THE IMPACT OF EXTERNAL DISTURBANCES ON THE PERFORMANCE OF A CELLULAR MANUFACTURING SYSTEM

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ABSTRACT

Cellular manufacturing has been proposed as an approach to cope with the uncertainty characteristic of customer driven markets. However, even cellular manufacturing systems are prone to the effects of varying demand patterns. In this study, the effects of some aspects related to demand variation such as the arrival of material, the variety of products and the variation in product mix are investigated to identify those system characteristics that -within the context of cellular manufacturing systems- represent an advantage in the presence of such disturbances. To do so, discrete event simulation is used to conduct the experimentation by modelling a cellular manufacturing system. Additionally, statistical design of experiment is employed to identify the factors contributing to higher system performance. The results show that, in spite of the demand related disturbance, machines with low set-up duration and highly skilled operators constitute the most important characteristics of an efficient manufacturing cell.

Keywords: cellular manufacturing system, manufacturing disturbances, simulation

1. INTRODUCTION

The current economic environment is characterized by customers having more power than producers in terms of shaping market demand. As a result of customer driven market, low volume and high variety have become an important characteristic in manufacturing. In the presence of these exigencies companies must develop the capability to respond in the shortest time, with the highest levels of quality and with the lowest possible cost. One manufacturing approach to meet the expectations customer driven markets is the cellular manufacturing configuration. This system configuration is characterized by the grouping of different types of machines according to the process combinations occurring within a family of parts, which means that material flows differ for different parts of the same family. However manufacturing cells are not exempt from the influences of disrupting factors or disturbances. According to Deane and Yang (1992), some of those factors affecting cell performance are: machine capacity constraints, complexity of job routing requirements, demand volume, demand pattern and product mix characteristics. In this study particular attention is paid to the last three factors which are originated outside the limits of the system and therefore are considered as external disturbances.

Customer driven markets have an important influence on the arrivals of materials into the manufacturing system. On the one hand, periods of low demand lead to a low utilization of the system's resources; on the other hand, periods of high demand lead to an increase in the arrival rate. Even though an increase in the arrival rate is associated with an increase in throughput and therefore an increase in income, similarly, an increase in the arrival rate inevitably leads to an increase in costly work-in-process (WIP) inventory. The arrival of materials and its influence on system's performance has been approached by a number of authors, among those Tielemans and Kuik (1996) studied the relationship between batching of arrived orders and WIP in order to reduce lead time; they recognised the impact long waiting times could have on system's performance. Chikamura *et al.* (1998) tested the influence of several lot arrival distributions on 7 production dispatching rules. The authors noticed that under most of the arrival scenarios, the best results were observed by a dispatching rule considering variables such as set-ups, waiting times and processing times. Govil *et al.* (1999) focused on the time of new lot arrivals in order to determine ways to predict average queue length at manufacturing resources. Prabhu (2000) claimed that arrival time determines the evolution of events in the manufacturing system, the sequence in which parts are processed and the machine idle time between processing parts. Given the important impact of arrival time on system's performance, this author proposed the arrival time to be selected as a control variable in manufacturing systems. Moreover, Van Ooijen and Bertrand (2003) investigated the effects varying arrival rates have on throughput and WIP for a job shop; they concluded that an acceptable throughput would not necessarily imply a high arrival rate. In addition, they identified a trade-off between the costs associated with controlling the arrival rate and the revenues obtained by throughput.

Another implication of customer driven markets is an increasing demand for more variety. A higher product choice leads to more problems occurring in manufacturing systems; this is due to the level of complexity increasing along with variety. Research on product variety is a divergent topic; some views claim a significant impact of product variety on manufacturing performance, whereas other views suggest that there is actually no impact. MacDuffie *et al.* (1996) identified a trade-off associated to product variety; the authors noticed that whereas there is a higher revenue resulting from a wider variety, there are related higher costs and a loss of economies of scale as well. Although Fisher and Ittner (1999) acknowledged some common negative effects of variety, they also recognised that variety leads to benefits such as increased revenue. Berry and Cooper (1999) claimed that, in order to gain competitive advantage through product variety, it is necessary a proper alignment between marketing and manufacturing strategies in terms of process and infrastructure along with pricing and inventory. Randall and Ulrich (2001) argued that variety does not necessarily mean higher performance; they stated that regardless of variety strategies, the proper alignment between the supply chain and the product variety strategy is what is important. Thonemann and Bradley (2002) investigated the effects of product variety on supply chain performance and found that variety has an important effect on costs, especially when set-ups are significant. Fujimoto *et al.* (2003) stated that more variety causes less efficiency and higher costs; they presented a methodology to manage variety by synthesizing product-based and process-based approaches. Zhang *et al.* (2007) evaluated the impact of response time and product variety strategies on system's performance; they concluded that a higher performance is achieved when both strategies are combined.

The consideration of a wider product variety inevitably leads to another problem for manufacturing systems, which is the variation within the product mix. This is caused by a varying demand for different products, especially when a number of products are at different stages in their life cycle. Variation in product mix also has an important effect on system's performance mostly due to an increased complexity in the system; such complexity is caused by more processing flows and varying production quantities. Among some authors investigating product mix, Deane and Yang (1992) investigated the impact of product mix on the performance of a manufacturing cell; the authors found that in the presence of set-up times, reductions in terms of flow time can be realized by increasing the homogeneity of products. Anderson (1995) analyzed product mix heterogeneity and performance; she confirmed that an increase in manufacturing costs is associated with increases in the number and severity of set-ups and with an increased heterogeneity in process specifications of the product mix. This same author (2001) later found that product variety may have worst consequences for quality than for efficiency. Seifoddini and Djassemi (1996) recognized that changes in product mix lead to performance deterioration and presented a procedure for performance evaluation under product mix variations. The same authors (1997) also compared the performance of two manufacturing system configurations, namely job shop and manufacturing cell for a range of product mix variations; they found the cellular configuration showed the best results only when there were small changes in product mix. Liang *et. al.* (2011) studied the combination of virtual cells idea to construct new manufacturing systems in response to changing market dynamics. Egilmez *et. al* (2012) developed a non-linear mathematical model to the stochastic cellular manufacturing systems design problem to cope with a particular risk level, then simulated the obtained results to validate the proposed model and assess the performance of the designed cellular manufacturing system

The purpose of this study was to identify those components in a cellular manufacturing system contributing to maintain a higher system performance under the influence of external disturbances such as demand variations in both volume and pattern. This has been achieved by using the combined advantages of discrete event simulation and statistical design of experiments. The former was used to model a cellular manufacturing system with its main components; the latter provided the analysis structure for the identifications of those components with a major significance in terms of system performance. The consideration of both tools provided the capacity to adopt a wider perspective in the analysis and, therefore, not only did it facilitate the study of particular system components but also facilitated the study of the interactions occurring within the system.

2. RESEARCH METHOD

2.1. Simulation model

Discrete event simulation has been used to represent a semi-automated cellular manufacturing system consisting of 9 different work centres. Each work centre comprises one input buffer, one machine and one output buffer. All the work centres are connected by an automated material handling system. Each work centre is assisted by one of the six operators within the cell whose job basically consists on loading, controlling and unloading machines. Figure 1 graphically represents the cellular system previously described.

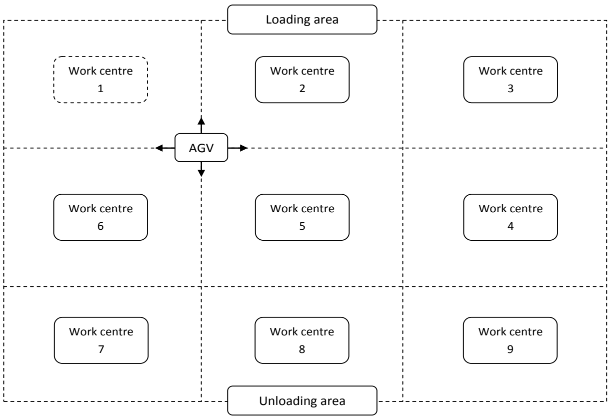

Figure 1: Cellular Manufacturing System Layout

2.2. Simulation model operation assumptions

The following are list of the assumptions considered during the development of the simulation model:

2.2.1. Parts

- Parts arrive in the system one at a time and following an exponential distribution with an average inter-arrival time of 45 minutes
- There are five different products involved; each product with different processing requirements, i.e. different processing times and routes. Process routing is fixed for each of the products.

2.2.2. Machines

- Each machine represents a specific manufacturing process within the system, therefore their different operative features.
- Machines can process only one piece at a time.
- Although all of the machines are assumed to follow a normal distribution in both processing and set up times, the times are different from each other.
- There is a different usage cost per minute associated to each machine.
- Machines do not have any automation level, therefore each machine do require an operator.
- It is assumed that all machines breakdown from time to time, consequently a different efficiency level has been predefined for each machine.
- When machines fail, repairs are assumed to be done by external personnel (not considered for the purposes of this research). Machine repairs are assumed to follow an exponential distribution with different average times for each machine.

2.2.3. Buffers

- Blocking does not occur.
- Buffer capacity is limited; all the buffers have the same capacity. There is a storage cost per item per minute associated to the capacity, i.e. the higher the capacity the higher the storage cost.
- Parts in buffers are prioritized according to FIFO dispatching rule, i.e. parts are dispatched either into a machine or vehicle considering a first come first served rule.

2.2.4. Operators

- Operators have different abilities; in consequence labour cost is associated to the skill level.
- Operators are assumed not to be always available, therefore different availability percentages and absence times have been specified for each operator.
- Travelling times for operators have not been considered.

2.2.5. AGV

- The material handling system is totally independent from human operators.
- The AGV travels at a constant speed along a fixed route connecting all the work centres.
- Material handling costs are omitted and no vehicle breakdowns are assumed.
- The AGV's travelling time is determined based on its speed.

2.2.6. Finished product

- Revenue per finished product regardless of its type has been assumed.

2.3. Model Verification

Model verification can be carried out in three different and complementary ways: Checking the code, performing visual checks, and inspecting output reports (Robinson, 1994). Code checking was facilitated by the capabilities of the simulation software, which made possible to interactively check the coding line by line. Visual checks were performed by keeping track of parts progressing throughout the system, allowing the behaviour of all the components intervening along the process to be monitored. Additionally, the model was run in an *event-by-event* mode in order to complement the verification process. This verification procedure made possible to guarantee that each element within the model would behave as it was originally intended. The last method of model verification consisted in checking the outputs of the main components within the model; to do so 30 replications, each with a run time of 400 simulation-hours, were conducted. After analysing some of the most important system outputs it was possible to confirm that all the model components performed according to what had been defined during the model coding process.

2.4. Model validation

Model validation provides the confidence during the experimentation stage and is basically concerned with the extent to which a certain model is representative of a real system. The level of representation will be judged upon the viability of making decisions based on the information provided by the simulation model. Ideally, a model would be better validated when compared to a real system (Pidd, 1993); however, models do not always represent real systems. Because the latter is the case in the present research, it was not necessary to compare the model with either empirical data or the behaviour of a real system (Maki and Thompson, 2006). Validation techniques are classified in two groups, namely subjective techniques and objective techniques. Objective validation-techniques do require the existence of real systems in order to establish input-output comparisons between systems. Subjective techniques, as their name imply, does not necessarily require the existence of a real system since they are more dependent on the experience and “feelings” of its developers (Banks, 1998). The proposed model has been validated using a sensitivity analysis as a subjective validation method. The sensitivity analysis capability is a built-in feature in Simul8; its function is to test the assumed probability distributions in terms of how sensitive the results are to changes in these inputs. A number of probability distributions particularly related to machine processing times and set-ups have been randomly selected to be tested. The sensitivity analysis confirmed the validity of the assumptions.

2.5. Experimental design

A minimum model warm-up period of 50 hours was calculated by using Welch’s graphical method. A minimum run length of 220 hours was also calculated by a graphical approach. Both approaches are described in Robinson’s (1994).

To measure the performance of the modelled manufacturing cell three different response variables were selected, namely number of completed parts, total cost and average time in the system. Regarding the design factors, three aspects related to work centres and three aspects related to the material handling sub-system were selected, those are the following:

1. The skill level of operators. It is determined by the number of different machines a single operator is able to control.
2. The capacity of inter-storage buffers. It is related to the maximum number of parts the system is able to hold.
3. The duration of machine set-ups. It is the time it takes for machines to switch from producing one specific type of part to producing a completely different type of part.
4. The number of AGVs. It is related to the total number of material handling vehicles within the system.
5. The speed of AGVs. It is the distance covered by material handling vehicles during a specific period of time.
6. The loading capacity of AGVs. The maximum number of parts a material handling vehicle can transport between work centres.

To investigate the effects of external disturbances on the performance of the modelled manufacturing cell, four different scenarios were considered as shown in the following subsections.

2.5.1. Irregular pattern of raw material arrivals

This scenario simulates the situation in which, due to some external cause such as demand variation or supply delays, the pattern of raw-material-arrivals into the system is disrupted in such a way that there is a higher variation in both the time between arrivals and the arriving number of parts. The variation in the arrival pattern in this scenario with respect to the arrival pattern in the baseline model is contrasted in figures 2 and 3 below.

In order to generate the pattern of arrivals in figure 3 a gamma distribution has been used. The parameters used in the gamma distribution generating the interarrival times in this scenario are a shape parameter (α) of 10 minutes and a scale parameter (β) of 38 minutes. Additionally, a normal distribution with an average of 10 parts and a standard deviation of 5 parts has been also considered to generate the variation in the arriving batches.

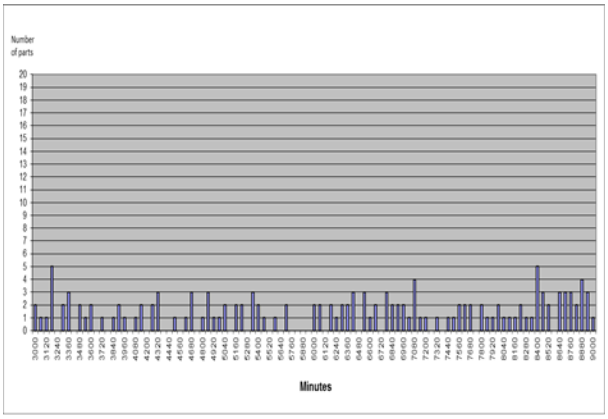

Figure 2: Pattern of Material Arrivals per Time Interval in the Baseline Model

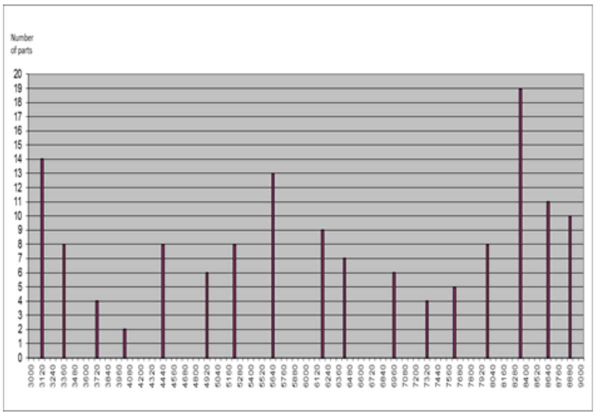

Figure 3: Pattern of Material Arrivals per Time Interval in the Disturbance Scenario

2.5.2. Increased arrivals of raw material scenario

As opposed to the previous scenario, in this scenario the pattern of material arrivals is not modified but amplified in order to simulate a condition where the MS needs to cope with an unexpected increase in production orders. Figure 4 shows the difference between arrivals of raw material in the baseline model and arrivals of material in the disturbance scenario.

To simulate the disturbance condition shown in the figure above, the original interarrival time in the baseline simulation model has been decreased from 45 to 30 minutes with no change in the probability distribution originating the arrivals.

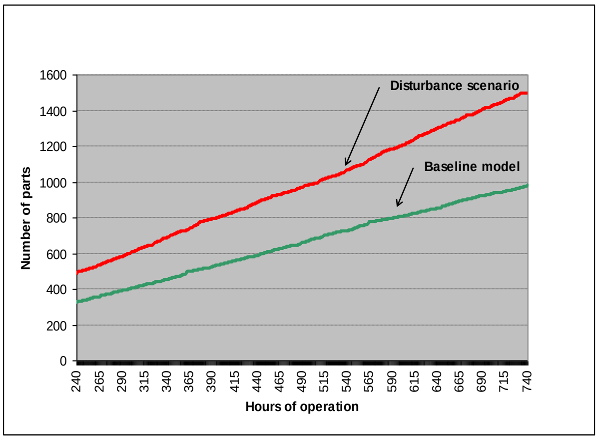

Figure 4: Number of Raw Materials Arrivals

2.5.3. Increased product variety scenario

The range of parts produced by the system has been increased from 5 to 10 parts in this scenario; each part has different processing characteristics. Since the purpose is to investigate product variety and not product mix variation, the product mix range in this scenario with respect to the baseline model has been increased by only 2%. Table 1 compares the increased product variety in this scenario with respect to the product variety in the baseline model.

Table 1: Comparison of Product Varieties

Product	Baseline model	Disturbance scenario
1	23%	10%
2	17%	9%
3	20%	7%
4	18%	8%
5	22%	6%
6	N/A	13%
7	N/A	14%
8	N/A	11%
9	N/A	12%
10	N/A	10%
TOTAL	**100%**	**100%**

2.5.4. High variation in product mix scenario

As opposed to the previous scenario where a wider choice of products is investigated, this scenario explores the demand variation existing among products. To simulate this scenario, the same five original products defined in the baseline model are considered, however, the product mix has been adjusted in order to reflect a bigger difference in the demand for each product in relation to the rest of the products. Table 2 illustrates a comparison between the original product mix and the mix considered in this scenario.

Table 2: Comparison of Product Mix

Product	Baseline	Disturbance
1	23%	18%
2	17%	3%
3	20%	26%
4	18%	8%
5	22%	45%
total	**100%**	**100%**
Range	**6%**	**42%**

It can be noticed from the table 2 above that the range in the product mix for the disturbance scenario is considerably larger than the range in the baseline model.

3. MODEL REPLICATIONS AND DATA ANALYSIS

The number of necessary replications for each simulation scenario was determined by calculating a maximum error estimate out of a series of initial model replications. The maximum error estimate together with a desired error was taken into account to determine the required number of replications for each model. According to such calculation, a minimum of 250 replications per model were enough to guarantee statistical reliability.

Considering that there were 6 design factors involved, each at two levels, a 2^6 full factorial design was employed. Given the high variation in the resulting data related to the responses cost and time, the original data has been normalized using a log transformation. Subsequently an analysis of variance was conducted to identify the significant factors. Main effects plots and interaction plots were used to identify factor levels and factor interactions respectively. Minitab was the statistical software used to analyse the data generated by each simulation scenario.

4. RESULTS

The following sections report on the obtained results including the analysis of variance. Due to space limitations, all the analysis of variance tables and the interactions effects are not included but will be presented at the conference.

4.1. Irregular pattern of raw material arrivals

After conducting an analysis of variance and calculating the factor effect estimates for each of the considered responses, the most important effects were confirmed by the main effects plots in figures. 5, 6 and 7.

In terms of the number of completed parts, figure. 5 and the factor effect estimates in appendix 2 indicated that four influential factors are: high operator skills, high buffer capacity, high number of vehicles and low duration of machine set-ups; all with a combined percent contribution of approximately 61%. Although high vehicle speed also appeared as main effect in figure. 5, its percent contribution was only of 1%.

In figure 6 two key factors to minimize cost were identified, namely low buffer capacity and low duration of machine set-ups; both with a combined percent contribution of 96%. Although low operator skills and low number of vehicles also appeared in figure. 6 as main effects, the calculation of effect estimates in appendix 2 indicated a low percent contribution of 1.5%.

Moreover, high operator skills and low duration of machine set-ups were identified by figure. 7 as the most important factors to achieve minimum time in the system; both factors with a combined percent contribution of approximately 89% according to appendix 2. Low buffer capacity, high number of vehicles and high vehicle speed, although also identified as main effects, showed a combined percent contribution of only 3%.

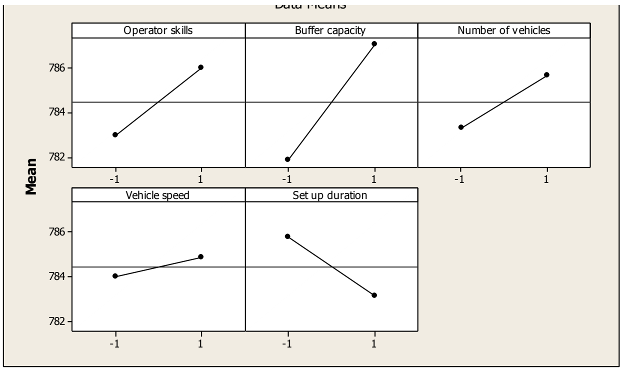

Figure 4: Main Effect Plot for Parts

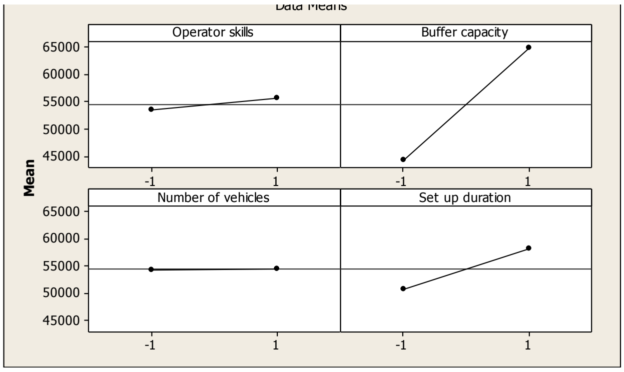

Figure 5: Main Effect Plots for Cost

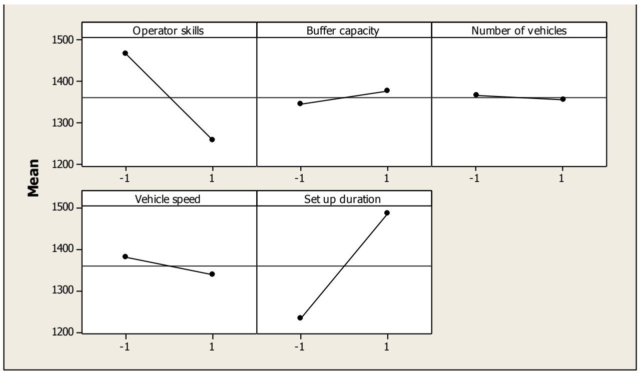

Figure 6: Main Effect Plot for Time

4.2. Increased arrivals of raw material

The main effect plots in figures. 8, 9 and 10 validated the significant factors previously identified by the analysis of variance.

As shown by figure 8, to achieve a maximum number of completed parts, high operator skills, high buffer capacity and low duration machine set-ups were the most significant factors with a combined percent contribution of approximately 67%.

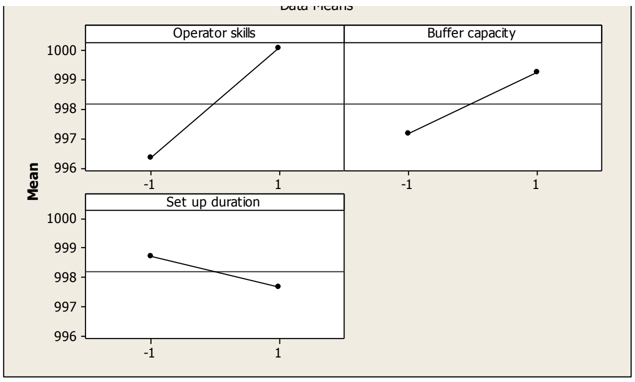

Figure 7: Main Effect Plot for Parts

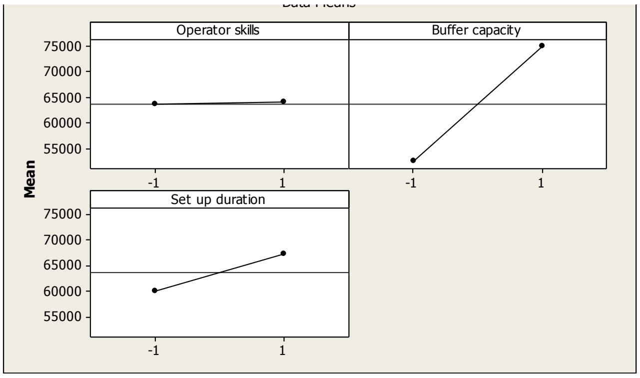

Figure 8: Main Effect Plot for Cost

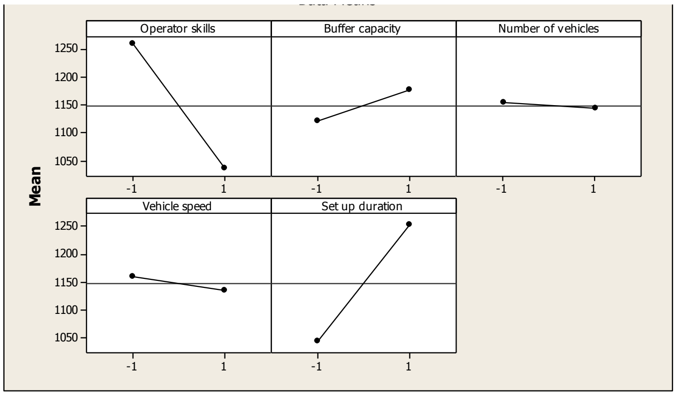

Figure 9: Main Effect Plot for Time

As shown by figure 8, to achieve a maximum number of completed parts, high operator skills, high buffer capacity and low duration machine set-ups were the most significant factors with a combined percent contribution of approximately 67% according to appendix 3.

Figure 9 confirms that low buffer capacity and low duration of machine set-ups, both with a combined percent contribution of approximately 97% according to appendix 3, were the most significant factors to achieve minimum cost.

Concerning a minimum time in the system, figure 10 shows that high operator skills, low duration of machine-set ups and low buffer capacity are the three most influential factors with a combined percent contribution of approximately 88% consistent with appendix 3. A high number of vehicles and high vehicle speed, both with a combined percent contribution of nearly 1%, were not influential enough.

4.3. Increased product variety

After conducting an analysis of variance the most significant factors in a scenario characterised by a wider product variety have been confirmed by figures 11, 12 and 13.

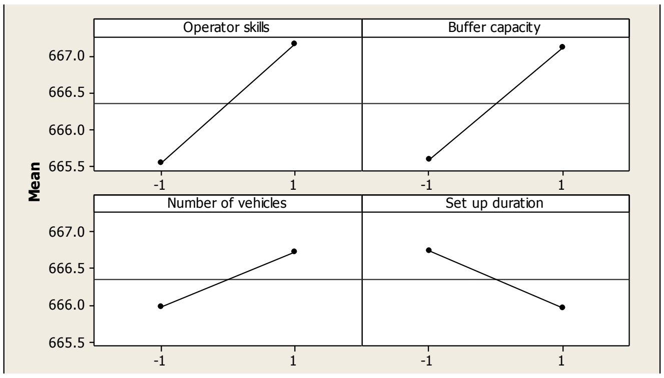

Figure 10: Main Effect Plot for Parts

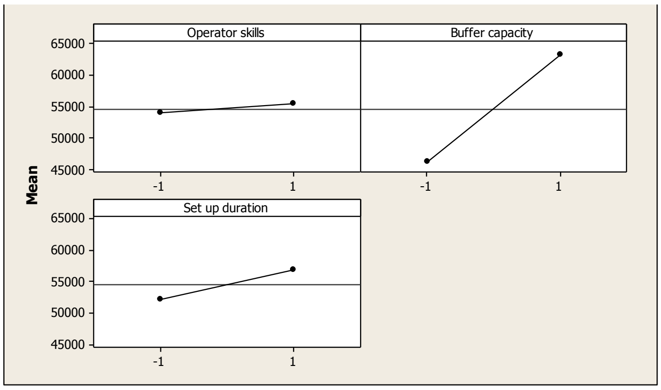

Figure 11: Main Effect Plot for Cost

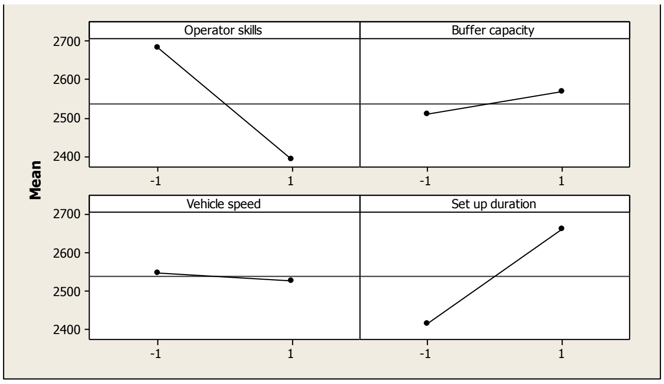

Figure 12: Main Effect Plot for Time

Figure 11 indicates that, to achieve a maximum number of completed parts, the first and most significant factor was high operator skills with a percent contribution of 26%, followed by high buffer capacity with a percent contribution of 23%; the third and fourth important factors were low duration of machine set-ups and high number of vehicles with percent contributions of 6% and 5.6% respectively.

Figure 12 shows that there were only two main factors for achieving minimum cost, those were low buffer capacity and low duration of machine set-ups, both with a combined percent contribution of approx. 97%.

Figure 13 confirmed that, to minimize time in the system, high operator skills and low duration of machine set-ups were key factors with a combined percent contribution of approx. 87% (see appendix 4 for the percent contributions of each factor in terms of the three considered response variables).

4.4 High variation in product mix

Figures 14, 15 and 16 show the most influential factors in achieving higher performance in a scenario characterized by high variation in product mix. See appendix 5 for the analysis of variance from where the initial significant factors were identified.

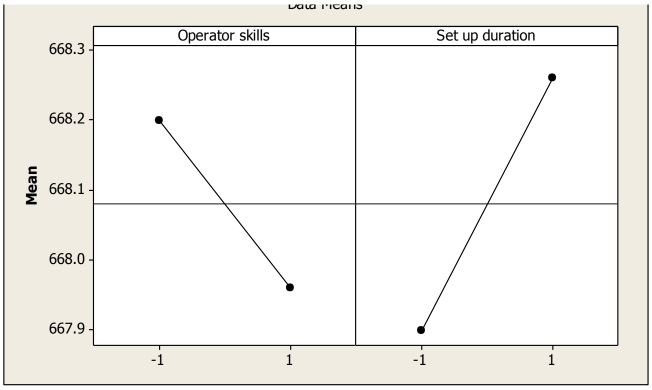

Figure 13: Main Effect Plot for Parts

Figure 14 shows that, in terms of a maximum number of completed parts, the only two significant factors were high duration of machine set-ups and low operator skills, both with a combined percent contribution of approx. 24%. The analysis of variance in appendix 5 shows that an important interacting factor to achieve a higher number of parts was high vehicle speed.

Figure 15 confirms that, in terms of minimum cost, low buffer capacity was the most influential factor with a percent contribution of 92% according to appendix 5. Low operator skills and low duration of machine set-ups were also important factors with a significantly lower percent contribution of 4% each.

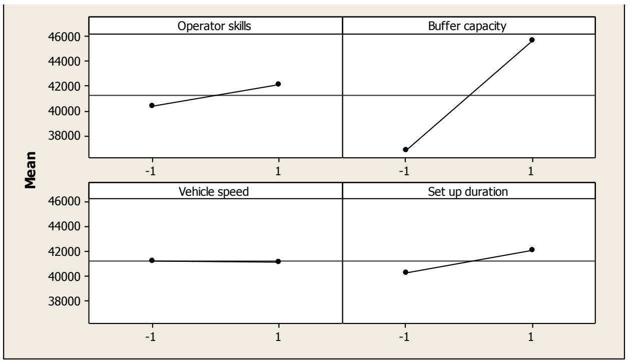

Figure 14: Main Effect Plot for Cost

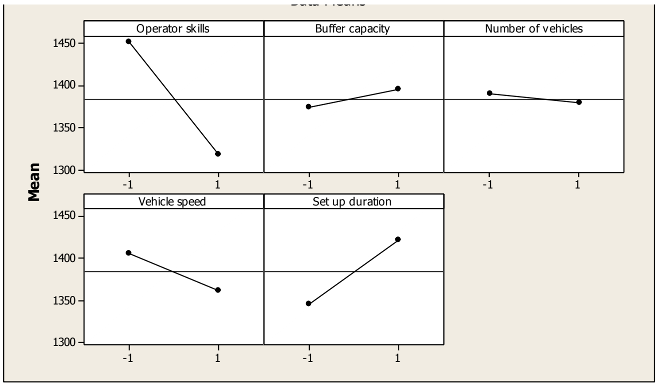

Figure 15: Main Effect Plot for Time

Although figure 16 shows the existence of five significant factors in terms of minimum time in the system, according to appendix 5 only three factors were truly significant; those were high operator skills, low duration of machine set-ups and high vehicle speed; all with a combined percent contribution of approx. 92%.

5. DISCUSSION AND FUTURE WORK

As it was mentioned at the beginning of this study, demand aspects such as volume and pattern are among some of the factors affecting manufacturing cell's performance. As Van Ooijen and Bertrand (2003) claimed, periods of high and low demand lead to unbalanced workload and variation in resource utilization. The same authors identified the trade-off existing between a higher throughput resulting from an increase in the arrival rate and higher costs particularly associated to high levels of WIP inventory. In addition to approaches like arrival rate control policies, other mechanisms to cope with material arrivals associated problems have been identified in this study. To achieve a maximum number of completed parts in scenarios characterized by either irregular or increased arrivals of raw material, the most important factors identified in this study were highly skilled operators and high buffer capacity. These same factors also were the most influential to achieve a maximum number of parts in a scenario characterized by increased product variety. Highly skilled operators are important especially during periods of high demand in order to guarantee better resource utilization. A higher buffer capacity is similarly necessary to store the excess of WIP inventory originated during those periods. In scenarios characterized by a high variation in product mix, dedicated operators are more suitable since old products, going through the last stage of their life cycle, will experience a low demand allowing more resource attention to be paid on products with higher demand.

The trade-off existing between the responses throughput and high costs resulting from high levels of WIP inventory, has been mentioned in the previous paragraph. The experiments conducted in this study have shown that, in all of the considered disturbance scenarios, the two most important factors were low buffer capacity and low duration of machine set-ups. High costs resulting from high WIP inventory levels can be overcome by limiting WIP levels; this can be achieved by setting work centres with low buffer capacity. Scenarios of variation in the demand pattern like product variety and product mix are particularly associated to higher costs. On the one hand, a product variety scenario implies higher costs associated to lower economies of scale, more set-ups and lower labour productivity (Thonemann and Bradley, 2002). On the other hand, a product mix scenario involves increased manufacturing costs resulting from increased heterogeneity in process specifications of a product mix (Anderson, 1995). Therefore low duration of machine set-ups is another characteristic that needs to be considered to reduce costly WIP inventories, particularly those caused by variation in the demand pattern.

To cope with a changing environment, a crucial task to a quicker throughput and to an improved performance is lead time reduction. In order to achieve a reduced job flow time, improvements in delivery speed have been proposed along with improvements in WIP inventory and response to market requirements (Deane and Yang, 1992). In the manufacturing system analysed in the present study, two essential features to achieve the minimum time in the system were highly skilled operators and low duration of machine set-ups. These two characteristics were the most significant ones for all of the considered scenarios. Similarly, high speed of vehicles was other factor that resulted significant exclusively for the scenario involving high variation in product mix.

Looking at the whole picture, the system's features that consistently resulted significant for all the considered scenarios, in terms of the three considered performance measures, were low set-ups duration in the first place followed by highly skilled operators. Cellular manufacturing systems with similar operating characteristics to those specified in this study, and which are constantly facing frequent changes in the volume and pattern of the demand, may find that, counting on versatile machines able to accomplish quick changeovers and skilled human operators able to keep the system operating under different circumstances, are key characteristics to maintain an acceptable performance.

Future work on the topic could adopt a wider perspective on the origin of disturbances affecting manufacturing systems. Both internal and external disturbances could be considered to investigate their effect on performance and to identify aspects providing manufacturing systems the capability to cope with a number of disrupting situations. To complement the present study, it would be interesting to consider a range of variation in the intensity of disturbances and identify how certain system characteristics become significant at varying disturbance intensities. Moreover, other systems layouts could be investigated to confirm the advantages offered by cellular manufacturing against uncertainty. Another important aspect to consider in future research is related to the implications for the manufacturing system to hold a certain degree of flexibility, i.e. the effects, in terms of different performance measures, of system adjusting to a number of situations, together with the trade-offs involved.

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