System Reactivity Components in Cellular Manufacturing Subjected to Frequent Unavailability of Physical and Human Resources

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Abstract: In manufacturing systems, different types of disturbances influence system's performance. In this paper those components within a manufacturing cell contributing to maintain a higher performance, despite the influence of internal disturbances such as machine breakdowns and operator unavailability, are investigated. Discrete event simulation is used to model the processing and material handling subsystems within a cellular manufacturing. Experimentation is conducted using a full factorial design and data analysis is performed using analysis of variance. The results indicated that, in terms of systems reactivity, processing subsystems aspects such as the skills of the operators, the capacity of the buffers and the duration of machine set-ups are more efficient in coping with work-in-progress (WIP) resulting from the effect of disturbances than aspects related to the material handling sub system.

1 INTRODUCTION

In a current economic environment characterised by increasing uncertainty, manufacturing systems are more vulnerable to the effects of unpredictable or random events commonly referred to as manufacturing disturbances. A particular type of disturbances includes all the disrupting events occurring within the limits of manufacturing systems. These are known as internal disturbances and are characterised by the limited availability of a specific resource (Saad and Gindy, 1998). In order to remain competitive in an environment of uncertainty, it is necessary for manufacturing systems to identify those components providing the system with the capability to efficiently perform under such disrupting conditions.

Manufacturing systems are determined by a transformation process where inputs are converted into outputs by means of an internal process. The internal process is an assembly of interconnected components (e.g. machines, material handling devices and human resources) whose interaction determines the outcome of the system. A cellular system is a particular layout configuration of a manufacturing system where different types of machines are grouped together according to the process combination occurring within a family of parts. Among some benefits of cellular manufacturing, Williams (1994) reported an increased efficiency by reducing material handling and transportation cost. Compared to other layout configurations such as functional layouts, where machines are grouped together based on similar functions, cellular systems offer better results in terms of work-in-process inventory, particularly when there are small batches and short run times involved (Logendran and Talkington, 1997). Eckstein and Rohleder (1998) claimed that cellular configurations also offer more advantages in terms of human issues such as the operator's learning rate and the number of workers employed.

Modern manufacturing systems operate under uncertain conditions originated within the boundaries of the system; such internal conditions range from uncertainty about processing times to uncertainty about resources' reliability. Having into consideration that, for a considerable number of organizations, it is prohibitive to acquire additional capacity in order to guarantee a safe operation against uncertainty, the only way for manufacturing systems to meet deadlines is by using available resources. Reactivity has been defined as the capacity if the system to react to internal disturbances and constitutes a significant aspect

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regarding the evolution of manufacturing systems. Reactivity, according to Ounnar and Ladet (2004), is achieved by exploiting the flexibility of physical resources.

On the one hand, processing machines are the most pervasive physical resources in manufacturing systems. On the other hand, the human element is another physical resource mainly associated with control tasks within such systems. Both types of resources have received significant research attention, particularly in issues regarding the reactivity of manufacturing systems. Regarding processing machines, one important aspect of system reactivity is the capability of machines to efficiently perform despite the presence of frequent breakdowns, which is one of the most inherent disturbances within systems' limits. Dynamic scheduling, where real time decisions are made in order to offer a rapid response to disturbances, is one of the most favoured approaches to cope with machine breakdowns. Nihat *et al.* (2006) claimed that it is possible to reduce the adverse impact of machine breakdowns by using intelligent scheduling policies that exploit available information about sources of uncertainty. They proposed a stochastic scheduling approach to characterize uncertainty using probability distributions and generated optimal policies under different distributional assumptions. Ounnar and Ladet (2004) investigated reassignment strategies and proposed a multi-criteria algorithm for reassigning parts from a broken down machine into an alternate machine and by considering the best compromise between the variables time, cost and machine reliability. Ozmutlu and Harmonosky (2004) stated that conventional re-routing strategies become more difficult to achieve as the complexity of manufacturing system increase; therefore they proposed a threshold –based selective rerouting strategy to minimize the mean flow time in a system with machine breakdowns. Their strategy achieved superior results compared to other strategies and also has the advantage of being simpler in its application. Chen and Chen (2003) recognised that a frequent rescheduling due to recurrent machine breakdowns can make the behaviour of the system hard to predict, reducing the effectiveness of dynamic scheduling . To avoid this, the authors proposed adaptive scheduling, which consist in updating the job ready time and completion time, and the machine status on a rolling horizon basis; they also suggested considering machine availability in generating schedules.

Other approaches to cope with machine breakdowns look at the improvement of repair times and facilities in order to reduce machine down time, the implementation of preventive maintenance policies to either avoid or reduce failures, the consideration of wok-in-process inventory buffers as a safety measure, etc (Buffa, 1972). Taylor *et al.* (1982) used network modelling in order to analyse alternative approaches for maintaining desired levels of system output in the presence of machine breakdowns. Hillier and So (1991) analysed the effects of inter-stage storage on the performance of a system subjected to machine breakdowns; they concluded that, in the event of a machine breakdown, a suitable inter-stage storage capacity helps to provide parts for downstream machines, reducing the effect of the disturbance. In a very unconventional approach Liao and Chen (2004) proposed maximising set-up time subject to a due date constraint in order to reduce machine breakdowns rate.

Concerning the human resource element of manufacturing systems, aspects particularly related to the level of skills and the extent of human resource involvement in manufacturing processes, have been investigated as determinants of system's reactivity.

Concerning the human element, it is clear that despite increasing automation of manufacturing systems, the human element is still an essential component (Hwang et al., 1984). It has been demonstrated that success in the implementation of advanced manufacturing technology is due not to technical failures but to human related issues such as the capability of workers in terms of skills, knowledge and attitude (Chung, 1996). In a study carried out by Kahn and Lim (1998), the authors found strong evidence that productivity growth was increasingly concentrated in the more skill-intensive manufacturing industries. Pagell *et al*. (2000) pointed out that a key advantage of skilled workers is their ability to more easily cope with increasing complexity and uncertainty; however, the higher costs associated to high skilled workers and the dependence upon scarce resources can be discouraging factors. This may just be the reason why despite of the existing evidence on the relationship between productivity and a skilled workforce, a considerable number of manufacturing organisations still rely on low skilled workers.

Regarding the fact of manufacturing systems and their current uncertain environment, the link between uncertainty and an increased need for more flexible workers has been established. There is extensive research focusing mostly on the impact of human resource practices on the performance of manufacturing systems. Among some of the relevant research, Pagell *et al*. (2000) suggested that a poorly developed human resource strategy often leads to low performance levels in environments of advance manufacturing technology. Huselid (1995) investigated the impact of human resource management practices, such as new skills acquisition, on corporate financial performance. The authors suggested that such practices lead to an improved performance, particularly in terms of employee turnover and productivity. Similarly, Jayaram *et al.* (1999) also investigated the impact of common human resource practices on a series of performance measures, namely cost, quality, flexibility and time. The authors found a strong positive relationship between employee-skills related factors and performance. Udo and Ebienfung (1999) confirmed such relationship by investigating the impact of human factors, such as employee training, on performance indicators like ROE, reduced cost, quick throughput , competitiveness, control, response, improved condition and quality.

The purpose of this study is to understand how the key components of a cellular manufacturing system can contribute to system's reactivity. In this section, it has been mentioned that components such as machines and human workers may possess particular characteristics or abilities that make them able to individually contribute to a better system performance. In this study the technical aspect of manufacturing systems, represented by machines and material handling equipment, is combined with the human aspect in order to identify those features that provide the system with the capability to perform under uncertain environments characterised by frequent machine breakdowns and frequent operator unavailability.

The objective of this study is achieved by using discrete event simulation combined with statistical design of experiments. Simulation has enabled the representation of a complex manufacturing environment and a full factorial design of experiments has made possible the consideration of the interactions occurring between all the components within the defined system. As opposed to other research on the topic of system reactivity, this study looks at a combination of factors and different experimental scenarios. This consideration of a bigger picture enables a better understanding of system reactivity and the alternative ways to achieve it.

2 RESEARCH METHODOLOGIES

2.1 Simulation Model

The cellular manufacturing system considered in this paper consists of nine work centres. Each work centre is composed of one input buffer, one machine, and one output buffer. Parts arrive one at time into the system following a representative probability distribution. A loading area receives five different types of parts corresponding to five different products. As soon as ten parts of a particular type are available in the loading area, those parts are pushed into their corresponding processing route. Each part type follows a specific processing route with different processing times. When a batch of parts is delivered to a work centre the parts are directed into an input buffer first. Afterwards, a machine operator collects one part from the input buffer and loads it into the machine for its processing. The operator stays next to a machine during the whole machine processing time. Once the machine finishes processing the part the operator takes the part and places it into an output buffer. Both the machine and the operator become available for the next part to be processed. Parts placed in output buffers are ready to be taken to the following work centre along the processing route. The flow of parts between the work centres is assisted by an AGV based material handling system. After parts have gone through all the processes along the route they are delivered to an unloading area from where they are subsequently shipped to customers. The described manufacturing system is represented in figure 1.

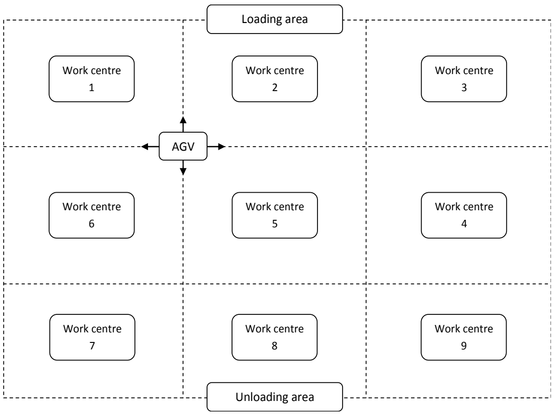

Figure 1: Manufacturing system layout.

2.2 Operating Assumptions

The system represented in figure 1 operates under the following assumptions:

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. The exponential distribution has been selected because of the existing resemblance between such distribution and the inter arrival times for real world systems (Law and Kelton, 2000).
- 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; they 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 with 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 carried out 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 with 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 with 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 Automated Guided Vehicle

- 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.

2.3 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.

3 EXPERIMENTAL DESIGN

The experimental design of this study was concerned with:

(i) Selecting the response variables;
(ii) Determining the model running time;
(iii) Choosing the experimental factors and settings; and
(iv) Defining the statistical design of the experiments.

3.1 Selection of Response Variables

The performance of the investigated manufacturing system was measured in terms of three complementary response variables, namely number of completed parts, manufacturing cost, and average time in the system.

3.2 Model Running Time

In a simulation model, the total running time consists of a warming-up period, during which the model reaches normal operating conditions, and a run length period, during which the model collects results. In order to determine the model warm-up period Welch's graphical method was used. In this method, the model will be run several times with different random number seeds in order to calculate a mean average of a key output for specific periods of time, afterwards moving averages are calculated (Robinson, 1994). For the proposed model, Welch's method indicated a minimum warm-up period of 50 hours (Welch, 1983).

On the other hand, the run length period of the simulation model was determined by means of another graphical approach described by Robinson (1994). According to such approach, a minimum run length period of 220 hours was required to gather enough data.

3.3 Experimental Factors

Considering that this study has a special interest in the physical components of manufacturing systems, the design factors were grouped in aspects concerning the two main subsystems in the model, i.e. work centres and the handling of material. See Table 1 below.

Table 1: Design factors.

Subsystem	Aspect (Design factor)	Definition
Work centre	The skill level of operators	It is determined by the number of different machines a single operator can control.
	The capacity of buffers	It is related to the maximum number of parts the system is able to hold.
	The duration of machine set-ups	It is the time it takes for machines to switch from producing one type of part to producing a completely different part.
Material handling system	The number of AGVs	It is related to the total number of material handling vehicles within the system.
	The speed of AGVs	It is the distance covered by material handling vehicles during a specific period of time.
	The loading capacity of AGVs	The maximum number of parts a material handling vehicle can transport between work centres.

4 MODELS SCENARIOS

In order to reflect the effects of internal disturbances and taking into consideration technological and human resources, two different noise factors were considered, namely an increase of machine breakdowns and an increase in operator unavailability. See Table 2 below for a definition of each disturbance scenario.

Table 2: Internal disturbances.

Disturbance	Definition
Machine breakdowns	The purpose of this scenario is to identify system components contributing to maintain a higher performance when there are recurrent failures in machines throughout the system. It is widely known that when a manufacturing system does not have the capability to cope with frequent machine breakdowns, the system will eventually come to a stop as a result of increasingly accumulating WIP inventory. To simulate this scenario, the original machine efficiencies, ranging between 83% and 96%, have been decreased. The new machine efficiencies ranging between 60% and 70% have been randomly assigned to each machine within the system.
Operator unavailability	In this scenario, the system is subject to long unavailability periods of human operators in order to identify suitable system's responses. In a similar way to the previous scenario, the unavailability of human resources for long periods of time can significantly affect performance by interrupting the production flow along the system. To simulate this scenario original operator availability percentages have been decreased from a range between 96% and 97% to a range between 91% and 95%. The average absence time per operator ranges from 480 to 600 minutes. Both availability percentages and absence times are randomly assigned to operators.

There is a direct relationship between these two scenarios given that both are characterised by the unavailability of a specific resource during a period of time; however, the aim of each scenario is different since two different aspects of resource unavailability are examined. The machine breakdowns scenario examines the aspect of frequency of unavailability, whereas the scenario of operator unavailability examines the aspect of the duration of resource unavailability.

4.1 Factor Levels and Range

The objective of the experiment is to identify the factors with a higher influence on the response variable, it is recommended to keep a low number of factor levels, with a relatively large range between levels (Montgomery, 2009). After establishing and testing a series of ranges for each of the considered factors, the levels and ranges shown in Tables 3 and 4 were chosen for the factors in the two considered scenarios.

Note that factor levels are different in both tables because each table corresponds to a specific scenario where the effect of a particular disturbance was analysed before choosing adequate factor levels.

4.2 Number of Necessary Replications

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 at a 95% confidence interval.

4.3 Data Structuring and Analysis

The simulation experiments were conducted according to a complete factorial experimental design , which was a suitable design due to the fact that possible factor interactions needed to be considered (Mason et al., 2003). 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 provided by each simulation scenario.

Table 3: Frequent machine breakdowns scenario: Factor levels.

FACTOR	DESCRIPTION	LEVEL 1	LEVEL 2
A	Operator skills	4 unskilled operators and 2 semi-skilled operators.	3 semi-skilled operator and 3 skilled operators
B	Buffer capacity	Buffer capacity of up to 10 parts; cost per item per minute $0.010.	Buffer capacity of up to 29 parts; cost per item per minute $0.030.
C	Number of vehicles	1 AGV.	4 AGVs.
D	Vehicle speed	Vehicle speed 5 km/hr.	Vehicle speed 60 km/hr.
E	Loading capacity of AGV	3 parts loading capacity. (load/unload = 0.5 min)	10 pieces loading capacity (load/unload = 1.2 min)
F	Machine set-ups duration	Set-up time between 1 and 5 minutes.	Set-up time between 20 and 29 minutes.

Table 4: Frequent operator unavailability scenario: Factor levels.

FACTOR	DESCRIPTION	LEVEL 1	LEVEL 2
A	Operator skills	4 unskilled operators and 2 semi-skilled operators.	2 semi-skilled operator and 4 skilled operators.
B	Buffer capacity	Buffer capacity of up to 10 parts; cost per item per minute $0.010.	Buffer capacity of up to 29 parts; cost per item per minute $0.030.
C	Number of vehicles	1 AGV.	5 AGVs.
D	Vehicle speed	Vehicle speed 5 km/hr.	Vehicle speed 80 km/hr.
E	Loading capacity of AGV	4 parts loading capacity. (load/unload = 0.5 min)	10 pieces loading capacity (load/unload = 1.2 min)
F	Machine set-ups duration	Set-up time between 6 and 10 minutes.	Set-up time between 20 and 29 minutes.

5 ANALYSIS AND RESULTS

5.1 Machine Breakdowns Scenario

The analysis of variance of the results, in terms of each of the three considered response variables, has been calculated for this scenario. Tables 5, 6, and 7 show the ANOVA tables for the responses number of parts, cost, and average time in the system respectively. Note that the statistical package used to analyse the results – Minitab – automatically omits those main factors whose direct contribution to the response is not significant. For this reason the factor vehicle speed is not included in Table5 and the factor loading capacity is not considered in Tables 6 and 7.

Table 5: ANOVA table for the response number of parts.

```
Source                                 DF       SS       MS      F      P
Operators skills                        1  0.60567  0.60567  11.03  0.002*
Buffer capacity                         1  2.15831  2.15831  39.30  0.000*
Number of vehicles                      1  0.00838  0.00838   0.15  0.698
Loading capacity                        1  0.11816  0.11816   2.15  0.149
Set up duration                         1  0.05766  0.05766   1.05  0.311
Operators skills*Loading capacity       1  0.47699  0.47699   8.69  0.005*
Operators skills*Buffer capacity        1  0.27227  0.27227   4.96  0.031
Operators skills*Number of vehicles     1  0.00296  0.00296   0.05  0.818
Buffer capacity*Number of vehicles      1  0.06154  0.06154   1.12  0.295
Buffer capacity*Loading capacity        1  0.00439  0.00439   0.08  0.779
Buffer capacity*Set up duration         1  0.00152  0.00152   0.03  0.868
Loading capacity*Set up duration        1  0.00197  0.00197   0.04  0.851
Operators skills*Buffer capacity*       1  0.35865  0.35865   6.53  0.014*
  Number of vehicles
Buffer capacity*Loading capacity*       1  0.37574  0.37574   6.84  0.012*
  Set up duration
Error                                  49  2.69103  0.05492
Total                                  63  7.19523


S = 0.234348   R-Sq = 62.60%   R-Sq(adj) = 51.91%
```

Table 6: ANOVA table for the response cost.

```
Source                               DF        SS        MS          F      P

Operators skills                      1  0.002607  0.002607    1397.28  0.000*
Buffer capacity                       1  0.487377  0.487377  261253.72  0.000*
Number of vehicles                    1  0.000016  0.000016       8.52  0.005*
Vehicle speed                         1  0.000002  0.000002       1.18  0.282
Set up duration                       1  0.035603  0.035603   19084.53  0.000*
Operators skills*Buffer capacity      1  0.006888  0.006888    3692.30  0.000*
Operators skills*Number of vehicles 1  0.000022  0.000022      11.69  0.001*
Operators skills*Set up duration      1  0.000383  0.000383     205.40  0.000*
Buffer capacity*Number of vehicles   1  0.000038  0.000038      20.25  0.000*
Buffer capacity*Vehicle speed         1  0.000011  0.000011       5.66  0.022
Buffer capacity*Set up duration       1  0.000389  0.000389     208.40  0.000*
Number of vehicles*Vehicle speed      1  0.000000  0.000000       0.19  0.669
Number of vehicles*Set up duration   1  0.000103  0.000103      55.25  0.000*
Vehicle speed*Set up duration         1  0.000107  0.000107      57.50  0.000*
Operators skills*Buffer capacity*     1  0.000290  0.000290     155.68  0.000*
  Set up duration
Buffer capacity*Vehicle speed*        1  0.000013  0.000013       6.93  0.011
  Set up duration
Number of vehicles*Vehicle speed*     1  0.000048  0.000048      25.52  0.000*
  Set up duration
Error                                  46  0.000086  0.000002
Total                                  63  0.533982


S = 0.00136584   R-Sq = 99.98%   R-Sq(adj) = 99.98%
```

Table 7: ANOVA table for the response time.

```
Source                               DF         SS         MS        F      P
Operators skills                      1  0.0612929  0.0612929  8727.27  0.000*
Buffer capacity                       1  0.0013389  0.0013389   190.64  0.000*
Number of vehicles                    1  0.0000364  0.0000364     5.18  0.028
Vehicle speed                         1  0.0014422  0.0014422   205.34  0.000*
Set up duration                       1  0.0597981  0.0597981  8514.42  0.000*
Operators skills*Buffer capacity      1  0.0014947  0.0014947   212.82  0.000*
Operators skills*Number of vehicles 1  0.0002010  0.0002010    28.61  0.000*
Operators skills*Vehicle speed        1  0.0001284  0.0001284    18.28  0.000*
Operators skills*Set up duration      1  0.0030511  0.0030511   434.43  0.000*
Buffer capacity*Number of vehicles   1  0.0000356  0.0000356     5.07  0.029
Buffer capacity*Vehicle speed         1  0.0000016  0.0000016     0.22  0.640
Buffer capacity*Set up duration       1  0.0001578  0.0001578    22.48  0.000*
Number of vehicles*Vehicle speed      1  0.0001291  0.0001291    18.38  0.000*
Number of vehicles*Set up duration   1  0.0003161  0.0003161    45.01  0.000*
Vehicle speed*Set up duration         1  0.0003820  0.0003820    54.39  0.000*
Operators skills*Buffer capacity*     1  0.0000464  0.0000464     6.61  0.014
  Number of vehicles
Operators skills*Buffer capacity*     1  0.0002124  0.0002124    30.24  0.000*
  Set up duration
Operators skills*Number of vehicles*1  0.0000465  0.0000465     6.61  0.014
  Set up duration
Number of vehicles*Vehicle speed*     1  0.0001051  0.0001051    14.97  0.000*
  Set up duration
Error                                  44  0.0003090  0.0000070
Total                                  63  0.1305251


S = 0.00265012   R-Sq = 99.76%   R-Sq(adj) = 99.66%
```

In Tables 5, 6, and 7, low p-values, at alpha = 0.05, identify those important main factors and interactions. To make the identification easier, significant factors and interactions have been marked with a *. Even though the analysis of variance identified significant factors and interactions, it was necessary to confirm their level of significance by looking at the percentage of contribution of each factor and factor interaction. Percentage of contribution is an indication of the weight of each factor and factor interaction in relation to the response variable; Percentage of contribution calculation is part of Minitab's capabilities. Table 8 below shows these calculations of the identified significant factors and interactions as calculated by Minitab.

See Table 8 for the percentage of contributions of the important factors and interactions to the related response variable.

Regarding the response number of completed parts, the information presented in Table 8 confirms the results presented previously in Table 5. From upper left section of Table 8, it can be noticed that the combined percentage of contribution of the factors operators' skills and buffer capacity was of approximately 39%. Additionally, the contribution of the two significant interactions adds up to slightly over 10%. As evidenced by the main effect plot in the lower left section of Table 8, buffer capacity at the highest level was the most important factor in terms of number of completed parts; operators' skill at the lowest level was the second important factor.

Concerning the response cost, the percentage contribution section at the upper middle section of the table shows that only two out of the four important factors identified in Table 6 were in fact significant; those were buffer capacity and set-up duration, both with a combined percentage contribution of approximately 98%. Interaction's contribution was negligible. The main effect plot at the lower middle of the table shows that buffer capacity at its lowest level was the most significant factor followed by set-up duration at its lowest level.

In relation to the response time in the system, the percentage contribution section at the upper right corner of Table 8 confirms that only 2 out of the originally 4 identified important factors were actually significant; those were operators' skills and set-up duration, both with a combined percentage contribution of approximately 93%. No significant interactions were presented. The main effects plot in the lower right section of Table 8 indicates that the factor operators' skills at its highest level and set-up duration at its lowest level were the only significant factors in terms of a minimum time in the system.

5.2 Operator Unavailability

Similarly to the previous scenario, Minitab automatically excluded those insignificant factors in the analysis of variance, which are presented in Tables 9, 10 and 11 below.

Table 8: ANOVA table for the response number of parts.

```
Source                              DF       SS      MS       F       P
Operator skills                      1   72.740  72.740  209.35  0.000*
Buffer capacity                      1   50.297  50.297  144.76  0.000*
Number of vehicles                   1    3.038   3.038    8.74  0.005*
Loading capacity                     1    0.869   0.869    2.50  0.119
Operator skills*Buffer capacity      1   30.792  30.792   88.62  0.000*
Operator skills*Loading capacity     1    2.858   2.858    8.22  0.006*
Error                               57   19.805   0.347
Total                               63  180.398


S = 0.589452   R-Sq = 89.02%   R-Sq(adj) = 87.87%
```

Table 9: Significant factors and factors interactions in terms of three response variables; machine breakdowns.

<table>
<tr><th>Number of completed parts</th><th>Cost</th><th>Time in the system</th></tr>
<tr>
<td>
<table>
<tr><th>Model term</th><th>Percentage of contribution</th></tr>
<tr><td>Operators’ skills</td><td>8.46 %</td></tr>
<tr><td>Buffer capacity</td><td>29.97%</td></tr>
<tr><td>Rest of main factors</td><td>2.3%</td></tr>
<tr><td>Operators’ skills*Loading capacity</td><td>6.66%</td></tr>
<tr><td>Operators’ skills*Buffer capacity*Number of vehicles</td><td>5.01%</td></tr>
<tr><td>Buffer capacity*Loading capacity*Set-up duration</td><td>5.21%</td></tr>
<tr><td>Rest of interactions</td><td>42.39%</td></tr>
<tr><td>Total</td><td>100%</td></tr>
</table>
</td>
<td>
<table>
<tr><th>Model term</th><th>Percentage of contribution</th></tr>
<tr><td>Buffer capacity</td><td>91.27%</td></tr>
<tr><td>Set-up duration</td><td>6.67%</td></tr>
<tr><td>Rest of main factors</td><td>0.49%</td></tr>
<tr><td>Operators’ skills*Buffer capacity</td><td>1.29%</td></tr>
<tr><td>Operators’ skills*Set-up duration</td><td>0.07%</td></tr>
<tr><td>Buffer capacity*Set-up duration</td><td>0.07%</td></tr>
<tr><td>Rest of interactions</td><td>0.14%</td></tr>
<tr><td>Total</td><td>100%</td></tr>
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</td>
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<table>
<tr><th>Model term</th><th>Percentage of contribution</th></tr>
<tr><td>Operators’ skills</td><td>46.96%</td></tr>
<tr><td>Buffer capacity</td><td>1.03%</td></tr>
<tr><td>Vehicle speed</td><td>1.10%</td></tr>
<tr><td>Set-up duration</td><td>45.81%</td></tr>
<tr><td>Rest of main factors</td><td>0.03%</td></tr>
<tr><td>Operators’ skills*Buffer capacity</td><td>1.15%</td></tr>
<tr><td>Operators’ skills*set-up duration</td><td>2.34%</td></tr>
<tr><td>Rest of interactions</td><td>1.58%</td></tr>
<tr><td>Total</td><td>100%</td></tr>
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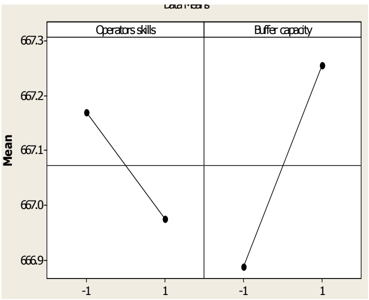
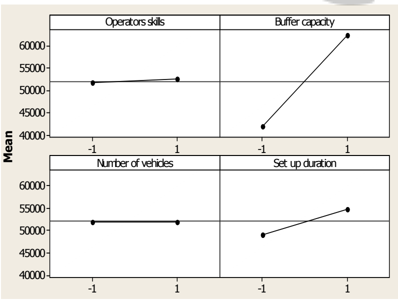
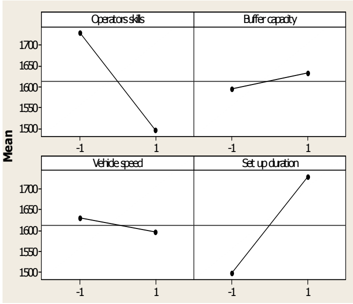
<td> </td>
<td> </td>
<td> </td>
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Table 10: ANOVA table for the response cost.

```
Source                          DF        SS        MS         F      P
Operator skills                  1  0.002513  0.002513    390.45  0.000*
Buffer capacity                  1  0.492206  0.492206  76469.78  0.000*
Set up duration                  1  0.011401  0.011401   1771.32  0.000*
Operator skills*Buffer capacity  1  0.009631  0.009631   1496.23  0.000*
Operator skills*Set up duration  1  0.000157  0.000157     24.41  0.000*
Buffer capacity*Set up duration  1  0.000067  0.000067     10.45  0.002*
Error                           57  0.000367  0.000006
Total                           63  0.516343


S = 0.00253705   R-Sq = 99.93%   R-Sq(adj) = 99.92%
```

Table 11: ANOVA table for the response time.

```
Source                              DF        SS        MS        F      P
Operator skills                      1  0.076130  0.076130  4999.58  0.000*
Buffer capacity                      1  0.003489  0.003489   229.15  0.000*
Number of vehicles                   1  0.000091  0.000091     5.97  0.018
Vehicle speed                        1  0.002846  0.002846   186.90  0.000*
Set up duration                      1  0.018487  0.018487  1214.06  0.000*
Operator skills*Buffer capacity      1  0.003524  0.003524   231.40  0.000*
Operator skills*Number of vehicles   1  0.000357  0.000357    23.44  0.000*
Operator skills*Set up duration      1  0.000954  0.000954    62.64  0.000*
Number of vehicles*Vehicle speed     1  0.000325  0.000325    21.33  0.000*
Vehicle speed*Set up duration        1  0.000158  0.000158    10.37  0.002*
Error                               53  0.000807  0.000015
Total                               63  0.107168


S = 0.00390223   R-Sq = 99.25%   R-Sq(adj) = 99.10%
```

Note that in this scenario the models generated by the analysis of variance were much less complex than the models in the first scenario, i.e. the models had fewer terms in each of the considered responses.

The analysis of variance has preliminarily identified a series of important factors and factor interactions. By looking at the information presented in Table 12 it is possible to confirm the real significance of those factors in terms of the three considered response variables.

The upper left section in Table 12 indicates that, in terms of the response number of completed parts, the only two significant factors were operators' skills and buffer capacity; both with a combined percentage of contribution of approximately 68%. No significant interactions were present. The plot of main effects in the lower left section shows that these two factors were both significant at their highest level.

In the column related to the response variable cost, the upper middle section of Table 12 shows that there was only one significant factor out of the three originally identified factors. The factor buffer capacity on its own had a percentage of contribution to the response of approximately 95%. Compared to this contribution, the other factors together with all of the interactions cannot be considered significant. The effects plot in the lower middle of Table 12 indicates that the factor buffer capacity was significant at its lowest level.

In terms of the response time in the system, the upper right section of Table 12 indicates that only 2 out of the originally identified important factor were considerably significant; those were operators' skills and set-up duration. No significant factor interactions were present in the model. The effects plot in the lower middle section shows that the main factor operators' skill was significant to the response at its highest level, whereas the main factor set-up direction was significant at its lowest level.

6 DISCUSSION AND FUTURE WORK

From the results section it can be noticed that, although the level of significance may differ, the significant factors are similar in both scenarios. Regarding the response variable number of completed parts, in the model with frequent machine breakdowns the two most important factors were a high buffer capacity in the first place and low operators' skills in the second place. This result indicates that in a manufacturing environment characterised by recurrent machine breakdowns a higher buffer capacity to accommodate the excess of WIP inventory accumulated during machine down periods is the most desirable feature. According to Hillier and So (1991), additional buffer space reduces the adverse effect of machine breakdowns and increases the throughput of the line. Additionally, low skilled operators are more likely to be dedicated to only one or two machines; this guarantees the availability of the operator even when the machine is down.

In the model characterized by a more frequent rate of operator unavailability, the most important and second most important factors were high operators' skills and high buffer capacity respectively. In this type of environments, counting on skilled operators is much more important than relying on a high buffer capacity because skilled operators can take on any machine when other operators are absent during considerable periods of time. A high buffer capacity, similarly to the machine breakdowns scenario, contributes to increase the throughput.

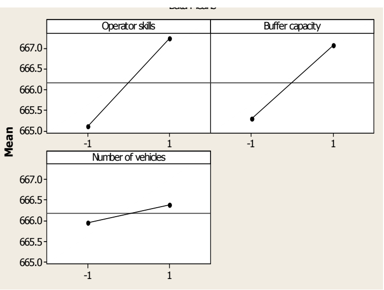
Concerning the response variable cost, both scenarios indicated low buffer capacity as the most important factor followed by low set-up duration. Considering that the different processes along cellular systems are accountable for WIP inventories (Srinivasan and Bozer, 1992), an important approach to keep costs down is to control the levels of costly WIP inventories along the system. In order to achieve this, the use of low capacity inter-storage-areas to limit the size of WIP is an important first step. In addition, a second important step to control WIP levels and therefore maintain lower costs in manufacturing environments characterized by the temporary unavailability of resources is the consideration of set-up reduction strategies.

In relation to the response variable time, the two most important factors in each considered scenario were high operator skills, in the first place, followed by low set-up duration. Under a time minimization criterion, the priority in both scenarios is to keep parts flowing throughout the system and high skilled operators, able to handle different processes, are the solution to maintain a smooth production flow. Set-up time reduction is also decisive for total production lead time reduction (Dimitrov, 1990). Low set-up durations contribute to maintain production flow by keeping low levels of WIP and compensating the time lost during periods of resource unavailability.

Table 12: Significant factors and factor interactions in terms of three response variables; operator unavailability.

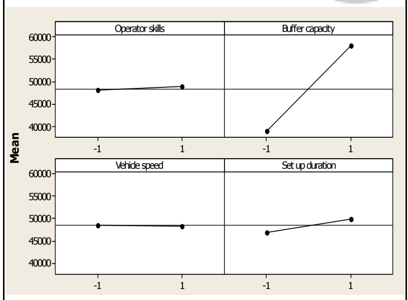
Number of completed parts

Model term	Percentage of contribution
Operators' skills	40.31%
Buffer capacity	27.88%
Number of vehicles	1.69%
Rest of main factors	1.17%
Operators' skills*Buffer capacity	17.06%
Operators' skills*Loading capacity	1.59%
Rest of interactions	10.3%
Total	**100%**



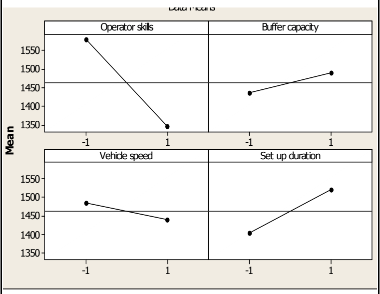
Cost

Model term	Percentage of contribution
Operators' skills	0.49%
Buffer capacity	95.33%
Set-up duration	2.21%
Rest of main factors	0.01%
Operators' skills*Buffer capacity	1.86%
Operators' skills*Set-up duration	0.03%
Buffer capacity*Set-up duration	0.01%
Rest of interactions	0.06%
Total	**100%**



Time in the system

Model term	Percentage of contribution
Operators' skills	71.04%
Buffer capacity	3.26%
Vehicle speed	2.66%
Set-up duration	17.25%
Rest of main factors	0.12%
Operators' skills*Buffer capacity	3.29%
Operators' skills*set-up duration	0.89%
Rest of interactions	1.49%
Total	**100%**



In both disturbance scenarios, aspects related to the processing subsystem of the manufacturing cell, such as the skill level of the operators, the capacity of buffers and the duration of machine set-up were determinant to control the level of WIP inventories within the system, which in turn was translated into a system's capacity to maintain a higher performance. The only aspect related to the material handling subsystem that appeared to be more important, particularly for the response time, was the speed of the vehicle. Similarly to the indentified significant factors, vehicle speed is strongly linked with WIP reduction (Srinivasan and Bozer, 1992). No other of the aspect concerning the material handling subsystem was considerably significant.

In addition to the consideration of system's reactivity, where manufacturing system's behaviour under the effect of internal disturbances is analysed, the effect of external disrupting forces like those related to the market could also be investigated. Furthermore, both internal and external disturbances could be investigated in the context of manufacturing flexibility. By adopting a more inclusive approach on the analysis of manufacturing flexibility and the effect of disturbances, those particular system components providing the system with flexibility capabilities under a number of disrupting situations could be identified. The identification of such components could lead to a number of system configurations, especially able to absorb the effects of several disturbances.

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