix as in the case of the Positional Move heuristics PM matrix.

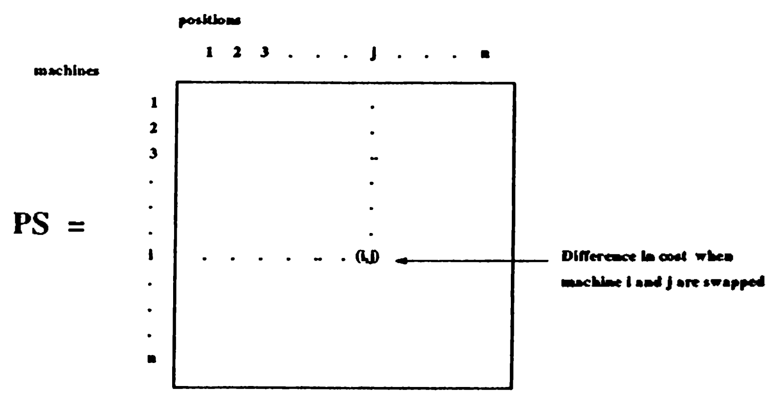

Figure 4.9. The PS matrix

Our second algorithm Positional Move-Pairwise Interchange Heuristic is a combination of the heuristics Positional Move Heuristic and Pairwise Interchange Heuristic.

4.1.6 Positional Move-Pairwise Interchange Heuristic:

The operation of the Positional Move-Pairwise Interchange Heuristic is the same as the independent heuristics; positional move and pairwise interchange. In the search for the best solution we will use these two heuristics in the following way. Initially a solution will be improved with the positional move heuristic alone. As mentioned before we continue our search until all the entries in the PM matrix are nonpositive. When no more improvement can be attained from the positional move heuristic we pass to the pairwise interchange heuristic. Input to the pairwise interchange heuristic is the last assignment vector obtained from the positional move heuristic. Pairwise interchange heuristic will try to improve the solution by making pairwise position changes between the machines. When no more improvement can be obtained from the pairwise interchange heuristic, positional move heuristic will carry on with the last assignment (the best solution obtained up to time). This procedure will continue until both heuristics will not give any improvement.

Algorithm:

- Step 1. Initialize an nxn matrix $\grave{W}$ by setting $\grave{W} = W$, where $W = (w_{ij})$ is the part flow matrix.

- Step 2. Initialize an $nx1$ vector $\grave{\alpha}1$ by setting $\grave{\alpha}1 = \alpha$, where α is an arbitrary machine assignment vector.
- Step 3. Move machine i to location j for all i, j. Calculate $Z(\alpha 1) - Z(\grave{\alpha}1)$.
- Step 4. Generate the PM matrix. Change $\grave{\alpha}1$ according to maximum improvement satisfying assignment vector.
- Step 5. Repeat Step 3 until all the entries in the PM matrix are non-positive.
- Step 6. Set $\grave{\alpha}2 = \grave{\alpha}1$, where $\grave{\alpha}1$ is the best assignment obtained by positional moves.
- Step 7. Change positions of machines i and j. Calculate $Z(\alpha 2) - Z(\grave{\alpha}2)$
- Step 8. Generate the PS matrix. Change $\grave{\alpha}2$ according to maximum improvement satisfying assignment vector.
- Step 9. Repeat Step 8 until all the entries in the PS matrix are nonpositive.
- Step 10. Set $\grave{\alpha} = \grave{\alpha}2$ and go to Step 2.

In chapter 5 we will give the computational results of the heuristics. We will compare our heuristics with Kouvelis and Kim's three heuristics (KK-1, KK-2 and KK-3) and the pairwise interchange heuristic. Before going through the computational results we introduce the Kouvelis and Kim's heuristics to the reader.

Kouvelis and Kim's heuristics are based on the dominance rules presented in Kouvelis and Kim 1992. The Dominance Rules suggest to locate a machine with only incoming part flow from other machines to the last position. Similarly, a machine that has only outgoing part flow should be assigned to the first position.

Heuristic KK-1:

The motivating idea behind KK-1 is to locate machines with higher outflows ahead of the others. KK-1 does not consider the distances between the positions of the machines and works on the part flow matrix W. **Algorithm:**

- Step 0. Initialize an nxn matrix $\grave{W}$ by setting $\grave{W} = W$, where $W = (w_{ij})$ is the partflow matrix.
- Step 1. Calculate the row sums $\grave{R}_j$ of the matrix $\grave{W}$.
- Step 2. Determine k such that $\grave{R}_k = max_j \grave{R}_j$. Break ties arbitrarily. Assign the workstation k to the first available candidate location.
- Step3. Erase column k and row k of matrix $\grave{W}$. Repeat Steps 1-3 until the new matrix $\grave{W}$ consists of a single element.

Heuristic KK-2:

Algorithm:

This second heuristic works like KK-1, but on a different matrix .

- Step 0. Using as input the workflow matrix $W = (w_{ij})$, develop the matrix $E = (e_{ij})$, where:

$$e_{ij} = \begin{cases} 1+\delta & \text{for } e^1_{ij} = w_{ij} - w_{ji} > 0, i \neq j \\ 1 & \text{for } e^1_{ij} = w_{ij} - w_{ji} = 0, i \neq j \\ 0 & \text{otherwise} \end{cases}$$

  and δ is a small positive number ($\delta < \frac{1}{n}$).

- Step 1. Apply Heuristic **KK-1** on matrix E.

Heuristic KK-3:

Algorithm:

- Step 0. Initialize an nxn matrix $\grave{W}$ by setting $\grave{W} = W$, where $W = (w_{ij})$ is the workflow matrix.
- Step 1. Calculate the row sums $\grave{R}_j$ and the column sums $\grave{C}_j$ of the matrix $\grave{W}$.

- Step 2. Determine a pair (k, l) such that $RC_{kl} = Max_{(i,j,i \neq j)} RC_{ij}$, where

$$RC_{ij} = (\grave{R}_i - \grave{C}_i) - (\grave{R}_j - \grave{C}_j) + \grave{w}_{ji} - \grave{w}_{ij}.$$

Kouvelis and Kim state the motivating idea behind KK-3 as follows:

Since the machine assignment at the first and the last candidate locations determines the values of a relatively large number of entries in the objective function, the error of having a pair of machines assigned to these positions in an incorrect order should be avoided. This error is captured by the quantity RC_{ij}, which is called to be the backbone of the heuristic.

For more explanation on the heuristic procedures KK-1, KK-2, KK-3 refer to Kouvelis and Kim 1992.

In Chapter 5 computational results of the heuristics, Positional Move Heuristic, Pairwise Interchange Heuristic, Positional Move-Pairwise Interchange Heuristic, Heuristic KK-1, KK-2, and KK-3 will be given.

Chapter 5

Computational Results

In chapter 4, we formulated the Unidirectional Loop Network Layout Problem and proposed two heuristics, Positional Move Heuristic and Positional Move-Pairwise Interchange Heuristic. In this chapter we will discuss the effectiveness of these heuristics. Also a discussion on the factors influencing the results of the heuristics will be provided.

The Unidirectional Loop Network Layout Problem we consider is a special case of the Quadratic Assignment Problem when the workflow matrix is balanced and the distance matrix is circular. This special structure of the problem does not seem to be enough to develop polynomial time algorithms. The difficulty is faced when the number of machines is increased. Obtaining exact solutions, even for a size of ten machines, is too time consuming. Our objective in developing heuristic procedures for the problem is to handle large size problems with a reasonable accuracy, in a reasonable time.

Computational Analysis of the heuristics will be performed in two parts;

- Initially we will compare our heuristics with other heuristics.
- In the second part we will try to determine factors, if there are any, affecting the problem solution.

For problems of size up to 10, we computed the exact value of the problem by enumeration. For larger sized problems, we used the LP relaxation of the IP model of Kiran,Unal, and Karabati 1992 . This model was discussed in chapter 3. Note that, the objective function value cannot be directly used because of the normalization of the loop length. In this way we were able to compute the deviation of our heuristics and others from lower bound on the value of the problem. The LP relaxation yields a lower bound on the optimal value.

5.1 Comparison With Other Heuristics

In this part of the computational analysis we will compare our heuristics with other heuristics, developed for the same problem. As we mentioned in chapter 4, for comparison purposes we will use the heuristics, KK-1, KK-2, KK-3, developed by Kouvelis and Kim 1992, and the pairwise interchange heuristic.

Heuristic procedures KK-1, KK-2, and KK-3 are construction heuristics. Pairwise interchange and our heuristics are improvement heuristics, i.e. these heuristics try to improve an initial solution.

Construction Heuristics	Improvement Heuristics
KK-1	PI: Pairwise Interchange
KK-2	PM:Positional Move (*)
KK-3	MI: Positional Move- Pairwise Interchange (*)

Table 5.1. Heuristics for ULNLP

We input three types of initial assignment vectors for the improvement heuristics. Initially we solved a particular problem with heuristics KK-1, KK-2 and KK-3. The best solution obtained from these heuristics used as an input to the other heuristics. Then we generated a random assignment of machines. The problem is again solved by using this random assignment with the improvement heuristics. Lastly, we considered assignining i'th machine to i'th position and used this assignment as the initial solution for the heuristics.

Hence, we solved a problem by considering three different initial assignments. In this way we were able to detect, if any, factors affecting the problem solution.

We generated random balanced, part flow matrices. The row sums and the column sums of the generated part flow matrices are equal to satisfy the balanced characteristic of the problem. In generating the random part flow matrices we imposed a constraint on the range of numbers in the matrix. We defined three ranges; 0-10, 0-50 and 0-100. In the first, type matrix variation in the part flow is small. In the second case it is medium, and in the third case variation is high.

	Range
Small Variation	10
Medium Variation	50
Large Variation	100

Table 5.2. Range of Part Flow

Best Assignment	B
Random Assignment	R
i to i Type Assignment	I

Table 5.3. Input Types

In our computational analysis, we considered the problem sizes 5, ..., 10, 15, 20, 30, 40 and 50. For each problem size we made 4 replications. Since we considered, three different types of the part flow matrix, and three different types of initial assignment, number of test runs made for each problem size is 4x3x3. This makes a total of 396 runs. This high number of test runs will higly support our conclusions about the heuristics.

Initially we consider the deviation of the solutions obtained from the heuristics from the exact values.

$$Deviation = \frac{Z_H - Z_E}{Z_E}$$

where,

Z_H = solution obtained from heuristics,

Z_E = exact solution value for sizes up to $n = 10$, and LP relaxation optimal value for sizes greater than 10.

In the following tables we will give the average and the maximum observed deviations from the exact solutions for all the heuristics used in our test runs.

Note that, the following acronyms are used;

- PM: Positional Move Heuristic,
- PI: Pairwise Interchange Heuristic,
- IM: Positional Move-Pairwise Interchange Heuristics,
- B: Best input assignment obtained from Kouvelis and Kim's Heuristics,
- R: Random input assignment, and
- I: i to i type input.

Average Deviation from Lower Bound (a)							
n	R	KK-1	KK-2	KK-3	PI(B)	PI(R)	PI(I)
5	10	15.87	3.65	0.49	0.00	0.00	0.00
	50	6.71	2.81	0.00	0.00	0.00	0.00
	100	3.13	5.74	0.00	0.00	0.00	0.00
6	10	5.00	8.16	1.08	0.71	1.43	0.36
	50	8.76	6.49	0.00	0.00	0.15	0.15
	100	11.16	6.01	0.00	0.00	0.00	0.93
7	10	4.59	2.53	1.47	0.00	2.89	0.00
	50	10.91	11.09	0.54	0.41	0.00	2.79
	100	7.67	2.75	0.74	0.00	0.14	1.32
8	10	7.16	4.26	1.76	1.03	1.24	0.83
	50	8.62	7.27	1.19	0.84	0.43	2.64
	100	4.95	3.94	1.24	0.52	0.90	0.55
9	10	5.89	6.21	1.52	1.05	2.70	1.82
	50	6.98	2.19	3.27	1.19	1.80	0.21
	100	4.78	5.01	3.15	1.03	0.87	2.09
10	10	16.17	17.49	13.36	9.70	10.45	9.84
	50	16.67	22.10	10.63	9.24	11.36	10.39
	100	13.39	17.66	10.74	10.16	9.41	12.40
15	10	14.93	16.54	11.87	11.19	11.29	12.29
	50	16.34	20.61	14.28	12.78	12.95	12.39
	100	15.86	14.05	11.38	10.47	11.06	11.81
20	10	17.55	16.52	13.54	12.15	12.58	12.83
	50	21.95	21.29	16.18	15.10	15.98	15.71
	100	21.23	23.03	17.17	15.83	15.78	16.38
30	10	20.54	19.37	17.21	16.18	17.28	15.69
	50	20.78	19.67	16.97	15.09	15.73	16.07
	100	19.03	18.68	15.77	13.71	13.50	14.17
40	10	25.11	24.23	21.19	19.46	19.60	19.52
	50	26.87	26.28	23.62	22.53	22.90	22.15
	100	28.16	28.06	24.10	22.44	22.46	22.72
50	10	27.51	25.97	23.57	22.66	22.34	22.53
	50	26.48	25.57	22.75	21.01	21.48	21.21
	100	22.50	21.03	18.76	17.48	17.92	17.16

Average Deviation from Lower Bound (b)							
n	R	PM(B)	PM(R)	PM(I)	MI(B)	MI(R)	MI(I)
5	10	0.00	0.00	0.00	0.00	0.00	0.00
	50	0.00	0.00.	0.00	0.00	0.00	0.00
	100	0.00	0.00	0.00	0.00	0.00	0.00
6	10	0.71	0.00	0.00	0.71	0.00	0.00
	50	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.00	0.00	0.00	0.00	0.00	0.00
7	10	0.00	0.00	0.00	0.00	0.00	0.00
	50	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.14	0.14	0.25	0.14	0.14	0.00
8	10	0.41	0.21	0.21	0.41	0.21	0.21
	50	0.00	0.12	0.00	0.00	0.00	0.28
	100	0.00	0.33	0.17	0.00	0.33	0.17
9	10	0.00	0.57	0.00	0.00	0.57	0.00
	50	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.48	0.52	1.33	0.48	0.52	1.33
10	10	9.31	8.70	9.06	9.31	8.70	9.06
	50	8.79	8.79	8.70	8.79	8.79	8.70
	100	8.70	8.74	9.77	8.70	8.74	9.77
15	10	9.99	10.50	9.41	9.99	10.50	9.41
	50	10.32	10.03	10.98	10.32	10.03	10.98
	100	9.27	9.06	8.99	9.27	9.06	8.99
20	10	10.07	10.48	10.96	10.07	10.48	10.96
	50	14.19	13.64	14.02	14.18	13.64	14.02
	100	14.45	13.72	13.64	14.45	13.72	13.64
30	10	14.10	14.15	13.71	14.10	14.15	13.71
	50	13.73	13.80	13.96	13.73	13.80	13.96
	100	12.07	12.16	11.77	12.07	12.18	11.77
40	10	18.36	18.49	18.37	18.36	18.49	18.37
	50	20.95	20.52	20.74	20.95	20.52	20.74
	100	20.84	20.63	21.23	20.84	20.63	21.23
50	10	20.78	20.73	20.64	20.78	20.73	20.64
	50	19.64	19.77	19.51	19.64	19.77	19.51
	100	16.36	16.30	16.36	16.36	16.30	16.36

Maximum Deviation from Lower Bound (a)							
n	R	KK-1	KK-2	KK-3	PI(B)	PI(R)	PI(I)
5	10	27.78	14.58	1.96	0.00	0.00	0.00
	50	14.35	7.50	0.00	0.00	0.00	0.00
	100	7.13	11.18	0.00	0.00	0.00	0.00
6	10	20.00	12.86	2.86	2.86	5.71	1.45
	50	21.97	14.01	0.00	0.00	0.62	0.62
	100	17.72	13.39	0.00	0.00	0.00	3.72
7	10	12.87	3.92	2.97	0.00	4.71	0.00
	50	16.62	18.66	2.17	1.62	0.00	10.61
	100	13.57	7.16	2.37	0.00	0.56	2.82
8	10	10.83	10.42	3.31	3.31	4.13	3.31
	50	15.62	17.46	2.39	1.84	1.40	7.52
	100	8.52	10.58	2.11	1.43	1.41	0.97
9	10	14.61	7.01	3.82	1.91	5.10	3.82
	50	12.53	4.57	9.33	3.47	3.73	0.86
	100	6.63	6.27	5.78	1.96	3.21	3.35
10	10	22.96	22.47	16.86	11.15	11.65	11.11
	50	21.53	31.63	14.23	10.39	12.09	12.50
	100	17.43	22.65	12.54	12.22	11.23	14.35
15	10	21.02	17.82	13.43	12.64	12.36	14.36
	50	18.07	24.35	15.50	14.25	13.93	14.84
	100	18.47	16.39	12.14	11.52	13.99	14.22
20	10	22.46	20.65	16.54	16.18	16.90	17.26
	50	22.18	22.59	17.22	16.14	18.66	17.02
	100	25.23	24.40	19.05	17.21	17.81	20.35
30	10	21.10	20.20	17.44	16.77	19.18	16.50
	50	21.38	21.58	18.20	15.68	16.29	19.02
	100	21.40	22.96	18.32	15.84	15.83	17.02
40	10	27.20	27.37	23.93	21.83	22.41	22.09
	50	27.70	27.32	24.94	23.00	24.20	22.68
	100	29.25	28.85	24.61	23.43	23.28	23.19
50	10	28.39	26.33	23.93	23.37	23.01	23.11
	50	28.22	27.18	24.10	22.43	22.36	22.11
	100	27.38	25.93	22.88	21.98	22.11	21.61

Maximum Deviation from Lower Bound (b)							
n	R	PM(B)	PM(R)	PM(I)	IM(B)	IM(R)	IM(I)
5	10	0.00	0.00	0.00	0.00	0.00	0.00
	50	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.00	0.00	0.00	0.00	0.00	0.00
6	10	2.86	0.00	0.00	2.86	0.00	0.00
	50	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.00	0.00	0.00	0.00	0.00	0.00
7	10	0.00	0.00	0.00	0.00	0.00	0.00
	50	0.00	0.00	0.00	0.00	0.00	0.00
	100	0.56	0.56	1.02	0.56	0.56	0.00
8	10	1.65	0.83	0.83	1.65	0.83	0.83
	50	0.00	0.00	0.00	0.00	0.00	1.13
	100	0.00	0.67	0.67	0.00	0.67	0.67
9	10	0.00	1.69	0.00	0.00	1.69	0.00
	50	0.00	0.00	0.00	0.00	0.00	0.00
	100	1.93	1.93	3.41	1.93	1.93	3.41
10	10	11.15	8.70	10.14	11.15	8.70	10.14
	50	9.07	9.07	8.70	9.07	9.07	8.70
	100	8.70	8.86	13.01	8.70	8.86	13.01
15	10	11.08	11.51	10.01	11.08	11.51	10.01
	50	11.03	10.10	12.58	11.03	10.10	12.58
	100	10.79	10.31	10.03	10.79	10.31	10.03
20	10	13.64	14.12	15.21	13.64	14.12	15.21
	50	15.20	13.64	14.63	15.20	13.64	14.63
	100	15.92	13.96	13.64	15.92	13.96	13.64
30	10	15.02	15.21	13.83	15.02	15.21	13.83
	50	13.86	14.08	14.70	13.86	14.08	14.70
	100	14.13	14.28	13.74	14.13	14.28	13.74
40	10	20.95	21.07	20.75	20.95	21.07	20.75
	50	21.79	20.59	20.93	21.79	20.59	20.93
	100	21.56	20.89	21.84	21.56	20.89	21.84
50	10	20.97	20.91	20.82	20.97	20.91	20.82
	50	20.49	20.93	21.14	20.29	20.93	21.14
	100	20.64	20.51	20.84	20.64	20.51	20.84

Average and maximum observed deviations from the exact values, for the heuristics are given above. In the overall, test runs indicate that improvement heuristics; pairwise interchange heuristic and our heuristics provide better results than the Kouvelis and Kim's three heuristics.

When average deviations are considered, heuristic KK-3 provides better results than KK-1 and KK-2. If the maximum deviations are also considered KK-3 has the highest observed deviation from the exact values.

Postional Move and Positional Move-Pairwise Interchange Heuristics, no matter what type of initial assignment is used provided the best observed results, both interms of average deviation and maximum observed deviation. In most of the problems up to sizes ten, these heurisics gave the exact solution value obtained by complete enumeration.

Below we give the observed ranks for all of the heuristics used in our test runs for comparison purposes. As can be seen from the tables, Positional Move and Positional Move-Pairwise Interchange Heuristics are in the first six ranks. This indicates that they have both the minimum average deviation and minimum observed maximum deviation from exact values.

Rank of Average Deviations		
1	PM(B)	7.63
2	MI(R)	7.64
3	MI(B)	7.69
4	PM(R)	7.69
5	PM(I)	7.69
6	MI(I)	7.69
7	PI(B)	8.60
8	PI(R)	8.99
9	PI(I)	9.06
10	KK-3	9.69
11	KK-2	13.82
12	KK-1	14.64

Rank of Maximum Deviations		
1	MI(R)	21.07
2	PM(R)	21.07
3	MI(B)	21.79
4	PM(B)	21.79
5	MI(I)	21.84
6	PM(I)	21.84
7	PI(I)	23.19
8	PI(B)	23.43
9	PI(R)	24.20
10	KK-2	28.79
11	KK-1	29.25
12	KK-3	31.63

In some of our test runs we used the best observed solution obtained from the improvement heuristics KK-1, KK-2, and KK-3. We observed that our heuristics provide better improvements than the pairwise interchange heuristic.

Percent Improvement from the Best Solution Obtained from KK-1, KK-2, KK-3				
n	R	PM	PI	MI
5	10	2.54	1.28	2.54
	50	1.81	0.52	1.81
	100	3.32	1.23	3.32
6	10	1.81	3.36	2.10
	50	0.70	2.10	3.36
	100	1.59	1.19	1.59
7	10	1.46	0.44	1.46
	50	1.21	0.70	1.21
	100	2.96	1.83	2.96
8	10	3.36	3.01	3.36
	50	2.47	1.95	2.47
	100	2.54	1.28	2.54
9	10	2.10	0.84	2.10
	50	2.19	0.70	2.19
	100	2.00	1.08	2.10
10	10	1.37	1.28	1.08
	50	2.27	1.72	2.86
	100	2.22	1.08	2.22
15	10	1.95	0.67	2.00
	50	2.77	1.72	2.86
	100	2.66	1.12	2.73
20	10	3.05	1.16	3.14
	50	2.17	1.20	2.22
	100	1.42	0.63	1.45
30	10	2.37	1.65	2.32
	50	2.83	1.66	2.92
	100	3.09	2.13	3.18
40	10	2.18	1.34	2.23
	50	2.01	1.06	2.06
	100	2.53	1.79	2.60
50	10	2.22	0.55	2.27
	50	2.64	1.28	2.71
	100	2.27	1.36	2.33
Average Improvement		2.24	1.35	2.35

5.2 Determining Factors Effecting the Solutions

In this part of the analysis we tried to determine the factors having an effect on the solutions of the heuristics. In our test runs we considered the factors; problem size, range of part flow matrix and the type of the initial assignment.

We performed an Anova test for determining the significance of these effects. We performed our tests on our heuristics and on the pairwise interchange heuristic because, the second proposed heuristic Positional Move-Pairwise Interchange Heuristics partially relies on pairwise interchange heuristic.

Although an effect of the type of initial assignment on the solutions was suspected, such an effect was not justified by the Anova results. Observing the same thing for all the heuristics, strengthens the result of no effect of the type of initial assignment.

The Anova results indicate that the type of partflow matrix and the number of machines in the problem has a significant effect on the solution. This is observed for all three heuristics.

Chapter 6

Conclusion

In this thesis the layout problem in Flexible Manufacturing Systems (FMSs) is discussed. Layout problem in a Flexible Manufacturing System environment is more complicated and more important than the layout of conventional manufacturing systems (Kouvelis, Kiran, and Chiang 1991 and Kouvelis, Chiang, and Kiran 1992). We presented a review of papers related or applicable to FMS layout problems.

Analysis of existing FMSs shows that the layout in a Flexible Manufacturing System environment is determined by the type of the material handling system being used. There are five specific layout types that are implemented; unidirectional loop network layout, circular machine layout, linear single row machine layout, linear double machine layout, and cluster machine layout. Each of these layout types are more appropriate for a specific material handling system device (Heragu and Kusiak 1988 and Afentakis 1986).

Unidirectional loop networks are preferred to other configurations due to their relatively lower initial investment costs, since they contain the minimum number of required material links to connect all workstations and possess higher material handling flexibility. In literature assigning machines in a unidirectional loop network with the objective of minimizing an appropriate objective function is referred as the Unidirectional Loop Network Layout Problem. We presented a state of art survey on unidirectional loop network layout problem.

In our formulation of the problem we consider the sum of partflows times distances between the machines as the objective function. Due to computational complexity we approached heuristically to this problem. We proposed two heuristics; Positional Move Heuristic and Positional Move-Pairwise Interchange Heuristic. Main idea of the heuristics is to improve an initial solution by making positional moves. A positional move is made by taking a machine from its current position to one of the other candidate positions, and shifting all affected machines by one position down in counter clockwise direction. If the new ordering of the machines result in an improvement in the value of the objective function, the ordering of the machines is changed to that of the new generated ordering. While Positional Move heuristic considers improving the solution by making positional moves, Positional Move-Pairwise Interchange Heuristic applies positional moves and pairwise change technique interchangeably.

We compared our heuristics with other heuristics, developed for the same problem. For comparison purposes we used the three heuristics developed by Kouvelis and Kim, and the well known pairwise interchange heuristic. Test runs indicated that our heuristics provide better solutions than others. In the overall Positional Move-Pairwise Interchange Heuristic gave the best results.

In this research we presented a new heuristic approach, positional move which provides better results then the well known heuristic approach pairwise interchange.

This approach can be applied to other configuration types in Flexible Manufacturing Systems, in determining the minimum cost assignment of machines.

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