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A Methodology for Investigating Effects of Cell Size on Operational Flexibility in Flexible Manufacturing Systems

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There are two aspects to cell formation in flexible manufacturing systems, cell sizing or deciding on the optimum number of machines to be allocated to each cell, and then allocation of specific machines to each cell. Although the latter problem has been investigated extensively there is a paucity of published work on the former. This paper discusses the effects of cell sizing on operational flexibility.

Operational flexibility is that aspect of flexibility that enables manufacturing systems to respond with speed and efficiency to changes in the manufacturing environment while maintaining an effective level of control.

Keywords: Cell size; Flexible manufacturing systems; Manufacturing cell control; Operational flexibility

1. Cell Sizing in FMS

Cell formation in flexible manufacturing systems consists of two stages:

1. Deciding cell size (cell sizing)
2. Allocating specific machines to each cell to process a family of parts.

This paper discusses the relationship between cell sizing and some of the factors that contribute to operational flexibility in a flexible manufacturing environment.

Greene and Sadowski [1] have defined the group characteristics of a family of parts processed in a flexible manufacturing cell in terms of:

1. Job routeing
2. Number of operations per job
3. Number of different job types
4. Job mix
5. Processing time
6. Due date

The methodology described in this paper for cell sizing is based on two of the above characteristics, number of operations per job and processing time.

It has been stated that no generalised methodology exists for calculating cell size [1,2]. The authors investigations indicate that a methodology based on the specified parameters has wide application and could be extended to various groups of components that are manufactured in a flexible manufacturing environment.

2. Flexibility of FMS

Browne et al. [3] have described the various aspects of flexibility in FMS in terms of:

1. Machine flexibility
2. Process flexibility
3. Product flexibility
4. Routeing flexibility
5. Volume flexibility
6. Expansion flexibility
7. Operation flexibility

Machine flexibility has been defined as the ease of making changes required to produce a given set of part types. Machine flexibility has increased considerably in recent times with the development of multi axis CNC machines equipped with a large number of tools. Ability to store a large number of programs within the machine controllers has enhanced this flexibility even further. An increase in machine flexibility would increase operational flexibility in turn.

Process flexibility is the ability to produce a given set of part types using different materials in several ways. Process flexibility is achieved with machine flexibility and a reduction of set-up times. An increase in process flexibility would increase operational flexibility.

Product flexibility is the ability to change over to produce a new set of part types very economically and quickly. Product flexibility is achieved by the use of effective production

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planning and control techniques and machine flexibility. An increase in product flexibility would increase operational flexibility. Routeing flexibility is the ability to handle breakdowns and continue producing a given set of part types. Routeing flexibility can be increased with increased reliability of machines and ability to process parts via several routes. The latter situation would lead to increasing complexity of the control system and as a result a reduction in operational flexibility. In practice, it is desirable to achieve routeing flexibility by increasing the reliability of machines which would in turn increase operational flexibility.

Volume flexibility has been defined as the ability to operate an FMS profitably at different production volumes. This is achieved in practice by increasing machine flexibility, having a layout not dedicated to a particular process and a sophisticated automated material handling system. An increase in volume flexibility is desirable and would lead to an increase in operational flexibility.

Expansion flexibility is the capability of building a system and expanding it as needed easily and modularly. This aspect of flexibility is measured by how large the FMS can become. The research effort described attempts to investigate how large each flexible manufacturing cell can be before operational flexibility is significantly reduced.

Operation flexibility has been defined as the ability to interchange the ordering of several operations for each part type. If it is accepted that computer-aided process planning techniques are used primarily to achieve efficiency through standardisation then operation flexibility would not be desirable. While it is accepted that an increase in operation flexibility would enable a flexible manufacturing system to operate "flexibly" it would also significantly increase the complexity of control of the system. Therefore an increase in operation flexibility would in most instances lead to a decrease in operational flexibility. In conclusion it could be stated that an increase in machine flexibility and machine reliability would increase flexibility in general and operational flexibility in particular of manufacturing systems.

2.1 Operational Flexibility in FMS

Kim [4] has stated that "any action which enables manufacturers to do things quicker or sooner than they were able to do before will increase operational flexibility". He also lists the following factors which increase operational flexibility:

1. Reduction in set-up time
2. Reduction in machine process time
3. Reduction in supply delivery time
4. Reduction in design cycle time

The author's definition of operational flexibility states that "operational flexibility is that aspect of flexibility which enables manufacturing systems to respond with speed and efficiency to changes in the manufacturing environment while maintaining an effective level of control". Operational flexibility is of particular importance to small companies which act as suppliers to large companies and wish to exploit the benefits obtained from implementing flexible manufacturing technologies. Operational flexibility would be enhanced by the following factors in addition to those listed by Kim [4]:

1. Increased machine flexibility
2. Increased machine reliability
3. Increased transporter speeds
4. Ability to process a large family of parts within the cell
5. Scheduling production within short planning periods

The authors definition of operational flexibility incorporates the concept of efficiency which would be translated in practice to mean continued achievement of the objectives of the manufacturing system. For the purposes of this project it has been assumed that the objective of the manufacturing system is to minimise throughput time and maximise production while maintaining low work in process levels.

2.2 Cell Size and Operational Flexibility

As the manufacturing cell is increased in size it would contain more machines and therefore the number of part types that could be processed in the cell would increase. This results in increased operational flexibility. However, an increase in cell size would also increase throughput time, thereby adversely affecting the objective of the manufacturing cell.

A decrease in cell size would lead to reduced throughput time and therefore improved performance in terms of achieving the objective of the cell. However, a decrease in cell size would result in a smaller number of part types being processed within it thereby reducing operational flexibility. Creating a larger number of small cells would also result in unnecessary machine duplication.

One could therefore state that there is an "optimum" cell size that would enable the achievement of manufacturing objectives while maintaining acceptable levels of operational flexibility. This paper describes an attempt to provide guidelines for deciding on this "optimum" cell size. Although the guidelines are confined to manufacturing systems with the specified objectives and components with specific characteristics the underlying methodology has wider relevance.

3. Control of FMS

Several researchers [5–10] have examined the control features of flexible manufacturing systems. There is consensus that a hierarchical type of control structure would be most suitable for the control of flexible manufacturing systems. There is also agreement that the type of control effected in terms of information flow and time constraints is different at each level of the hierarchy.

The levels of control could be described as:

Level 1. Machine control

Level 2. Manufacturing cell control

Level 3. Manufacturing system control

Level 4. Factory level control

The research effort described here is focused on level 2, i.e. manufacturing cell control. O'Grady [11] has described four levels of operation of the manufacturing cell control system. They are:

1. Highly centralized mode
2. Loading mode
3. Itemised mode
4. Decentralised mode

In the highly centralised mode little or no decision making is carried out at the cell level and as such the communication channel between the manufacturing cell (level 2) and the manufacturing system (level 3) is vital to the operation of the cell. If the communication between the cell and system levels is interrupted the cell activity ceases almost immediately.

In the loading mode a cell is loaded with a quantity of work to be done during a specified period of time. The cell control system has to schedule and control this quantity of work so that it is completed during the planned time period. Control is less centralised than with the highly centralised mode and if the channel of communication between the cell and the system control levels is interrupted the quantity of work allocated would be completed and then cell activity would cease.

In the itemised mode the manufacturing cell is loaded with individual jobs at relatively frequent time intervals. As compared to the loading mode the work quantity would be a single component. In the event of a breakdown of communications between the manufacturing cell and system control levels activity would continue in the cell until the components in the buffer stores are processed. Because the components arrive singly the cell control system has to complete the detailed schedule of cell activities more frequently than in the loading mode. As such, computing times associated with detailed scheduling could become an important factor. An advantage of this mode over the loading mode is that lead times and work in progress levels would be lower. A disadvantage over the loading mode is that there is considerably more communication between the cell and system control levels.

In the decentralised mode communication between the cell and system control levels is at a minimum. This mode of operation enables the cell to operate independently with the system controller intervening only if there is a deviation from planned activities.

For purposes of this investigation it has been assumed that the manufacturing cell control system operates in either the loading or decentralised modes which enables less complex control systems to be implemented with minimal interaction between cell and system controllers. These configurations also exploit the benefits to be obtained from current state of the art computer technology.

3.1 Manufacturing Cell Control

At the manufacturing cell control level short bursts of information are used to effect control in real time. The time interval between decisions could typically vary between a few milliseconds and several minutes. Kalkunte et al. [9] have described this level of control as dynamic operations planning and listed activities carried out as consisting of sequencing of parts between machines in the cell, despatching transporters to move parts between machines in the cell and monitoring the system to ensure satisfactory operation. Rana and Taneja [10] have described activities carried out at the manufacturing cell control level in terms of:

1. Inspector modules
2. Loading modules
3. Task despatcher modules

These activities are identical to those listed by Kalkunte et al. [9].

Pimentel [12] has observed that the activities carried out by the manufacturing cell controller consist of:

1. Distributed monitoring
2. Distributed control
3. Distributed scheduling

These activities are described as follows:

1. Distributed monitoring: controller monitors the state of all machines and devices belonging to the cell.
2. Distributed control: the controller controls the operation of all machines and devices in the cell.
3. Distributed scheduling: once the cell controller receives the commands and objectives from the system controller it generates its own schedule in order to meet the objectives. The schedule is generated by taking into account the resources available in addition to the predetermined objectives.

In summary it could be stated that the two types of functions carried out within the control system of a manufacturing cell are:

1. Directing activities that result in processing of components
2. Monitoring of the system to ensure satisfactory operation

3.2 Cell Size and Complexity of Control

As the manufacturing cell is increased in size the number of activities to be initiated and controlled within a specified time horizon are increased. As a consequence the complexity of the system is increased. The effectiveness of the control system would be dependent on the complexity of the system to be controlled and the hardware/software tools used to effect control. It would be reasonable to state that as the complexity of the system increases it is more difficult to maintain effective control and therefore operational flexibility. As such, the larger the size of the manufacturing cell the more difficult it would be to maintain an effective level of control.

As stated earlier the two types of functions carried out within the control system of a manufacturing cell are:

1. Directing activities that result in processing of components
2. Monitoring of the system to ensure satisfactory operation

The authors have defined complexity of control in terms of activities carried out to process components in the cell as investigations reveal that this activity is more "time critical" than the monitoring function in the circumstances under investigation.

Having chosen to define complexity of control in the terms described the problem of quantifying it in practice remained. The parameters chosen to quantify complexity of control were the maximum number of concurrent events, and if there were no concurrent events then the minimum interval between events occurring in the manufacturing cell. An event would be any activity that resulted in a change in the state of the system.

4. Simulation as a Design Tool

There are three approaches to designing flexible manufacturing systems and analysing their performance:

1. Analytical techniques
2. Petri-nets
3. Simulation

Analytical techniques such as queuing networks and perturbation analysis are based on several assumptions that restrict the validity of the results when applied to flexible manufacturing systems. Petri-nets [13] are best suited for modelling the information flow within flexible manufacturing systems, a subject beyond the scope of this project. Simulation techniques are ideally suited for investigating the effects of the various factors described previously on cell sizing as proven by various research efforts in allied areas of flexible manufacturing system design [14]. Simulation was chosen as the technique to be used in investigating the effects of cell size on operational flexibility. The particular simulation software selected for the task was MAST [15] or "Manufacturing System Design Tool" a software package developed specifically for the design and evaluation of flexible manufacturing systems.

5. Experimental Procedure

Investigation of the effects of cell sizing on operational flexibility was carried out in two stages. The first stage has been completed and involved the study of the effects of the following factors on cell formation:

1. Machine reliability
2. Machine flexibility
3. Transporter speed
4. Component processing time

Two models of flexible manufacturing systems were constructed and their performance compared using the MAST Simulation Software Package. Performance in this instance meant achieving the primary objective of the manufacturing system, i.e. minimising throughput time and maximising production while maintaining acceptably low work in process levels. One model consisted of a large cell able to process five part types and the other consisted of five small cells each capable of processing one of the part types processed in the large cell. Data for the simulation exercise was obtained by analysing the manufacturing profiles of some companies implementing flexible manufacturing technologies. The detailed experimental procedure is described elsewhere [16].

At the second stage of the investigation those factors considered previously that significantly improve the performance of the large cell will be analysed further in relation to the complexity of control of manufacturing cells. The experimental procedure will involve the decomposition of the model used in stage one to process five part types into one processing four, three, two and one part type in turn while varying the parameters that significantly improve the performance of the large cell. Each cell configuration will be investigated in relation to its complexity of control. This is done by analysing the event file of each simulation run and extracting values for certain parameters as described previously.

On completion of stage two of the investigation sufficient information would be available to provide guidelines for cell sizing so as to achieve the objectives of the manufacturing system while maintaining a significant level of operational flexibility.

6. Evaluating the Results

Figs. 1 to 3 compare the performance of the process layout [cell processing five part types] and the cell layout [cell processing one part type] in terms of total production achieved

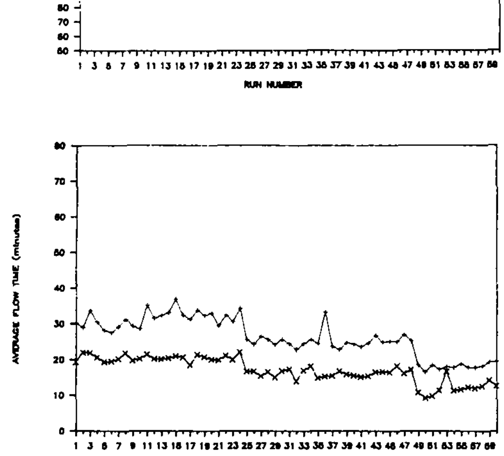

Fig. 1. Cart speed 20 m/min; reliability 98%. For all figures in this paper: +, process, ×, cell.

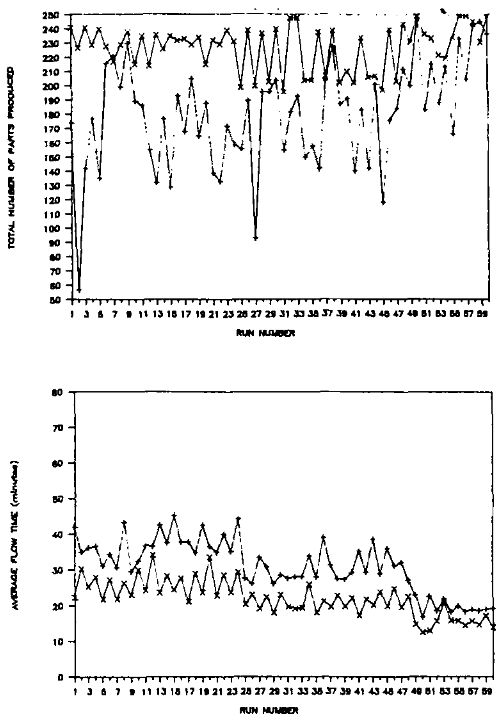

Fig. 2. Cart speed 20 m/min; reliability 90%.

and average flow time when machine reliability is reduced from 98% to 90% and then to 80%. The values for the cell layout are obtained by averaging the values for the five separate cells. It is apparent that the peformance of the process layout does not exceed that of the cell layout even at a reliability of 80%. This is especially significant as there is appreciable machine duplication in the process layout. One could therefore conclude that machine reliability does not significantly affect cell performance.

Figs. 4 to 6 compare the performance of the process layout and the cell layout when transporter speeds are increased from 10 m/min to 20 m/min and then to 35 m/min. It is seen that the performance of the process layout tends towards that of the cell layout with increasing transporter speed. As such it could be stated that increasing transporter speed improves cell performance.

Figs. 7 to 9 compare the peformance of the two layouts with varying machine reliability but also with flexibility of all machines increased by 100% (each machine carries out two operations, not one as before). There is an improvement in performance of the process layout relative to the cell layout especially with reduced machine reliability.

Figs. 10 to 12 compare the performance of the process layout and cell layout with varying transporter speed but again with machine flexibility increased by 100%. Here too

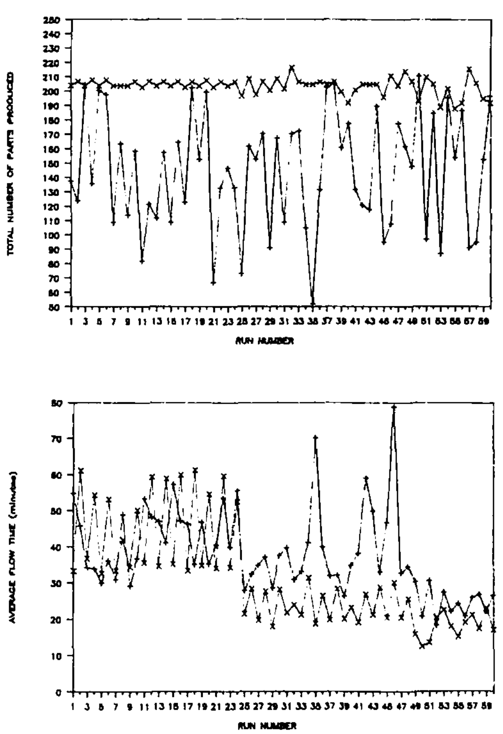

Fig. 3. Cart speed 20 m/min; reliability 80%.

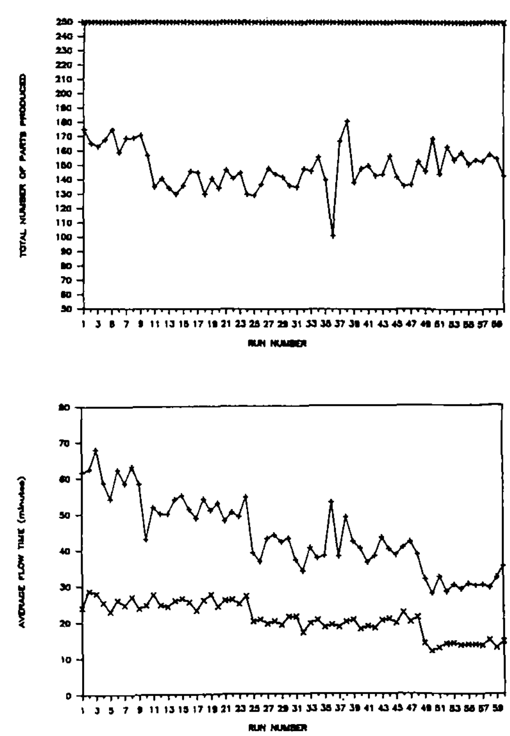

Fig. 4. Cart speed 10 m/min; reliability 100%.

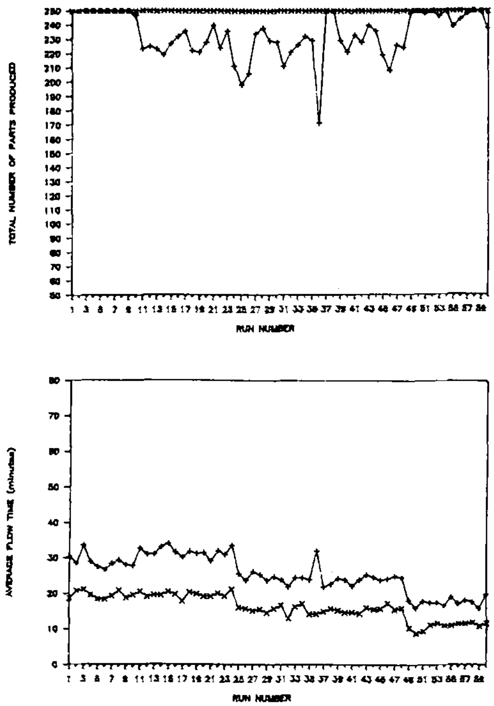

Fig. 5. Cart speed 20 m/min; reliability 100%.

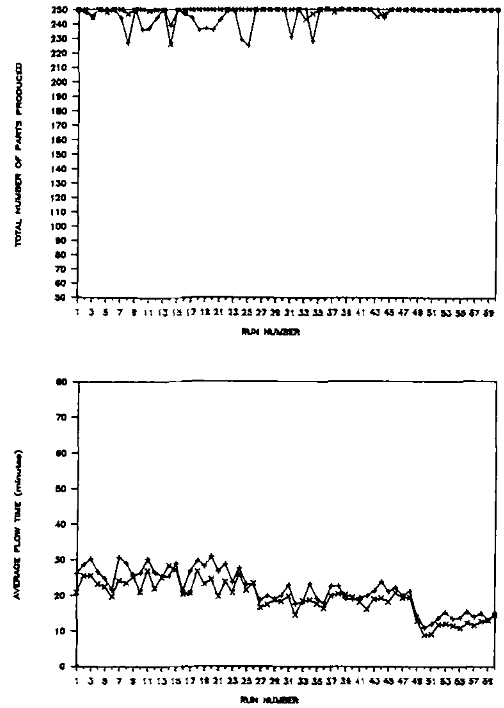

Fig. 7. Cart speed 20 m/min; reliability 98%.

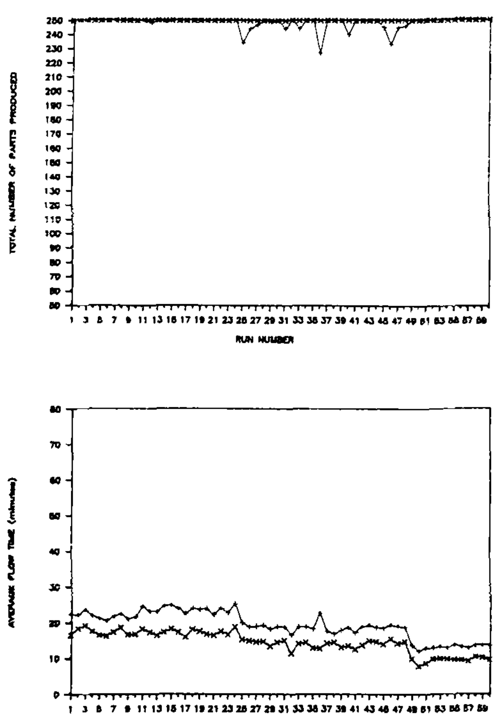

Fig. 6. Cart speed 35 m/min; reliability 100%.

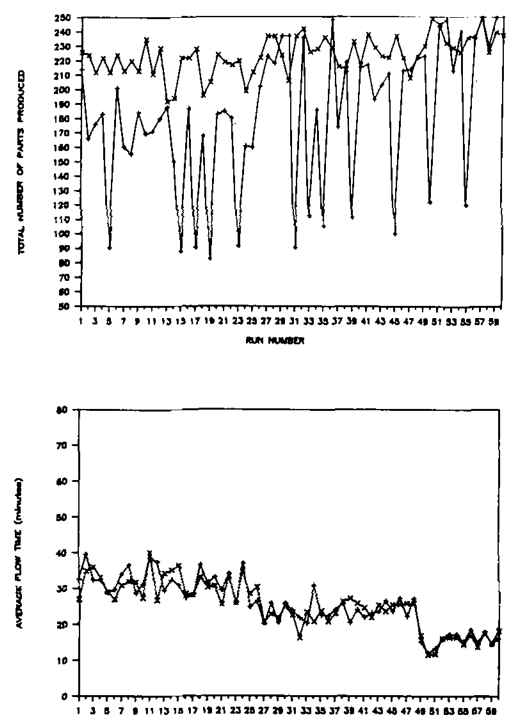

Fig. 8. Cart speed 20 m/min; reliability 90%.

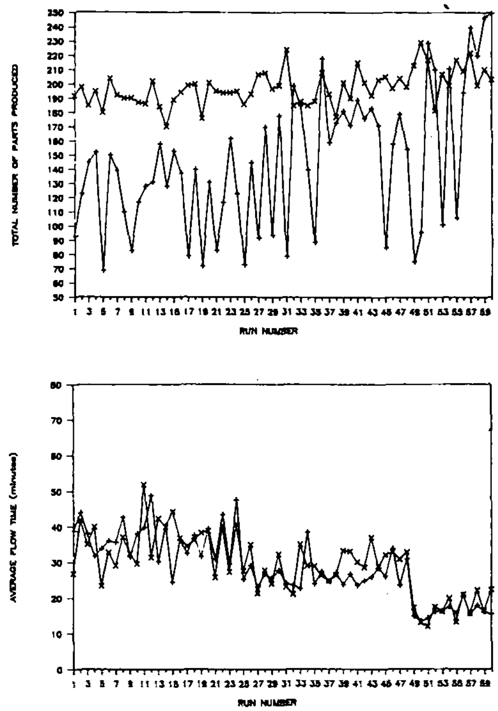

Fig. 9. Cart speed 20 m/min; reliability 80%.

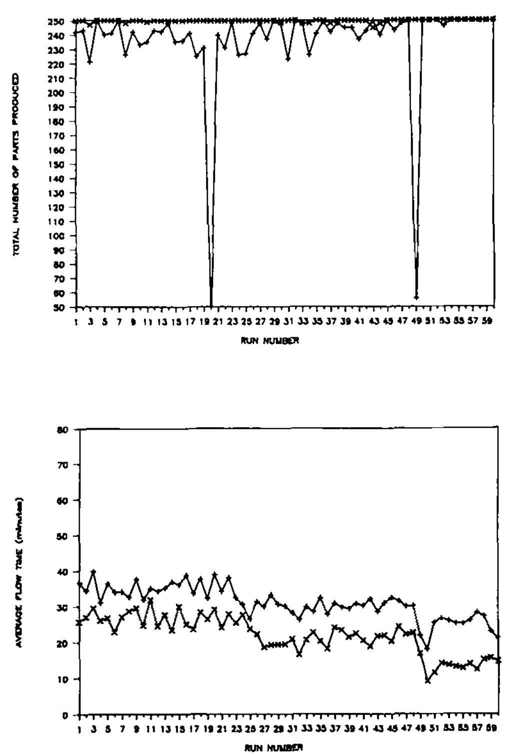

Fig. 10. Cart speed 10 m/min; reliability 100%.

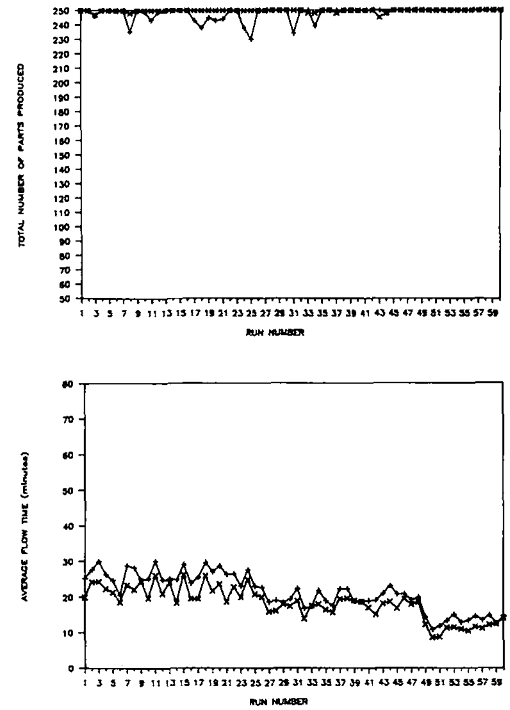

Fig. 11. Cart speed 20 m/min; reliability 100%.

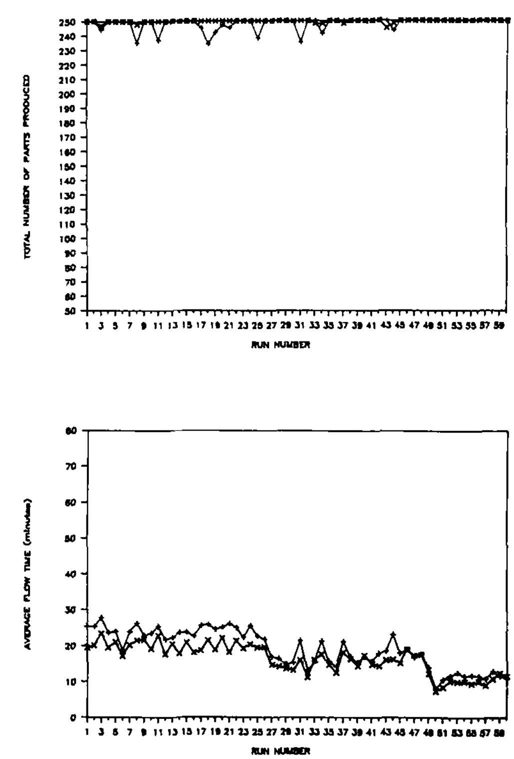

Fig. 12. Cart speed 35 m/min; reliability 100%.

there is some improvement in the performance of the process layout but the improvement is not as significant as with varying machine reliability. This is probably due to the fact that with increasing machine flexibility the process layout (cell processing five part types) has reduced in size in comparison with the cell layout. Nevertheless, in conclusion it could be stated that increasing machine flexibility improves cell performance and enables "large" manufacturing cells to improve performance in relation to "small" manufacturing cells.

Figs. 13 to 15 compare the performance of process and cell layouts when machine reliability is reduced from 98% to 90% and then to 80% while processing times for all components are reduced by 50% overall. It is observed that there is no significant improvement in the performance of the process layout relative to cell layout.

Figs. 16 to 18 compare the performance of the two layouts when transporter speeds are increased from 10 m/min to 20 m/min and then to 35 m/min, again with all processing times reduced by 50%. There is a significant improvement in the performance of the process layout relative to the cell layout but the improvements are not significantly greater than those obtained without a reduction in processing times. Therefore it could be concluded that a reduction in processing times does not lead to a significant improvement in the

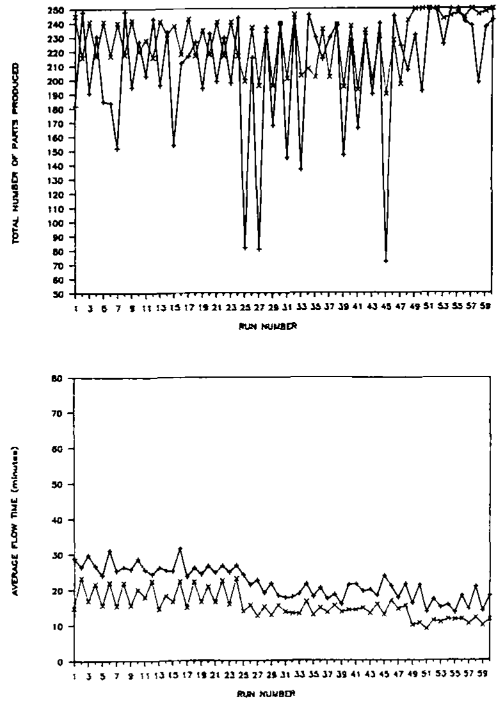

Fig. 14. Cart speed 20 m/min; reliability 90%.

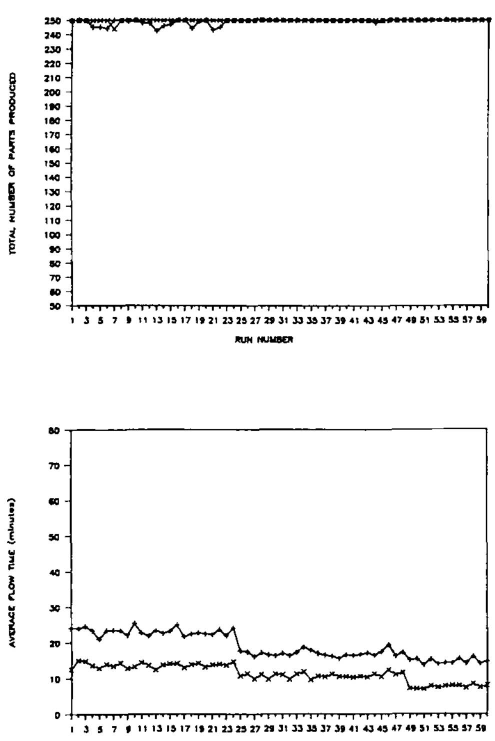

Fig. 13. Cart speed 20 m/min; reliability 98%.

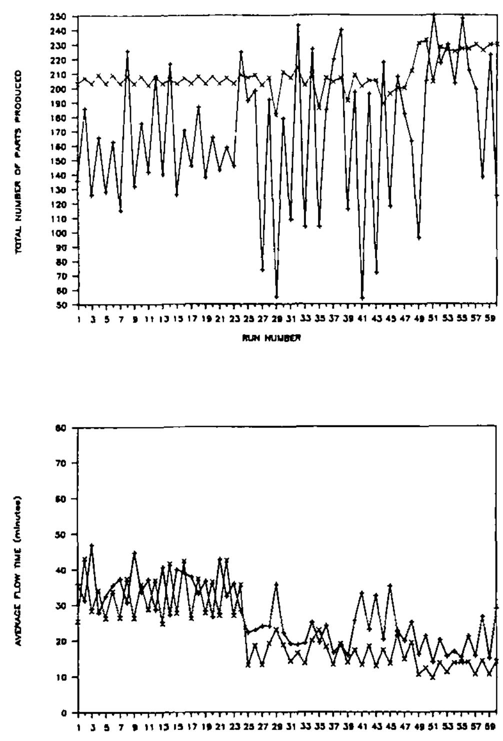

Fig. 15. Cart speed 20 m/min; reliability 80%.

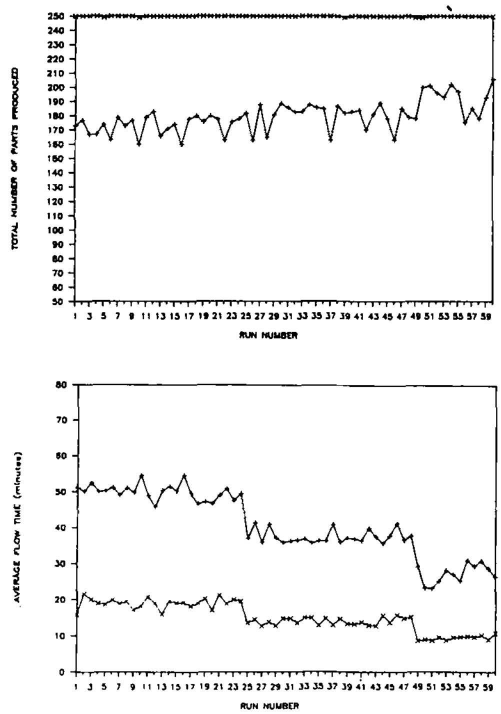

Fig. 16. Cart speed 10 m/min; reliability 100%.

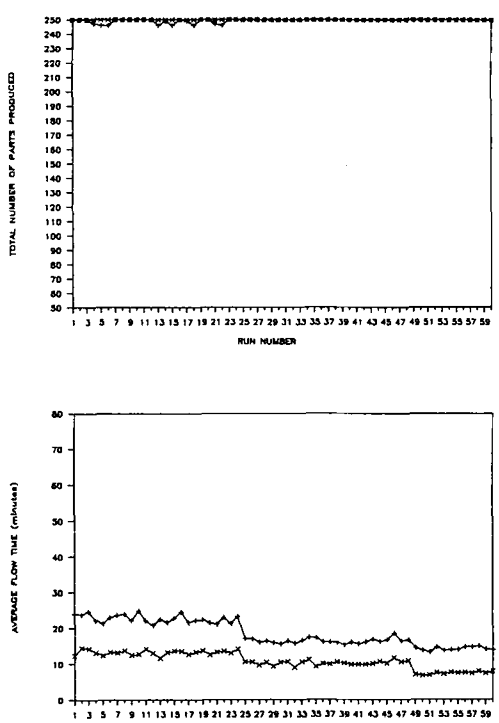

Fig. 17. Cart speed 20 m/min; reliability 100%.

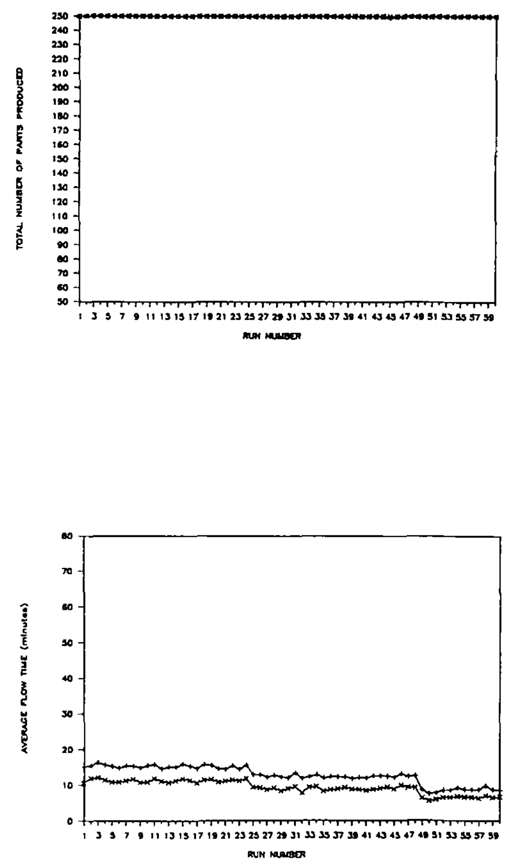

Fig. 18. Cart speed 35 m/min; reliability 100%.

performance of "large" manufacturing cells in relation to "small" ones.

In summary it can be stated that increasing transporter speeds and machine flexibility is effective in increasing operational flexibility by enabling "large" manufacturing cells to achieve performance levels comparable with those achieved by "small" cells.

7. Future Directions

The parameters of transporter speed and machine flexibility will be investigated further in relation to complexity of control of flexible manufacturing cells. This is to enable guidelines to be developed for sizing manufacturing cells that maintain acceptable levels of operational flexibility while achieving manufacturing objectives.

At the present time in quantifying complexity of control no differentiation has been made between the various activities carried out in processing components within a manufacturing cell. In reality, differences do exist. For example, the control function relating to despatching a transporter to move components between machines in a cell would be more complex than that involved in initiating a processing cycle on a component already present on a machine.

Future research efforts will be focused on quantifying complexity of control while differentiating between the various types of control activities carried out within a manufacturing cell. This would enable more accurate guidelines to be developed for sizing flexible manufacturing cells that maintain acceptable levels of operational flexibility while achieving manufacturing objectives.

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