# "Lattice Production Lines for Flexible Manufacturing Systems"

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## Abstract:

In this paper we apply lattice production lines to flexible manufacturing systems (FMS). As a preliminary, we review known facts about lattice production lines. A transfer line that is in current use by a company is presented for study. The transfer line is compared to a cell structured FMS that will produce the same goods via a set of production characteristics. Finally, a lattice structured FMS is compared to the transfer line and the cell structured FMS using the same set of characteristics.

## Introduction:

American industries, especially car manufacturers, are being forced to respond more quickly to consumer desires by the competition. In an effort to hasten their response, many are turning to outsourcing [1]. As a result, investment in manufacturing industries is expected to more than double between 1989 and 1992 [2]. So, many companies are gearing up for a new wave of competitiveness.

The factory that we will look at is such a company. This company, which will remain unnamed, produces differential gear cases for automobiles. Currently, the firm uses a transfer line for production. Although the transfer line is fast when operating, it is somewhat outdated and other problems exist in the production line.

The biggest problem is caused by interruptions. If the line could be operated at 80% or more of the rated throughput, it would meet the needs of the manufacturer and reduce current production costs as well. However, statistics recently compiled by the manufacturer show that the lines actually operate between 66% and 50% of the rated throughput.

It is important to note the types of interruptions that commonly occur on these lines. About 69% of the interruptions are caused by machine failures. About 30% are non-machine related problems such as pluming, flute modifications, etc. The balance is caused by operator difficulties.

Companies that use this type of equipment must have very fast workcenters that will produce a throughput that greatly exceeds their needs because break downs are so devastating to throughput. Interruptions become a major factor to consider when determining the theoretical throughput of a line. This drives up the cost of the production line.

The company under observation here requires four transfer line structured production lines to produce four different automobile differential gear cases. The differential cases are very similar to each other. However, their transfer lines are not capable of switching between the items. Each line is dedicated to a specific item. The goal of this paper is to define a production line that will remedy these problems using existing technology and off the self workcenters. Some general concepts and advantages of lattice production lines are given in the section that follows.

## An Overview of Lattice Production Lines:

The lattice production line has been proven to be the best general topology with regards to its interconnectivity capability and high reliability [3]. We observe that the reliability of an entire production line system is seen in the ability of the system to maintain a predetermined level of throughput when interruptions occur within the system.

The lattice is particularly well suited to high speed manufacturing and prototyping. A model of a lattice structured FMS is given in Figure 1-c. This is the same lattice that will be referenced during the comparison of the lattice oriented FMS to cell oriented FMS and a transfer line.

From Figure 1-c it is easy to understand some of the basic advantages. Notice that every node is connected to its adjacent nodes. This means that any part in this example will only have to travel across one connection or link to get to another workcenter. The term "part" is used throughout this document to refer to any material that is considered work-in-progress. The end products or finished goods of a production systems are called "items."

In many advanced production topologies parts have to travel through multiple links to get to the next workcenter. In these topologies, parts can be blocked by busy workcenters or links and have to wait for these resources to become free before travel to the next workcenter can continue. This is not the case in systems with a lattice topology. By definition parts travel to and from workcenters independently of their operational state. Furthermore, a busy link is less likely to stop a part in route to its next workcenter because there are multiple routes to every workcenter.

Each node is connected to the other nodes by more than one link. Although there is, at most, only one direct connection between any two nodes. There are indirect connections that will allow a part to get to the next processing station even if the direct connection is inoperable. Furthermore, because there are multiple links to each node, a node can send or receive multiple parts simultaneously. This can greatly enhance the throughput of the system. Nodes that can process two or more parts in the time it takes for other nodes to process one part are not restricted by a single stream of parts. This lends itself to a more consistent flow of parts in and out of the entire system while maximizing the capabilities of the individual nodes.

The nodes do not have to be physically moved for any change in processing order. Such changes can be accomplished from software only. With the proper software, producing completely different items can be as simple as the point and click mouse operations on a computer. Next, we will discuss transfer lines.

## A Standard Transfer Line:

Today it is common to see used in manufacturing plants what many people in machining industries refer to as transfer lines. A transfer line is a set of two or more workcenters that are linked together in such a manner that parts can be moved from one workcenter to another workcenter and work is performed at the workcenters. All transfer lines have the following three properties:

1) a fixed or static flow of parts
2) work and transportation are mutually exclusive events, ie. while any part is being worked on, no pieces are being transported and while any part is being transported, no work occurs
3) all workcenters must stop when one or more workcenters stop

In a standard transfer line the items are fixed, ie. if the system produces items A, B, and C, then it will always produce A, B, and C. It can not produce a different item D. Transfer lines that can produce one or more items that are different from the items currently produced by using software only are said to be flexible transfer lines.

Often, those who design transfer lines have the tendency to breakdown the machining tasks that must be performed into the smallest possible operations. An example of this would be to have one workcenter drill a hole and then have another workcenter chamfer that same hole. In most cases, the drill and chamfer operations can be performed simultaneously at a single workcenter. The goal of using the smallest possible operation is to increase speed by using one workcenter for each. The effect of this breakdown is a high number of dedicated workcenters that operate in a manner similar to a pipeline computer architecture.

A full operation is a set of one or more operations accomplished at one workcenter in such a manner that the area affected is in finished condition because it meets the specification of the item. This means that if a drilled hole also has to be chamfered to meet the specification then the full operation would be accomplished by performing the drill and chamfer operations at the same workcenter.

If a full operation can be accomplished with one tool then it is call a single step full operation. In an optimum scenario, all operations would be single step full operations that required only one pass of a tool over any one workarea. The transfer line under discussion has no full operations.

In the company being discussed, each production line is dedicated to a specific differential case. Figure 1-a shows the layout of one of the lines. During production, a single casting is machined to produce a single differential case.

The production line is divided into two sections, A and B. Each section is a transfer line. Section A has 8 workstations and produces 2 parts every 45 seconds. The parts from section A are placed into a buffer and passed to section B on demand. Section B has 20 workstations and 12 workplaces where no activity occurs. It produces a finished differential case every 28 seconds. All of the times given include workcenter to workcenter transfer times.

A summary of the performance characteristics can be found in Figure 3. Throughput as used in this paper is the gross maximum number of items that can be produced. Utilization is a rate that indicates the percentage of time the workstation is being used to produce a part.

All of the characteristics of this transfer line were taken from real world data with the exception of its performance during interruptions. After a warm-up period, each machine in section A has about the same throughput and utilization. The difference in throughput among these machines is less than 2 parts per 8 hour shift while the utilization is exactly the same. The section B machines had similar characteristics. Overall, section A has slightly higher throughput. On average, it runs about 25% more than section B. In the next section we will discus flexible manufacturing systems.

## A Cell Structured FMS:

Theo Williamson, the former Director of R & D at Molins in Deptford London, coined the term flexible machining system to describe a machining system that was designed to operate 24 hours a day [4]. Since that time the term has been expanded to flexible manufacturing system and has taken on many meanings to different people.

Today the term is most widely used to indicate what J. Buzacott called "job flexibility" [5]. The definition of FMS used in this paper has this concept in mind. We use the term FMS to mean a set of two or more workcenters that are linked together in such a manner that parts can be moved from one workcenter to another workcenter where work is performed at the workcenters forming a system where new items can be manufactured exclusively through use of software.

This definition of FMS implies many features that are often desired characteristics. For example, because the items output can be changed via software, a certain expediency is implied. Such changes will probably be performed close to the maximum speed of the workcenters. Furthermore, production lines that need to change tools to produce new items, but only have manual tool changing capabilities are eliminated from consideration.

Often flexibility is associated with such features as expandability, response time, minimum working capital, and fault tolerance and failure recovery. For the purposes of this paper, the term "robust" will be used to refer to these and other additional desired features.

There are many types of flexible manufacturing systems. One way to classify a FMS is by its topology. In this section we will focus on the most common type of FMS called a cell or cell structured FMS (CS FMS). Cells can be characterized as having a central flow of parts along a set of links that have all of the workcenters connected at various points. The set formed by the minimum number of links required to connect all workcenters is called the spinal cord of the system.

The spinal cord, itself, may be disjoint forming a line segment or nondisjoint forming a closed loop. Closed loop production lines have the advantage of being able to feed parts, that are out of specification and can be corrected back, into a line that has a unidirectional flow of parts along the spinal cord.

A CS FMS can overcome the limitations of a transfer line. The flow of parts through this type of FMS can be dynamic. It can be changed at runtime if required, to send parts around blocked workcenters. Work and transportation can occur simultaneously. The CS FMS does not have to process parts in a lock-step method. And best of all, operable workcenters can continue to process parts when other workcenters are down.

A CS FMS provides a significant performance improvement over the transfer line discussed in the previous section. The biggest increases were achieved by maximizing the number of full operations needed to produce the differential case. The reduced cycle time lowered the amount of capital investment needed to purchase the FMS.

A closed loop cell was selected as our model for comparison. A diagram of the layout is given in Figure 1-b. On preliminary estimates of operational performance, three cells of five workcenters each are used. Four types of workcenters A, B, C, and D are used in this production line, each of which perform a different function. Each cell uses 2 of type A and 1 of types B, C, and D for a grand total of 6, 3, 3, and 3 in all cells respectively.

The performance characteristics of this CS FMS are given in Figure 2. This configuration will produce 1 item every 20 seconds. The throughput of workcenters B, C, and D is one-half of throughput produced at workcenter A in each cell. The utilization of the workcenters within each cell varies quite dramatically. In general, workcenter A is about 12 times slower than the others. Next, we will discuss a lattice structured FMS.

## A Lattice Structured FMS :

A lattice structured FMS (LS FMS) is another type of FMS that is so named because of its topology. This type of production line has two prominent features. The first is that it meets the criteria previously given in the definition of FMS.

The second prominent feature is its topology. The basic element of a lattice is a closed regular polygon. The vertices of the polygon are called nodes. Nodes indicate the placement of workcenters in the lattice. The line segments that connect the nodes and form the external surface of the polygon are called external links. Each element in a lattice may also have internal links, which are line segments that connect two different nodes and touch the surface of the polygon only at the endpoints. All links are non-redundant, ie. between any two nodes there is at most one link.

The lattice structure can be formed by connecting a basic element to another basic element or a lattice constructed from the same basic element. Basic elements must be connect by N nodes, where N >= 2. After each connection, N nodes are overlaid and hence their workcenters coalesce. N must be maximized during each connection.

Many lattice structures are possible. The model in our example uses a square as its basic element. A diagram of the layout is given in figure 1-c. The LS FMS model uses the same workcenters and operations as the cell structured FMS. However, the composition is different. The lattice uses 7 of type A and 2 of types B, C, and D.

The performance characteristics of the LS FMS can be found in Figure 2. This configuration will produce an item every 17.14 seconds. The throughput and utilization of the individual workcenters is the same as in the CS FMS, but the CS FMS produces an item only every 20 seconds. Therefore, the LS FMS gives 17% greater throughput.

## Results:

All of the production lines presented in this paper are compared based on the results produced by simulation where real world data is not available. SIMFACTORY II.5 was used to simulate the production lines. The data used for the simulations was gathered from actual test times and studies of interruptions and other phenomena natural to manufacturing environments where possible.

Several interesting facts have resulted from this research. The LS FMS proved to be the most robust of the three. Notice the down sizing of the production lines between the models. The transfer line uses 28 workcenters; the cell structured FMS uses 15 workcenters; and the lattice uses 13 workcenters. The LS FMS has the highest throughput. The cell and lattice structured production lines have less work in progress because they don't have internal buffers and have less workcenters.

The lattice system is the most modular of the three production lines. It can be expanded more cost effectively than the others because single workcenters can easily be added or removed from endnodes. To expand the throughput of the transfer line, all of the slowest workcenters must be replaced or another transfer line must be added. In the first case, the burden is on the manufacturer to salvage or find a place for the slower workcenters. The latter choice is viable mainly when the production quantity needs become a multiple of the existing production line. This same deficiency exists in the CS FMS. In both models it is difficult to increase or decrease the scale of production in small increments, such as a single workcenter, while continuing to use balance of the existing configuration in an integrated environment.

The LS FMS outperformed the other production lines in every scenario. However, the CS FMS has one advantage. It is possible to stop production in the LS FMS by blocking two workcenters. In contrast, the CS FMS will always produce items when two workcenter are blocked. The LS FMS is only slightly more cost effective today then the CS FMS. Both are significantly more cost effective than the transfer line.

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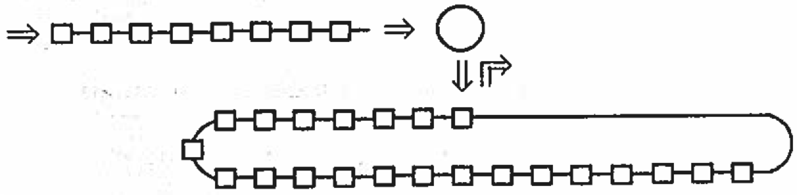

Figure 1-a Transfer Line

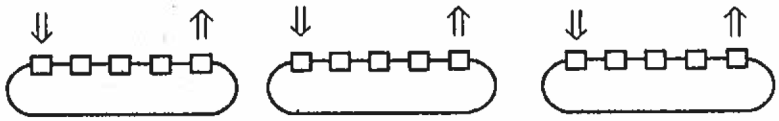

Figure 1-b Cell Structured FMS

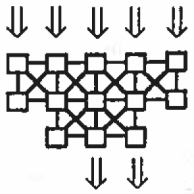

Figure 1-c Lattice Structured FMS

Legend

⇓ ⇑ ↱ - input/output

☐ - workcenter

○ - buffer for work-in-progress

PERFORMANCE/COST CHARACTERISTICS:

| | Transfer line | Cell FMS | Lattice FMS |
|---|---|---|---|
| warm-up time from cold start (no wip) | 21.94 min. | 2.67 min. | 2.67 min. |
| avg. workcenter utilization after warm-up with no interruptions at max production rate<br>max. / min. | 80%<br>80% / 70% | 50%<br>94% / 15% | 62%<br>94% / 15% |
| parts per hour after warm-up | 128.57 | 180 | 210 |
| est. capital cost of production system | $10 million | $6.295 mil. | 6.285 mil. |
| est. capital cost hourly per part | $311,114.56 | $34,972.22 | $29,928.57 |
| mean parts/hr produced (1 workcenter down)*<br>max. / min. | 0<br>0 / 0 | 120<br>150 / 120 | 180<br>210 / 180 |
| mean parts/hr produced (2 workcenters down)*<br>max. / min. | 0<br>0 / 0 | 60<br>120 / 60 | 150<br>180 / 0 |
| mean parts/hr produced (3 workcenters down)*<br>max. / min. | 0<br>0 / 0 | 60<br>120 / 0 | 120<br>180 / 0 |

*interruption occurred after warm-up and lasted for 24 hours

Figure 2. Performance/Cost Comparison

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