ABSTRACT

Manufacturing systems face now more than ever the effects of an uncertain environment, which is triggered by constantly changing customer needs. Numerous approaches have been proposed to provide manufacturing systems with the capability to satisfactorily perform under situations of uncertainty, particularly by improving their level of responsiveness. Manufacturing flexibility is a dimension of responsiveness which aims at reacting to unpredictable events with little penalty on performance.

Nonetheless, there is a strong perception that the achievement of manufacturing flexibility exclusively depends on the availability of highly automated equipment. This is a misleading belief considering that manufacturing systems are a collection of interacting components sharing a common objective and therefore there must be alternative system's aspects, other than automation, contributing to the achievement of manufacturing flexibility.

This study expands on existing knowledge by exploring the concept of manufacturing flexibility through the investigation of the dimension of uniformity. The analysis of this dimension has provided a valuable perspective from which to improve understanding of flexibility in manufacturing and identify alternative ways to achieve it. By combining the analytical capabilities of discrete event simulation, statistical design of experiments and optimisation, it has been possible to identify specific factors, optimal system configurations and response trade-offs that, within the context of semi-automated cellular manufacturing systems, constitute a significant contribution in the attainment of manufacturing flexibility.

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Carlos R. Gómez

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CHAPTER 1

INTRODUCTION

1.1 RESEARCH CONTEXT

The purpose of manufacturing systems is to efficiently transform inputs (e.g. material, energy and information) into outputs (e.g. material, energy and information). Such transformation is facilitated by the means of a series of interactions occurring among different components such as machines, material handling devices, and evidently, the human element. This transformation process may seem an easy task at first sight, unfortunately, there are always unexpected events making this process not as straightforward as it seems. Manufacturing systems are constantly exposed to the effects of unpredicted environmental influences generally referred to as disturbances, and which occur along the different stages of the transformation process. The effect of disturbances occurring within system's boundary, such as resource unavailability, and those arising outside system's boundary, such as variation in supply and demand, is invariably reflected on the overall performance of manufacturing systems.

1.1.1 Manufacturing responsiveness

The current economic environment is characterised by a severe competition fostered by market's globalization. A highly competitive economic environment, focused on satisfying every single one of the incessantly varying customer needs, and also characterized by a constant and unpredictable change, demands manufacturing systems able to efficiently perform under a number of unanticipated circumstances. A significant number of approaches to provide such systems with the ability to cope in the presence of disrupting conditions have been proposed along the development timeline of manufacture. However, since the competitive economic environment is in constant evolution, approaches that were considered suitable a few years ago, are not longer considered to be the most appropriate solutions nowadays. Manufacturing systems need to evolve in conjunction with the competitive economic environment so as to become more able to provide responses in accordance to the exigencies of the latter. In extremely competitive economic environments, where the exigency for the highest performance is paramount, the extent to which manufacturing systems are able to cope with disturbances is a determinant of the permanence of manufacturing organizations in the market. As a consequence of the prevailing competitive economic environment, modern manufacturing systems need to be equipped with the technological and organizational characteristics facilitating the ability to more efficiently react to unexpected and continuous change. Responsiveness is the quality that enables organizations to rapidly react to changing conditions and it has become a proven strategy to face uncertainty. On the other hand, flexibility is an enabler or dimension of responsiveness and it is particularly concerned with the manufacturing area of an organization.

1.1.2 Manufacturing flexibility

Manufacturing flexibility is an ambiguous concept; it involves several connotations depending on specific situations (Baykasoglu, 2007). Nevertheless, the predominance of research on the topic, focusing mostly in technological related issues such as machines, equipment, and processes, has contributed to a strong association between the concept of manufacturing flexibility and the consideration of highly automated systems (Mohamed et al., 2001). However, and according to Upton (1994), there are three elements of flexibility, or, similarly, ways to be flexible, namely range, mobility, and uniformity. The range element refers to the number of available options for a specific characteristic (e.g. the options available within a product family); mobility is the ability to move within the range, from one state to another with little transition penalty; and lastly, uniformity is defined as the ability of the system to maintain performance stability over a period of time. It is because differing views on each these elements that several focused approaches have been generated. The present study focuses on the dimension of uniformity, and therefore the definition of flexibility provided by Upton (1994) has been adopted for the purposes of this study. Consequently, flexibility is viewed as *the ability of the manufacturing system to change or react with little penalty on performance*, i.e. time, cost, productivity, etc.

1.2 PROBLEM STATEMENT

The strong association between the concept of flexibility and the use of automated equipment has, somehow, limited the view on manufacturing flexibility and therefore originated a significant number of approaches focusing solely on technological aspects. At the same time, this focused view has neglected alternative ways to achieve flexibility without necessarily relying on expensive and sophisticated manufacturing equipment.

Regardless of their technological advance, manufacturing systems' performance will always be determined by the interactions occurring among different system components. Therefore the search for flexibility must not only be limited to machines and other technological equipment but to have into consideration all of the key elements within a manufacturing system, i.e. work centres, material handling equipment, storage facilities, and obviously, human operators. Every one of these system components represents an opportunity for the whole system to achieve a certain level of flexibility. Consequently, it is important to identify those components providing manufacturing systems with the capability to maintain an acceptable performance under the influence of restricting conditions and, ultimately, achieve manufacturing flexibility.

1.3 RESEARCH OBJECTIVE

The general objective of the present study is twofold. On the one hand, the objective is to contribute to the achievement of a better understanding on the concept of manufacturing flexibility and the alternative means by which it can be achieved. On the second hand, the objective is also to demonstrate that not only can manufacturing flexibility be achieved by means of sophisticated equipment but also by the combined capabilities of different system components. In order to accomplish the general objective, the following specific objectives are considered:

- To identify different approaches to manufacturing responsiveness by reviewing relevant literature.
- To establish a research gap in the existing literature on manufacturing responsiveness.
- To categorize the different methods and tools by which the objective can be achieved.
- To develop a hypothetical model representing a particular manufacturing system, this will constitute the source of data for this study.
- To identify components, and their associated characteristics, providing the system with the ability to perform under different disrupting situations.

1.4 RESEARCH QUESTIONS

Taking into consideration the objective of this study, the following research questions are posed:

- How different disturbance scenarios affect the performance of a particular manufacturing system?
- What are the components providing the manufacturing system under consideration with the ability to more efficiently perform under such disrupting circumstances?
- What characteristics make the components in the previous question able to contribute to a better system performance?
- What are the trade-offs, if any, involved in the system's response to disturbances?

1.5 RESEARCH METHODOLOGY

In order to develop the research process, a hypothetical manufacturing system has been defined. Such system comprises the key elements interacting within common manufacturing systems, i.e. parts, machines, human operators, a material handling device, and material storage areas. Rules of interaction between the different system components are specified. Discrete event simulation is used as the modelling tool. In order to conduct the experiments, a 2^6 full factorial design is chosen. Accordingly, a number of experimental factors and their corresponding attributes are identified. Performance measures for the system are determined. Several simulation scenarios, each representing a specific disturbance, are also characterized. Statistical analysis is used to validate and analyse the outcome of experimental replications. Goal optimisation is used in order to identify existing trade-offs in system's response.

1.6 SCOPE

The concept of flexibility is an extensive concept; as a result, whenever the concept is applied to a manufacturing background, it is not limited to the production process itself. The concept of flexibility has also applications in other sub-systems within the organization such as the supply chain management, the distribution system, and even the organizational structure of the company. The present research focuses exclusively on manufacturing at the operational level, particularly in the context of a manufacturing cell consisting of work centres, controlled by human operators, and an automatic material handling subsystem. The main activities taking place between the reception of raw material and the shipment of finished products are considered. The rest of the activities within the manufacturing system are omitted in order to avoid adding unnecessary complexity to this study.

1.7 ASSUMPTIONS

Since the nature of the manufacturing system considered in the present study is completely hypothetical; the system components represented in the model, their associated characteristics, and the interactions occurring among the components, are assumed to be representative of those in a real manufacturing system. Similarly, it is assumed that the considered disturbances are some of the most common disrupting conditions affecting real manufacturing systems.

1.8 STRUCTURE OF THE THESIS

The present study consists of eight chapters in addition to this introductory chapter. Chapter 2 provides a background on the topic of manufacturing responsiveness and some of the existing research on the topic. After reviewing some representative approaches, tools, and techniques generally used by different authors, a research gap is identified amongst the existing literature. Chapter 3 establishes the research context for the present study by presenting a detailed account on concepts such as manufacturing systems, disturbances, and safety actions. Chapter 4 describes the characteristics of some of the most popular approaches in the design and analysis of manufacturing systems. In this same chapter, the advantages of simulation over the other techniques are emphasized. In chapter 5, a detailed account on the proposed simulation model and the description of each of the steps involved in its development process are presented. Chapter 6 provides details on the methodological aspect of this study by describing the experimentation process and the analytical tools employed. Chapter 7 presents the results of the experiments and a related statistical analysis. Chapter 8 presents the optimal results in terms of different response prioritization criteria. Finally, chapter 9 summarizes the findings from the research process and states the contribution to knowledge made by this study. The limitations of the research together with the identification of further research opportunities are also included in this last chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The purpose of this chapter is to provide a context of the existing research in the topic of manufacturing systems and their associated degree of responsiveness. This review of literature makes possible a general understanding of the important issues and current developments on the mentioned topic together with an identification of those areas which may need further research work. Because the topic in question is very extensive, it is not possible to include all the existing approaches in the same review. Therefore only those approaches with a higher relevance to the present research are cited. The chapter begins by describing some of the perspectives commonly adopted in the analysis and design of manufacturing systems. Subsequently, the chapter focuses on relevant approaches to counteract the effect of disturbances. Next, some representative approaches considering simulation in the design and analysis of flexible manufacturing systems are mentioned. The last part of the chapter identifies some gaps in the existing research on the topic of manufacturing responsiveness.

2.2 PERSPECTIVES IN THE DESIGN AND ANALYSIS OF MANUFACTURING SYSTEMS

In the topic of analysis and design of manufacturing systems there are two main categories of research approaches. The first category comprises research focusing only on the 'top level' or business aspects of manufacturing systems (MS), i.e. manufacturing is perceived as a part of a broader strategy. Within this category, research puts more emphasis on the external drivers that define MS. Among researchers in this first category, Miltenburg (1995) developed a customer-requirements based framework for analysing existing operations, generalizing and evaluating alternate strategies, analyzing competitor's strategies, and for developing a complete manufacturing strategy. Bhattacharya *et al.* (1996) believed it was important to consider more drivers in the design of robust MS and expanded Miltenburg's framework by additionally looking at disturbances affecting MS and identifying non-value-added activities. Dani and Harding (2004) developed an even broader view on the topic by putting forward the necessity to simultaneously analyse factors such as customers, suppliers, competitors, complementors, and the company itself in order to examine business processes.

The second category of research on the topic acquires a more focused view, and therefore it includes research concentrating exclusively on the manufacturing part of the business. Among the authors favouring a more focused view on manufacturing, Cochran *et al.* (2002) stated that the starting point when designing manufacturing systems is to define an overall objective for the system and then follow a decomposition process that relates the means to the objectives. Their approach was based on a cyclic process generating several decomposition levels, where the lower levels of the decomposition defined the specific details of the MS design. Within the same research category, other authors used methodologies and techniques that were originally developed to be applied into areas other than manufacturing; such techniques have also proven effective in the analysis and design of MS. Among those, Crowe and Cheng (1995) applied the Quality Function Deployment (QFD) methodology by considering internal business requirements in order to define the most suitable features in MS. Presley *et al.* (2000) complemented QFD with Soft Systems Methodology (SSM) and the Integrated Definition Functional Modelling tool (IDEF0) as an approach for product and process innovation. Similarly, Rodriguez-Ulloa and Paucar-Caceres (2005) combined systems dynamics (SD) and SSM, and proposed system dynamic methodology (SSDM) to ease the analysis and understanding of complex MS. Additionally, Wiendahl and Worbs (2003) considered different methods of non-linear dynamics in order to analyze complex production systems; and Meyer *et al.* (2007) employed static and dynamic analyses supported by simulation in order to study different levels of complexity in manufacturing systems.

Having understood the differences between the two research categories by reviewing some representative approaches, and taking into consideration both the objective and the scope of this study, the review of literature will omit further research on manufacturing as part of a wider strategy and focus exclusively on those approaches within the second category, i.e. those approaches with an exclusive focus on the manufacturing part of a business.

2.3 MANUFACTURING RESPONSIVENESS AND DISTURBANCES

MS are frequently exposed to the effects of a continuously changing environment, therefore the necessity for MS to rapidly react to change. According to Swamidass (2000), manufacturing responsiveness (MR) is a core competence which consists in the ability of a MS to quickly adjust to changes in either inputs (e.g. variations in supply or resources) or outputs (e.g. variations in demand). Given the changing economic conditions prevailing nowadays, a special interest has been shown in research aimed at increasing the level of MR. In consequence, the concept of uncertainty has acquired an important dimension, and a considerable number of approaches to protect MS against the effects of unexpected changes have been proposed.

Within the topic of responsiveness, there is a wide range of research focusing on the environmental influences affecting the performance of MS. Those influences, better known as manufacturing disturbances, are classified into internal and external disturbances, depending on whether they are inside or outside the control boundary of the MS. The analysis of MS under different disturbance scenarios constitutes an important context to understand the different circumstances in which system responsiveness can be achieved. In the following two sections some of the most representative research concerning the effects of different disturbances on performance and the approaches to counteract such disturbances will be reviewed.

2.3.1 External disturbances and manufacturing performance

Among external disturbances, uncertainty in the demand for products has been one of the most extensively investigated disturbances. Zäpfel (1998) aimed at reducing or eliminating the effects of demand uncertainty by synchronizing production and demand quantities as much as possible; this was achieved by modes of action enabling shorter throughput times and full utilization of existing capacity. This author acknowledged the importance of concepts such as Just-in-Time, Time Based Manufacturing, and Lean Production for achieving this goal. De Matta *et al.* (2001) investigated disruptions in production capacity caused by variations in demand, and proposed a model to find an optimal production plan incorporating short-term capacity adjustments to increase the production capacity and to minimize the total part production cost. Kirchner and März (2002) developed a planning support structure which constantly monitored the efficiency of a production system subjected to fluctuant demand through the product life cycle. Their model was based on a cyclic evaluation of the effects of different system configurations on the achievement of the company's objectives.

In a direct relationship with demand uncertainty, the arrival of parts into the system is another disturbance under exhaustive research. Tielemans and Kuik (1996) studied the relationship between batching of arrivals and the level of work-in–process; they recognized the impact long waiting times could have in system's performance. Similarly, Chikamura *et al.* (1998) analysed several lot arrival distributions in order to evaluate seven production dispatching rules in a high-technology, mass-production manufacturing environment. The authors noted that in this particular manufacturing environment and under most arrival scenarios, FIFO caused the lowest performance compared to other rules. Conversely, a dispatching rule considering more variables such as set-ups, waiting times, and processing times showed the best results. Prabhu (2000) emphasised the impact arrival times have on system performance and presented a distributed algorithm based on control engineering principles; his algorithm made MS robust to uncertainties by providing a dynamic response to changes in due dates and changes in the bulk arrival of parts. Van Ooijen and Bertrand (2003) investigated the effects varying arrival rates have on throughput and work-in–process (WIP) for a job shop; they concluded that an acceptable throughput would not necessarily imply a high arrival rate; however, they identified a trade-off between the costs associated with controlling the arrival rate and the revenues obtained by throughput.

Constantly changing customer’s needs lead to MS facing the necessity to widen the product portfolio, therefore making product variety another subject of analysis in the topic of external disturbances. In this regard, MacDuffie *et al.* (1996) conducted a investigation focused on the automotive industry in order to identify the effect of product variety on manufacturing performance. They identified some weaknesses associated with an increased product variety (e.g. higher costs) but also recognized advantages associated with an increased variety. Their results showed that even though product variety has a negative effect on productivity and quality, the effects of complexity can be diminished by implementing lean manufacturing and improved management policies. Similarly, Fisher and Ittner (1999) also based their research on automotive assembly operations and, even though they acknowledged some common negative effects of variety, they also recognised that product variety leads to benefits such as increased revenues. Their results showed that, at least in the automotive industry context, product mix variety has a significantly greater impact than product variety itself.

Moreover, Randall and Ulrich (2001) chose the bicycle industry to analyze the relationship between product variety and supply chain structure, together with the effects of such relationship on firm performance. Focusing particularly on the costs associated with product variety, they found that more variety does not necessarily mean higher performance for firms within such sector. They claimed that, no matter what product variety strategy is followed, what is important is the proper alignment between the supply chain and the product variety strategy. They added that the effectiveness of high variety strategies lies not only in the ability of the firm to deliver variety but also in the ability to communicate variety alternatives to customers. Thonemann and Bradley (2002) realized that an increase in product variety could lead to a decrease in supply-chain performance; these authors developed a mathematical model to analyze the relationship between these two concepts. They claimed that in order to provide an optimal solution to the question of how much variety should be provided, is necessary first to understand the cost of variety. The authors stated that, although there is an effect on supply-chain performance, such effect can be overcome by reducing setup times, unit manufacturing time, the number of retailers, or the demand rate. Fujimoto *et al.* (2003) recognized an existing trade-off between product variety and efficiency; they claimed that a balance between these two elements needs to be found when designing production processes. After realizing that neither process nor product approaches to cope with variety yielded the best results individually, the authors synthesized both approaches and developed a methodology to strategically manage product varieties. Their methodology is helpful in identifying issues at different stages in the design of assembly processes. It consists in evaluating assembly designs both from a product and process point of view; which leads to an improved efficiency by reducing redesign time and cost. Hu *et al.* (2008) developed a measure for evaluating complexity in multi-stage-mixed-model assembly systems and acknowledged a negative influence of product variety on manufacturing performance.

2.3.2 Internal disturbances and manufacturing performance

Just as in the case of external disturbances, internal disturbances have also been widely investigated; among these, machine related disturbances are probably the issues catching more research attention. Taylor and Clayton (1982) used network modelling to test different alternative approaches in order to control the impact of machine breakdowns and repair times on system output. Hillier and So (1991) developed an analytical model to investigate the effects of machine breakdowns and inter-stage storage on a production system. Realizing the significance of the effects on throughput, the authors put forward the importance of counting on internal buffers to counteract the effects of breakdowns. Logendran and Talkington (1997) compared cellular and functional layouts under the effect of significant disrupting factors such as machine breakdowns and batch size. They concluded that cellular layouts offer more advantages, in terms of in-process inventory and throughput time, than functional layouts, except in manufacturing environments characterised by large batch sizes and long run times. Chen and Chen (2003) proposed an adaptive scheduling approach to make scheduling decisions on part/machine and operation/tool assignments under the effect of machine breakdowns. The authors demonstrated that their method performed better compared to other existing dispatching heuristics. Ounnar and Ladet (2004) employed Petri nets to develop a work reassignment model based in three criteria, namely cost generated by machine breakdown, time corresponding to the machine change, and machine reliability.

In addition, Liao and Chen (2004) adopted an unconventional perspective on the problem of machine breakdowns and proposed to extend set-up times in order to reduce the breakdown rate. They developed a heuristics to maximize set-up times subject to the due date constraint and, in this way reduce machine breakdowns. Ozmutlu and Harmonosky (2004) demonstrated that in MS subject to machine breakdowns, the conventionally adopted strategy of re-routeing all the parts in the queue of a broken machine to an alternate machine may not yield the best results. The authors analyzed three re-routing strategies and proposed a simple selective re-routing heuristic aimed at minimizing mean flow time. This heuristic proved better result compared to conventional routing heuristics. Yong *et al.* (2005) studied the machine loading problem (MLP) in circumstances where machine breakdowns occur. The authors compared two different approaches to the problem and found that using neural networks in the MLP yielded better results than using other heuristic methods. Nihatt *et al.* (2006) put forward an intelligent scheduling process to reduce the impact of uncertain environments characterized by the existence of machine breakdowns. Their approach characterized uncertainty using probability distributions and derived optimal policies for different distributions.

In addition to the technical aspects of MS, the human aspect is also a source of internal disturbances, particularly when there is a specific level of system's dependence on human resources. In relation to the human element in 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 responsiveness. It is clear that increasing automation of MS, 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. Page *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.

After reviewing some representative research in terms of different disturbances and their effect on manufacturing performance, it can be noticed that different system aspects have been proposed to counteract the effect of disturbances. System's features such as reduced machine set-ups, intelligent dispatching rules, adequate inter-storage capacity, cellular layout configurations and skilled human operators have been suggested as means to either eliminate or decrease the influence of disturbances. However, and due to the fact that each one of these characteristics has been individually investigated, it is not easy to distinguish whether specific characteristics are useful only under particular circumstances or there are certain system characteristics which are useful under a number of different situations. Therefore, the necessity of further research investigating the contribution to manufacturing responsiveness, not only from an isolated component but from a number of interconnected system components, is evident. Moreover, establishing a more inclusive research context through the consideration, in a single study, of different performance disrupting conditions under which responsiveness can be achieved, would be helpful to reaffirm the knowledge generated by existing research on individual or specific disturbances.

2.4 FLEXIBILITY AND MANUFACTURING PERFORMANCE

Because changing market conditions had led to a paradigm shift from mass production to mass customization, it is necessary for companies to invest in resources making possible to react promptly to all those changes occurring in the market (Zahn et al., 1998). Flexibility is a dimension of manufacturing responsiveness which has been proposed in order to either eliminate or reduce the effects of disturbances on performance (Eraslan and Kurt, 2007). According to Shian-Jong (2007) the concept of flexibility is a multidimensional concept; however, the majority of dimensions in flexibility involve a transformation process and the efficiency with which such transformation is made (Baykasoglu, 2007). There are three basic dimensions for the concept of flexibility, namely range, mobility and uniformity (Upton, 1994). The first dimension involves the number of options available for a manufacturing system to cope with internal and external requirements; the second dimension refers to the outputs in terms of time, money, and quality, resulting from making changes between the available options; the third dimension is concerned with the ability of the system to maintain performance stability over a period of time.

In a customer driven market characterized by low volumes and high variety of products, MS 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 of a 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. In addition machines within cells are operated by machinists who work only within the cell. Cellular manufacturing constitutes a first step in achieving world class manufacturing status. Another manufacturing approach, in terms of system configuration, is flexible manufacturing systems (FMS); which are a more automated version of cellular manufacturing. In FMS a number of machines are linked by a material handling system; this kind of systems operate with little or no human intervention since all the aspects of the system are controlled by a central computer.

Both cellular manufacturing and FMS are important system configurations in the context of manufacturing flexibility; however, these systems are not exempt from the influences of disturbances. The effects of flexibility upon the performance of cellular systems and FMS is one of the major topics among researchers (Mohamed et al., 2001). Among those, Dimitrov (1990) concluded that flexibility has a positive impact on inventories after analysing a database of 750 FMS installed in 26 countries. Ram and Viswanadham (1992) evaluated the performance of cellular FMS by using a decomposition-based methodology involving queuing networks and Petri nets. Benjaafar (1994) examined the effects of varying flexibility in either production requirements or machine capabilities; as a result, he identified the conditions under which a positive correlation between flexibility and performance exists and also outlined control mechanisms for realizing the benefits of flexibility. Saad (1994) investigated the factors exerting major influence on the performance of flexible-hybrid assembly systems and concluded that buffer capacity together with the quantity and speed of material handling units are the factors affecting system's performance the most. Suri and Desiraju (1997) presented an analytical model to estimate performance outcomes of a FMS with a single material handling device. However, despite of the fact that the model was accurate for initial system design, his model was not able to predict the performance of manufacturing cells with different processing routes, which happen to be a key characteristic in a cellular system configuration.

Besides, Kim and Yano (1997) studied how various objectives related to maximization of steady-state throughput and machine grouping decisions affected measures of performance such as make span, mean flow time, and mean tardiness. They noticed that objectives, particularly related to workload balance, produced a positive effect on such measures. Nevertheless, it is important to mention that these authors considered only functionally identical machines in their experiments which may not produce the same results on systems with different operating-condition machines. Matsui *et al.* (2001) evaluated the performance of FMS by establishing a comparison between fixed and dynamic routing rules considering the use of finite local buffers; they found that dynamic routing exhibited a higher performance than fixed routing in terms of throughput; however, such performance could have been similar using fixed routing if some setting parameters had been changed.

Buitenhek *et al.* (2002) put forward a method to determine the maximum production capacity in a multiple-part-type FMS with fixed production ratios. They emphasized the importance of performance evaluation as a previous stage in the design of FMS and suggested the advantages of their method in providing information for the optimum design of FMS. Chan (2003) investigated the effects of both dispatching and routing flexibility on the performance of a FMS in terms of makespan, average flow time, average delay time at local buffers, and average machine utilization. However, a limitation of this study is the assumption that some resources such as tools, fixtures, and materials are always available. Chang *et al.* (2003) assumed that more flexibility would not necessarily lead to better performance, and investigated the compatibility between 3 business strategies in small and medium manufacturing companies and six types of external flexibility. They noticed that in order for a company to exhibit better performance, it is necessary a proper match between the business strategy and the type of flexibility adopted. This was later confirmed by Lloréns *et al.* (2005) who analysed how the determinants of manufacturing flexibility affected strategic change in organizations as well as their subsequent performance.

Chandra *et al.* (2005) developed a strategic planning model to evaluate flexibility in manufacturing systems facing demand uncertainty; their model used a number of scenarios representing different levels of flexibility enablers and allowed the evaluation of expected benefits, in terms of profitability, from adopting flexibility strategies. Karakayali and Azizoglu (2006) put emphasis on the importance of efficient tool management to maintain high productivity levels; they analysed the tool switching and sequencing problem on a single flexible machine and proposed a branch-and-bound algorithm in order to minimize the total flow time by optimizing the tool sequencing and switching times. Eraslan and Kurt (2007) presented a cognitive approach to identify the factors affecting performance of individuals and systems within FMS along with the quantification of their effects. The authors observed that the most important factors of individual performance are creativity, production speed, and production variety; and for system performance are purchasing/supplies cost, labour utilization, and set-up cost.

Research on the issue of selecting either the right type or level of flexibility include Gupta *et al.* (1992) who recognized the significance of machine changeovers as important determinant of manufacturing flexibility and proposed a model to design the optimal mix of dedicated and flexible capabilities in terms of investment and allocation. Barad (1992) addressed the question ‘How much flexibility is needed for the system to maintain a stable performance under changes in mix or changes in the planned utilization level?’ Unfortunately, in his analysis he only considered the contribution to performance out of machine capabilities and omitted the contribution from other important system components. Gerwin (2005) listed a series of uncertainties faced by manufacturing systems and proposed specific flexibility types in order to cope with each type of disturbance.

It is clear how most of the existing research on the topic of flexibility and manufacturing performance focuses exclusively on technical aspects of MS. Either the material handling system or specific machine characteristics are investigated to understand their impact to manufacturing flexibility; however, other key aspects of MS such as the human element and the interactions occurring among the different components within the system have been ignored or have not been exhaustively investigated. Because these neglected aspects must also contribute, to a certain extent, to system flexibility, it is fundamental to consider them, together with technical aspects, when investigating the concept of flexibility in MS.

Please refer to Vokurka and O’Leary (2000) for more information on the topic; these authors provide a detailed account of existing empirical research on manufacturing flexibility and its effects on performance.

2.5 THE ROLE OF SIMULATION IN THE ANALISYS AND DESIGN OF FLEXIBLE MANUFACTURING SYSTEMS

Discrete event simulation (DES) has been one of the most preferred tools to analyse different types of MS; among those, FMS have been especially associated with the use of simulation as analytical tool. Mishra and Pandey (1989) used simulation based on statistical design of experiments to analyze the effects of processing time, travel time, and arrival time on specific performance measures such as average machine utilization and number of tardy, completed, running, and waiting jobs. Together with the fact that the authors did not consider set-up times, another limitation is the fact that the study neglected the effect of waiting times due to the unavailability of tools and fixtures. Gupta and Goyal (1992) conducted a simulation study to investigate flexibility trade-offs associated with a FMS. They measured the impact of various types of flexibility, namely machine, product, routing, and volume flexibilities on the performance parameters of a FMS (e.g. machine idle time and job waiting time) under the effect of different loading/scheduling strategies and various system configurations. Nevertheless, this study could have been more valuable if it had considered the interactions between the experimental factors by employing a different experimental design rather than testing one factor at a time.

Moreover, Das and Nagendra (1993) studied the impact of routeing, machine, and product flexibility on manufacturing performance; they found that in complex production systems both routing and machine flexibility play an important role on manufacturing performance. Prakash and Chen (1995) evaluated the effects of three different scheduling rules (e.g. first come first serve, shortest processing time, and longest processing time) along with different conditions of automated guided vehicles (AGV) availability, different layout configurations, and different part processing times on the performance of a FMS subject to machine breakdowns and stochastic part arrival patterns. Chen and Chung (1996) analyzed system performance at various flexibility levels and under different operating conditions by combining simulation and design of experiments; they suggested alternative measures for the assessment of machine flexibility and routeing flexibility. D'Angelo *et al.* (1996) combined simulation, design of experiments, and regression analysis to identify significant variables affecting performance of MS. Later on, these same authors (1998) evaluated the effects of some statistically significant variables on the performance of MS but, this time, in terms of cost . They used Taguchi method to analyse the data previously generated by simulation. Unfortunately, the different statistical techniques they used in their research ignored the interactions occurring between variables.

In addition, Albino and Garavelli (1998) proposed a simulation model to investigate the effects of both routing flexibility and resource dependability on a cellular MS with constant and variable part family demand; they observed that the benefits of routing flexibility are inversely proportional to system's resource dependability and that the effect of resource dependability on system performance can lead to optimal system configurations other than the limited flexibility one. One downside of this research is the fact that the authors did not provide a high level of detail in their model since manufacturing cells were represented as black boxes, neglecting the interactions between elements occurring within such cells. Saad and Gindy (1998) investigated the responsiveness of a manufacturing system, particularly of a machining facility represented by resource elements. The authors conducted simulation experiments to analyse and compare the performance of three systems, namely machine-based system, resource element-based system, and resource element-based cell system; to do so, the authors considered four performance measures, namely average flow time in the system, mean tardiness, proportional tardy job, and machine utilization. Additionally they measured the system ability to make an appropriate balanced and rapid response to predictable and unpredictable change.

Furthermore, Mahmoodi *et al.* (1999) were aware of the importance of analysing system performance under the influence of constraining events, and extended previous research in order to evaluate the effects of scheduling rules, routing flexibility, and shop configuration on the performance of a MS subject to the influence of limited material handling capability and system breakdowns. They noted the significance of routing flexibility in achieving acceptable levels of performance. Tsubone and Horikawa (1999) investigated the effects of three types of flexibility, namely machine, routing, and volume flexibilities on the manufacturing performance of a production system consisting of a part fabrication process together with an assembly line. They realized that a significant improvement in performance was achieved when machine flexibility and routing flexibility were introduced simultaneously. Nagarur and Azeem (1999) conducted a simulation study in order to analyse the alternatives for a manufacturing system to deal with product variety while keeping high levels of productivity. Their main objective was to analyze the individual and combined impacts of component commonality and flexibility on the performance of a given MS. Devise and Pierreval (2000) recognised the great influence material handling systems have in system's performance and showed the necessity of indicators to evaluate performance; they studied the relationship between workshops' morphology and material handling systems to suggest indicators for evaluating the flexibility of MS; they also identified the existence of a trade-off between flexibility and cost.

Moreover, Boremstein (2000) considered different scenarios to examine the effects of routing flexibility on performance measures such as work in process, lead time, and throughput when the system is subjected to machine breakdowns and different dispatching rules. Garg *et al.* (2001) used simulation to determine the right mix for a system relying on safety stock for meeting demand uncertainties and for a system relying in additional capacity and routing flexibility to cope with uncertainties. The authors determined the extent of flexibility required in three different manufacturing configurations, namely dedicated manufacturing, partially flexible manufacturing, and fully flexible manufacturing. Chan (2004) focused specifically on the concept of operation flexibility and used simulation to analyse the effects of different levels of such flexibility along with various dispatching rules on the performance of a FMS. The author's findings revealed that altering the dispatching rules would have a more significant effect on the performance than changing the levels of operation flexibility; however, an important limitation in this study is the fact that the author assumed the existence of a perfect system, i.e. he assumed that materials were available all the time, that machine breakdowns never occurred, and that resources such as operators and tools were always available. Krishnamurthy *et al.* (2004) analysed control strategies and compared the effects of MRP and kanban strategies on system performance. In order to do so, they employed simulation to conduct their experiments and observed that, particularly in multi-product cells, push strategies significantly outperformed pull strategies by generating less in-process inventory and a shorter lead time.

Also, Feyzioglu *et al.* (2005) developed a simulation-optimization approach to size a variety of manufacturing systems, including FMS. Their approach was not based on the achievement of the best possible performance but on finding the minimum number of resources allowing the performance requirements, given in the design specifications, to be met; by doing so the associated cost would be indirectly minimized. Buyurgan and Mendoza (2006) studied the complexity of scheduling activities in FMS and developed a dynamic scheduling model which constantly monitored desired performance outcomes and specified system behaviour accordingly. The authors found that their model outperformed some well-known priority rules. Even though the idea of a predictive model is interesting, a drawback in this model is related to the fact that components such as machines and processing routes were modelled separately.

Wadhwa *et al.* (2006) proposed a conceptual framework to identify three different types of flexibility, namely transformation, sequencing, and product flexibility. Once the difference between the three concepts had been established, the authors investigated the influence of each type of flexibility on performance; they measured performance in terms of lead-time, and used simulation to conduct their experiments. They concluded that product flexibility has the greatest influence on performance due to a lower movement of products within the MS. Muriel *et al.* (2006) considered a multi-product, multi-plan MS in order to evaluate the impact of different flexibility configurations on manufacturing performance. They found that, under such context, partial flexibility can lead to a significant increase in production variability but the performance of a flexible system is also dependent upon proper capacity allocation policies. Lastly, Chan *et al.* (2008) examined manufacturing flexibility by adopting a decision and information system point of view. The authors combined simulation and Taguchi's method in order to identify critical parameters to improve performance in FMS. They observed that just as in the same way as performance depends on flexibility, the need for information systems and control also depends on the level of flexibility. This study, unfortunately, did not consider other important elements in FMS such as material handling devices; it also did not consider the effect of disturbances on performance, which might mean an important omission considering the fact that the study focuses on FMS.

For further information on other research about the use of discrete event simulation in the analysis and design of MS, Smith (2003) provided an extensive review on the topic.

A particular characteristic of the different approaches to flexibility from a simulation perspective is the fact that there is much emphasis on the flexibility dimensions of range and mobility. Consequently, this has led to a strong link between the concept of manufacturing flexibility and counting on sophisticated technological capabilities. Existing research predominantly concentrates on aspects such as machine and routing flexibility, exploring different numbers of technical capabilities within a range and the process of going from one alternative to another in order to achieve flexibility. Nevertheless, the uniformity dimension of flexibility has not yet been widely investigated. This dimension indicates that flexibility is also the capability to maintain a stable performance over a period of time despite the occurrence of disturbances; therefore approaches to flexibility considering the uniformity dimension need to be further investigated.

2.6 DEFINITION OF RESEARCH GAP

From the literature mentioned in this chapter, particularly from the previous two sections, it can be noticed how even though there is a significant amount of research covering different aspects of manufacturing flexibility and performance, most of the literature considers only very specific elements of flexibility, i.e. existing research exclusively considers mainly technical aspects or elements such as machines, material handling, production planning, etc. It is evident that there is not much research considering different components of flexibility under the same study. Moreover, another important characteristic of the existing research on the topic is the fact that flexibility is strongly associated with the technological aspects of MS such as automation and sophisticated equipment as a consequence of a strong research attention on the dimensions of range and mobility.

According to the literature reviewed in this chapter, flexibility can be achieved by a variety of means and in different levels. Therefore adopting an exclusive perspective in the analysis of flexibility neglects the possibility to consider either other dimensions or additional alternatives to achieve flexibility. As a result of a technological orientated view on the topic, aspects as important as the role of the human factor in achieving flexibility have not been exhaustively investigated. In addition to the fact that existing research in the design and analysis of FMS focus mainly in technological aspects, it can also be noticed that, regarding the analysis of performance, it is mainly carried out in circumstances where there is only one or two specific disrupting scenarios, again mainly related to either machine or supply problems, and not exploring other different scenarios.

Based on the previous observations, a research gap on the topic of analysis and design of FMS has been identified. In order to develop complementary research on the topic of manufacturing flexibility the following aspects must be taken into consideration:

- There is a necessity for achieving a more complete understanding on the concept of manufacturing flexibility.

- In order to properly comprehend the concept of flexibility in manufacturing, it is important to be aware of the context in which flexibility is developed. Given that flexibility is generated as a response to uncertainty, it is essential to understand how unexpected situations affect the performance of manufacturing systems and how flexibility provides protection against such situations. In this sense, research featuring different scenarios where flexibility is required, can provide a wider perspective on the concept and therefore contribute to a better understanding of it.

- Because there is a predominance of research where manufacturing flexibility is strongly associated to automation and sophisticated equipment, it is fundamental to develop a more inclusive approach to the concept. This is an important issue considering that flexibility is a multidimensional concept and therefore the different elements leading to its achievement need to be equally investigated.

- Particular attention must be paid to the dimension of uniformity, which has been neglected by most of the existing research on the topic of flexibility.

- In connection with the previous two paragraphs, it is elementary to fully understand the basic levels or dimensions of flexibility before understanding upper levels. More experimental factors, including the human element, must be considered in order to identify the contribution to manufacturing flexibility from different components and under diverse unpredicted circumstances. This will enable to identify the components and the features which make them more suitable to contribute to manufacturing flexibility in the majority of the situations.

- Given that the objective of flexibility is to maintain an acceptable performance during conditions of uncertainty, and that performance measurement in manufacturing is not limited to a single indicator, flexibility needs to be evaluated in terms of different performance measures in order to identify possible trade-offs between them and to categorize the performance criteria under which systems show the best performance.

2.7 CONCLUSION

Flexibility within a manufacturing context is a topic that has emerged as a result of the prevailing competitive environment. The application of flexibility in a variety of areas within the manufacturing industry has been extensively investigated along with the development and implementation of a number of approaches to achieve different levels of flexibility. However, the majority of research on the topic focuses on issues related to the achievement of flexibility as a result of highly automated systems. This has lead to a limited understanding of the concept of flexibility in manufacturing. In order to better understand the concept of flexibility, especially when applied to manufacturing, it is important to adopt a wide perspective considering the following: First, it is fundamental to understand the different contexts in which flexibility is applied and how flexibility constitutes an advantage in such contexts. Second, all the key components in a manufacturing system, and not only machines, need to be considered. Other system components such as the human factor, which is generally omitted in most of the research on the topic, may have a special significance in the achievement of flexibility and therefore must also be considered. Additionally, it is important to understand how flexibility is viewed in terms of different performance indicators and how prioritizing particular indicators affects other complementary measures.

CHAPTER 3

MANUFACTURING SYSTEMS, DISTURBANCES, AND SAFETY ACTIONS

3.1 INTRODUCTION

MS have always faced different challenges resulting from the environment within which they operate. Nowadays, and as a consequence of an increasingly competitive and demanding environment, MS need to develop a series of capabilities making possible for them to cope with unexpected change. In this chapter, some of those capabilities are described. The chapter begins with an overview of MS, which includes a definition, the main attributes by which performance is evaluated, and a description of cellular manufacturing as a representative system in this study. Next, the chapter moves on to explore the concept of manufacturing disturbances together with their associated causes and effects. Some of the most common disturbances and their characteristics are also reviewed. The last part of the chapter explores some of the most common safety actions against manufacturing disturbances, putting emphasis in the concept of flexibility as one of the most effective approaches when dealing with disturbances.

3.2 MANUFACTURING SYSTEMS

Manufacturing is a concept consisting of several other aspects, i.e. processes, machines, management, etc. However, and for analytical purposes, manufacturing is commonly divided into three specific areas, namely *Manufacturing processes*, which are all the means by which materials are transformed into finished products; *manufacturing equipment*, which are the physical resources to conduct manufacturing processes; and *manufacturing systems*, which is the combination of processes, equipment, and humans sharing a common material and information flow (Chryssolouris, 2006). In this study particular attention will be paid on the area of manufacturing systems.

3.2.1 Definition of manufacturing system

A MS is formally defined as a transformation process where a series of inputs are, by the means of an internal process, converted into a series of outputs (Wu, 1994). Within the internal process, there is an assembly of interconnected components or subsystems whose interaction with other components determines the behaviour of the entire system. Figure 3.1 below illustrates a graphical representation of the transformation process and the elements involved.

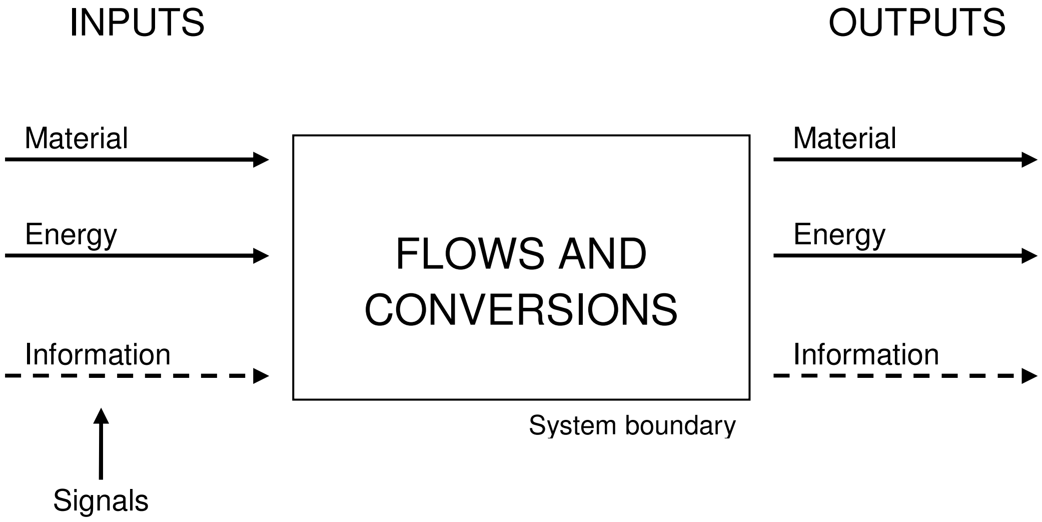

Figure 3.1 - Graphical representation of a manufacturing system (from Williams 1994)

It can be noticed, from figure 3.1, that inputs and outputs are the main interface between the system and the environment given that the system components or subsystems are enclosed by a boundary which prevents any other contact with the external environment. Inputs generally take the form of raw material, energy, and information, whereas outputs consist of finished products, scrap, and information (i.e. performance). The components limited by the boundary are classified in machines and processes, transport and handling for parts and tools, and a control subsystem (Williams, 1994). The efficiency with which manufacturing systems transform inputs into outputs is evaluated in terms of a series of performance attributes namely, cost, time, quality, and flexibility. According to Chryssolouris (2006), when either designing or operating manufacturing systems, it is important to consider that because of the existence of trade-offs between these attributes, decisions on optimal parameters would depend on the objectives and prioritization criteria of top management.

3.2.2 Cellular manufacturing systems

Depending on whether parts are made or put together, MS are grouped into processing MS and assembly MS respectively. Among processing MS, a particular layout configuration is the group technology layout or cellular system. A general representation of a cellular MS is shown in figure 3.2; as it can be noticed, in a cellular arrangement different types of machines are grouped together according to the process combinations occurring within a family of parts, which means that material flow differs for different parts of the same family (Chryssolouris, 2006). A small variety of similar parts are produced within a cell and those parts are transported within the cell either manually or automatically.

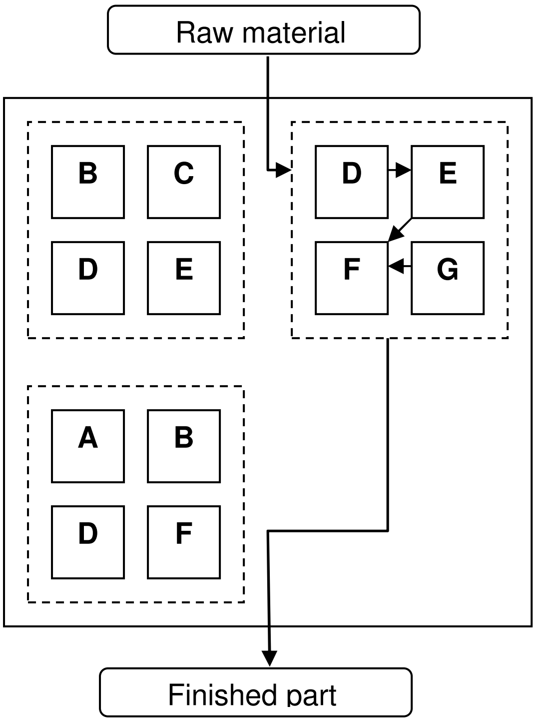

Figure 3.2 - Schematic of a cellular manufacturing system (from Chryssolouris 2006)

Reportedly, cellular arrangements contribute to WIP reduction and increase efficiency by reducing material handling and transportation costs (Williams, 1994). Some of the most important characteristics of a representative manufacturing cell, according to Shahrukh (1999), are the following:

- Number of human operators: 1 to 6.
- Number of workstations: 1 to 10.
- Machines are close from each other to simplify and minimize material movement.
- Low to medium production volume.
- Medium part time similarity.
- Most of the work is completed within the cell.
- There are production sequences and routes for all the parts.
- Own inspection and work scheduling.

3.2 MANUFACTURING DISTURBANCES

Now more than ever current MS face the challenge of uncertainty. Uncertainty is the result of highly dynamic markets triggered by varying and unstable customer needs. In a high product variety environment characterized by a high number of differentiated products, higher variations in demand, and lower production volumes, MS are prone to the slightest changes in the environment. Therefore MS are more vulnerable to the effects of unpredictable or random events which are commonly referred to as manufacturing disturbances. According to Prabhu (2000), in the face of increasingly dynamic markets, MS need to be robust to disturbances.

3.2.1 Definition of disturbances and other generalities

In the context of manufacturing, disturbances are generally defined as all those unanticipated events that will cause the system to deviate from normal operating conditions, leading, as a result, to a negative impact on the overall system performance (Lindau and Lumsden, 1995). It is the extent to which the MS deviates from its stable operating conditions that determines the magnitude or size of disturbances. According to Bhattacharya *et al*. (1996), disturbances can be originated from a number of unpredicted changes, which can be grouped in internal changes (e.g. failure of equipment, human mistakes, etc.) and external changes (e.g. changes in volumes). Additionally, Chong *et al*. (2003) claim that disturbances have direct implications for the MS in terms of its capacity to meet customer demand and its ability to cope with fluctuating workloads.

Although the magnitude and effect of disturbances vary along the different stages of a MS (Bhattacharya et al., 1996), three basic aspects within the system seem to be the most affected by the influence of disturbances; such aspects are operation time, speed, and quality (Jonsson and Lesshammar, 1999). First, impacts on operation time occur when machines and equipment breakdown or when there are an important number of set-ups or adjustments involved in the manufacturing process. Second, speed is the affected aspect when there are idle machines or when the system is subject to minor stoppages; speed is also affected when the production equipment performs under its original capacity. Lastly, consequences in quality result when defects and reworks are present due to malfunctioning of production equipment. Furthermore, quality can also be affected during the ramp up of new production equipment incorporated into the system.

3.2.2 Classification of disturbances

Disturbances are classified according to different criteria; in terms of their source, they are classified in internal and external disturbances (Saad and Gindy, 1998). Internal disturbances are originated within the limits of the MS (e.g. equipment breakdowns or resource unavailability). In contrast, external disturbances have their origin out of the context of the MS and can be either related to demand (e.g. unexpected orders) or related to supply (e.g. delayed deliveries). Moreover, disturbances are also classified in terms of their inherent nature of occurrence into normal and abnormal disturbances (De Matta et al., 2001). Normal disturbances are those events that are part of the day-to-day operation of MS and therefore can be predicted to a certain extent, producing only small production variations in consequence (e.g. equipment maintenance, tool deterioration, etc.). In contrast, abnormal disturbances are less predictable and less frequent events, usually resulting in large production variations (e.g. major machine breakdowns, product re-designs, etc.).

One more classification of disturbances is the one specifically related to their frequency of occurrence. Under such criterion, disturbances are divided into chronic and sporadic disturbances (Jonsson and Lesshammar, 1999). Chronic disturbances are generally small, hidden, and complicated events that occur repeatedly; their identification may be difficult because they are seen as the 'normal state' and, if unattended, generally lead to low equipment utilization and high costs (e.g. drop in machine performance due to defective components). On the contrary, sporadic disturbances are more noticeable than chronic disturbances in the sense that they are easily identified because they cause large variation; even though they occur irregularly, their effects may cause serious problems for the MS (e.g. drastic changes in production orders).

According to Chong *et al.* (2003), a last but not least important categorization is the one relating disturbances to their specific root cause; thus, disturbances are grouped into disturbances related to capacity, disturbances related to orders, and disturbances related to measurement of data.

3.2.3 Most common disturbances and their characteristics

Reportedly, some of the most common disturbances occurring in manufacturing are: material shortage, absenteeism, machine breakdowns, tool shortage, and technical documentation shortage (Lindau and Lumsden, 1995). These, together with other common manufacturing disturbances are included in table 3.1 below.

Table 3.1 - Common disturbances in manufacturing (Adapted from Koh and Saad, 2003)

SOURCE	DISTURBANCE	TYPE	DESCRIPTION
Internal	Labour shortages	Absenteeism	Sickness Holiday Maternity
	Labour shortages	Lack of skills	Inherent shortage of skilled labour Unexpected demand for particular skill
	Labour shortages	Schedule/Work-to-list not followed	Schedule/work-to-list not controlled Schedule/work-to-list not available to labour Schedule/work-to-list not produced
	Labour shortages	Labour overload	Unexpected changes to schedule MRP plan overload
	Machine capacity shortages	Machine overload	Unexpected changes to schedule MRP plan overload
	Machine capacity shortages	Unplanned machine downtime	Planned maintenance/repair time exceeded Planned setup/changeover time exceeded Breakdown

Table 3.1 (continued)

SOURCE	DISTURBANCE	TYPE	DESCRIPTION
Internal	Machine capacity shortages	Idle machine waiting for resources	Waiting for labour Waiting for tooling Waiting for material
	Scrap/Rework	Unacceptable product quality	Defective raw material Labour error Machine error
		Engineering design changes during/after production	Customer design changes during/after production Internal design changes during/after production
	Undelivered finished products	Awaiting quality clearance	Waiting for inspection
		Awaiting dispatch	Items on-hold Transport unavailability Awaiting balance of order Seeking concession
External	Material shortages	Inaccurate stock records	Items missing in BOM Insecure stores Poor transaction recording
		Incorrect stock control rules	Unexpected demand pattern changes Demand/usage analysis not used to drive stock control rules
		Poor supplier performance	Incorrect items supplied Delivered with shortages Late delivery Rejected by quality

Table 3.1 (continued)

SOURCE	DISTURBANCE	TYPE	DESCRIPTION
External	Material shortages	Unexpected changes to production schedule	Customer changes delivery lead times Customer changes ordered product Customer design changes during/after planning Customer changes ordered quantity Inaccurate forecast Internal design changes during/after planning Customer changes specified level of quality

Disturbances in manufacturing have a number of different qualities; however, there are five main characteristics that have a significant impact on manufacturing performance, those are the following:

1. Type of disturbance. Related to the nature of events affecting the system.
2. Size of disturbance. The extent to which disturbance affect the system.
3. Interval of disturbance. The frequency with which the manufacturing system is subject to the same type of disturbance.
4. Incidence of disturbance. Related to the time when a particular disturbance occurs.
5. Early notification of disturbance. The extent of time in advance with which the system becomes aware of an imminent disturbance.

In addition to these main characteristics, there are other characteristics that, either directly or indirectly, derive from the five main characteristics described above (Chong et al., 2003).

3.3 SAFETY ACTIONS

Similarly to the way in which the occurrence of disturbances varies throughout the MS, the responses to turbulences also vary depending on the type of turbulence being faced and on the part of the system being affected (Bhattacharya et al., 1996).

3.3.1 Classification of safety actions

There are number of approaches to cope with disturbances that have been reported by experts in the topic; some of those approaches focus exclusively on the technological capabilities of the equipment; others approaches put more attention in the planning and control aspects of manufacturing processes (Gerwin, 1993). Regardless of the nature of the method employed, the available approaches to counteract the effect of disturbances on manufacturing performance, also known as safety actions, can be grouped into formal and informal approaches (Lindau and Lumsden, 1995). On the one hand, formal safety actions are characterized by their capability to reduce the effect of disturbances via actions originated within the planning and control structure of the system; some of the most common formal safety actions, particularly focused on tactical aspects of the materials flow, are the following:

- Safety stock. An additional inventory of parts which is held to protect MS against uncertainty in supply and demand as well as from disruptions coming out of internal factors.
- Safety capacity. It occurs when productions orders are planned below the full capacity in order to have an extra capacity available when unexpected events arise.
- Safety lead-time. As opposed to safety capacity, safety lead time consists of production plans considering an actual lead time plus an additional lead time.
- Over planning. Refers to the action of deliberately overstate the ordering of specific parts in order to count on an additional number of available parts if they were needed.

On the other hand, informal safety actions are spontaneous measures, generally executed and controlled manually, which are applied when formal actions are unable to counteract disturbances on their own. Some of the most common informal actions are the following:

- Subcontracting. Refers to the action of allocating the production of a specific part or product to alternate manufactures in order to reduce production workload and meet lead times.
- Expediting. To perform a series of time saving activities along the manufacturing process in order to facilitate the on time delivery of parts.
- Partial delivery. A situation where a total production order is divided into smaller batches; the completed batches are delivered to the customer while the in-process batches are processed.
- Short term re-planning. Occurs as a response to problems where it is possible to readjust the production schedule within a limited system.

Moreover, safety actions can also be grouped in accordance to their level of application in resource level and system level safety actions (Kadar, 2001). Resource level safety actions are those activities that require a degree of resource management in order to exploit the capabilities of physical resources (e.g. machine tool controllers, exploitation of creativity, experience and competence of employees). System level safety actions, in contrast, result from the development of more inclusive planning and control practices (e.g. shop floor control techniques). Other important ways to cope with disturbances at a system level are decentralization of functions and concentration on the core skills of the company (Monostori et al., 1998).

3.3.2 Flexibility

In addition to all the safety actions that have been already mentioned in the previous section, flexibility has also been recognised as another approach to cope with manufacturing disturbances (Gerwin, 1993). Flexibility, within the manufacturing context, is defined as the ability to change or react to disturbances with a little penalty in performance (Upton, 1994). Therefore, and considering the concept of MS, the level of flexibility in a particular MS is determined by the individual capabilities of its components. In a FMS, according to Carrie (1992), the components providing the system with flexibility capabilities are the following:

- Work stations. Including machines of different types.
- Loading/unloading stations. Introducing/releasing parts into/out of work stations.
- Material handling equipment and accessories. Including conveyors, vehicles, robots, pallets, etc.
- Machine tools. Including fixtures and accessories.
- Buffer storage at workstations. Consisting of both input and output buffers.
- Other storage facilities. Like storage areas for raw material, WIP, equipment, etc.
- Human operators. Involved in activities such as loading/unloading of parts, tool preparation, inspection, etc.
- Computerized control system. Scheduling and controlling activities performed by machines and the material handling equipment.

In relation to the different components forming a FMS, different types of flexibility have been identified (Miltenburg, 1995). Table 3.2 shows the different types of flexibility.

Table 3.2 - Different types of flexibility in manufacturing (from Miltenburg 1995)

TYPE OF FLEXIBILITY	DEFINITION
Machine	The ease to change equipment and machine settings.
Process	The availability of different alternatives to manufacture a specific product.
Product	The ability to change production of one product to another.
Routing	The availability of different paths to produce a product.
Volume	The capacity of machines and processes to operate at different volumes.
Expansion	The capacity of a manufacturing system to be increased in order to augment capacity.
Operation	The ability to alter the operations sequence for a specific product.
Production	The totality of products that a system can produce.

Regarding the connection between the different types of flexibility above and the three dimensions of flexibility mentioned in the previous two chapters, i.e. range, mobility and uniformity, figure 3.3 below illustrates how each dimension is linked to a particular type of flexibility. The range dimension, related to the number of different available options for a particular characteristic, is directly linked to those flexibility types similarly involving a range of different alternatives (e.g. process, routing, volume, and production flexibilities). In the same way, the mobility dimension, involving the ability to shift within a range of options, is directly associated with those flexibility types implying a change in the status of the system (e.g. machine, product, expansion, and operation flexibilities). Concerning the uniformity dimension the relationship with the different types of flexibility is not as evident as in the case of the range and mobility dimensions. Given the uniformity dimension implies the ability of the system to maintain a stable performance over a period of time, and that any of the different types of flexibility directly introduces performance in their definitions, the relationship between different types of flexibility and the uniformity dimension must be established by taking into consideration those aspects or characteristics that ultimately determine the performance of a MS.

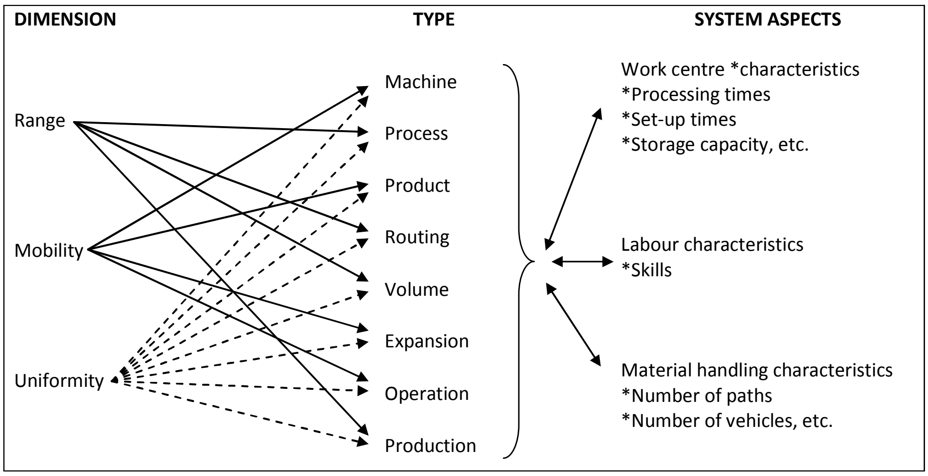

Figure 3.3 – Relationship between dimensions and types of flexibility

From figure 3.3 above, it can be noticed that there are three main aspects that, at an operational level, determine the performance of a MS; those are characteristics related to work centres (e.g. processing and set-up times, storage capacity, etc.), characteristics related to labour (e.g. level of skills) and characteristics related to the material handling subsystem (e.g. number of paths, number of vehicles, etc.). Varying levels of these different aspects of the system also determine each of the different types of flexibility. For instance, being volume flexibility the capacity to operate at different volumes, the main system characteristics determining this capacity could be specific processing times and inter-storage capacities, a particular level of labour skill, and specific material handling characteristics. Therefore, it can be concluded that the dimension of uniformity has an indirect relationship with all the types of flexibility in the sense that different levels of specific system characteristics define each of the different flexibility types and, consequently, also determine system's performance.

Having understood the concept of flexibility together with its associated characteristics it is not difficult to realize that, regardless of the type of flexibility to be accomplished, the extent of flexibility in the manufacturing system is the result of the interactions occurring among the different components within the system together with the individual capabilities of such components. In other words, the system's capacity to perform under the influence of a particular disturbance mainly depends on the capabilities of its components to counteract that particular disturbance.

3.4 CONCLUSION

Nowadays MS face tougher challenges derived from an increasingly competitive environment. In order to perform satisfactorily, modern MS must be able to cope with unexpected events or disturbances. There are different types of disturbances with varying effects on system's performance. A number of approaches have been developed in order to either eliminate or reduce the effect of manufacturing disturbances; among those, flexibility offers the capability to react to disturbances avoiding a considerable impact on performance. However, a strong research emphasis on the range and mobility dimensions of flexibility has originated a focused view on the concept of flexibility, establishing a strong association between flexibility and technological sophistication. In order to expand the limited view on the concept of manufacturing flexibility, more research attention must be paid to the dimension of uniformity, which looks at those aspects or characteristics influencing system's performance and, ultimately, determining system's flexibility.

In the following chapter, different approaches to analyse and design MS will be described.

CHAPTER 4

APPROACHES IN THE ANALISYS AND DESIGN OF MANUFACTURING SYSTEMS

4.1 INTRODUCTION

In the previous chapter it was mentioned that the very essence of a MS is the transformation of inputs into desired outputs by means of an internal process. It was also mentioned that such transformation process needs to be performed as efficiently as possible in terms of a series of performance measures, namely cost, time, quality, and flexibility. What was not mentioned in the previous chapter is that, in order to achieve efficiency in the transformation process, it is imperative to have a clear understanding of the MS under consideration. A series of techniques in the design and analysis of MS are available to achieve a deeper understanding of the transformation process. In this chapter, some of the most popular techniques are described. The chapter begins with some generalities about modelling; afterwards, each of the considered techniques is described. It is important to mention that it is not the objective of this chapter to provide extensive details on the mechanics of the different techniques but to provide basic information for a general understanding of the approaches.

4.2 GENERALITIES ON MODELLING AND ANALYSIS

4.2.1 Definition of modelling and the role of models in manufacturing

Modelling, in terms of manufacturing, is the process by which a real-world MS is represented to a specific level of detail (Kochikar and Narendran, 1994). Generally, models can be either physical or abstract. Physical models are mainly used for teaching and training purposes, whereas abstract models are mostly used for designing, implementing, and operating MS. Regarding the analysis of complex interactions, like the ones occurring within MS, it is extremely complicated to consider every aspect of the system under analysis. Therefore, models represent systems in such a way that the analysis can be focused on specific issues rather than having to deal with the whole picture. In order to achieve such focused view, some assumptions need to be made, some issues need to be further investigated, and some other not interesting aspects need to be ignored (Buzacott and Yao, 1986). Reliable models lead to the identification of improvement alternatives; however, the efficacy of a model ultimately depends on the extent to which it reflects the behaviour of the system it represents.

4.2.2 Common modelling and analysis approaches for manufacturing systems

There is a wide range of alternatives available for the modelling and analysis of MS. The range varies from common Operations Research techniques to very specialized applications, all with very different characteristics and modelling capabilities. Amongst the selection of modelling and analysis techniques, queuing networks, Markov chains, Petri nets, and simulation are some of the most popular methods. Generally, Operation Research techniques are used for performance evaluation, whereas more mathematical approaches are used for the development of scheduling and operating procedures (Buzacott and Yao, 1986). The main characteristic of all these popular techniques is that they are all stochastic, i.e. they are defined by random probabilities. There are also nonstochastic analysis techniques which, although not as accepted as stochastic techniques, help by providing an understanding of the temporal behaviour of MS (Amon and Hulgaard, 1996). Given that stochastic approaches are more useful in the analysis of MS, this chapter will consider only models within such category.

4.2.3 Evaluation criteria

According to Kochikar and Narendran (1994), the following is a set of characteristics that could be taken into consideration in order to evaluate suitable models.

- *Sufficient modelling and decision power*. Modelling power refers to the extent to which a model represents the features of a real system, whereas decision power is related to its ability to provide enough analytical capabilities.
- *Ability to represent different levels of abstraction*. Models should be able to represent varying degrees of detail.
- *Model verifiability*. Ease of verification is important to assure a correct representation of the real system.
- *Ability to represent system evolution*. In order for the model to be effective, it must be able to represent the evolution of the represented system along time.
- *Efficacy on computational considerations*. Computational aspects such as speed, automation, and data requirements need to be considered.
- *Quality of results*. Results provided by models should be as close as possible to real indicators.
- *Interactivity*. The feedback on the implications of particular decisions provides a better understanding of the decision process.
- *Ease of understanding and* use. Models must be compact and able to represent system's features graphically.

Although not all the techniques exhibit the complete range of characteristics mentioned in the last paragraph, the selection of a particular model depends upon its ability to satisfy most of the characteristics.

4.2.4 Limitation of models

Given the fact that MS have very complex arrangements or structures, the most significant limitation of models is concerned with their ability to represent all the events occurring in a real system. However, and taking advantage of statistical analysis, it is possible to identify those elements with a higher level of influence on system's output, narrowing down the selection of important factors and therefore making it easier for models to represent real systems.

4.3 CLASSIFICATION OF MODELLING AND ANALYSIS TECHNIQUES

In general terms, models are grouped under two different categories, namely generative models and evaluative models (Suri, 1985). One the one hand, generative models are those providing an optimal solution able to satisfy an objective function (e.g. mathematical programming, stochastic optimization). On the other hand, evaluative models cannot provide an optimal solution because they aim at evaluating a giving set of decisions (e.g. queuing network, Petri nets, simulation). In relation to the techniques used in the modelling/analysis process, the different approaches are classified in three main groups, namely operations research, artificial intelligence, and simulation approaches (Chryssolouris, 2006). The following sections describe in more detail each of the different approaches.

4.3.1 Operations Research approaches

According to the Operations Research Society of America, "*Operations Research is concerned with scientifically deciding how to best design and operate man-machine systems, usually under conditions requiring the allocation of scarce resources.*" In a broad sense, Operation Research (OR) is a collection of mathematical models and techniques for analysing operational problems such as allocation, inventory, queuing, replacement, scheduling, etc. (Ravi Ravindran, 2008). In most OR techniques, solutions are determined by algorithms providing fixed computational rules which are applied iteratively to the problem and which move the solution closer to the optimum with each iteration. The most important characteristics of OR, as stated by Hillier and Lieberman (2010), are:

- OR has the ability to provide positive and understandable conclusions when they are needed.
- OR adopts a broad viewpoint by attempting to resolve conflicts of interest among the different components of a system/organization.
- OR attempts to find the best (optimal) solution for the model representing the problem under consideration.
- OR encourages a team approach given that knowledge in a wide variety of disciplines (e.g. mathematics, statistics and probability, computer science, engineering, economics, etc.) is required in order to fully understand the issues arising in the operational area of organizations.

Amongst the different OR techniques mathematical programming, dynamic programming, and queuing theory, are some of the most used approaches in manufacturing (Chryssolouris, 2006). A detailed description of each of these is given next.

4.3.1.1 Mathematical programming

Mathematical programming is one of the most developed OR approaches and therefore one of the most used. Under this approach, a particular problem is represented entirely in mathematical terms. The mathematical representation is referred as the objective function, which is subject to a set of constrains, and which is either minimized or maximized depending on the optimization criterion. After a calculation process, an optimal solution satisfying the constraints is provided for the objective function. Among the most popular mathematical programming techniques are linear, nonlinear, goal, and integer programming.

Linear programming

Linear programming (LP) is, reportedly, the most well-known technique in OR (Taha, 2007). It consists in using a mathematical model to describe a specific problem; all the functions involved in the model are required to be linear functions, i.e. a first degree polynomial function. A LP model adopts the following standard form:

Maximize/Minimize

$$Z = c_1x_1 + c_2x_2 + \cdots + c_nx_n,$$

subject to the restrictions

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \leq b_1$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \leq b_2$$

$$\vdots$$

$$a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \leq b_m,$$

and

$$x_1 \geq 0, \qquad x_2 \geq 0, \ldots\ x_n \geq 0.$$

Where the function being either maximized or minimized is called the *objective function*; the restricting functions are referred to as *constraints*. A *solution* would be any specification of values for the *decision variables*$(x_1, x_2, \ldots, x_n)$; a *feasible solution* would be a solution for which all the constraints are satisfied, whereas an *infeasible solution* would be a solution for which at least one constraint is violated. A *feasible region* is the collection of all feasible solutions and an *optimal solution* is a feasible solution that has the better value of the objective function. In order for the LP model above to apply, it must satisfy 3 basic assumptions (Taha, 2007):

1. Proportionality. The contribution of each decision variable (in both the objective function and constraints) must be directly proportional to the value of the variable.
2. Additivity. The total contributions of all the variables (in both the objective function and constraints) must be the direct sum of the individual contributions of each variable.
3. Certainty. All the objective and constraints coefficients must be deterministic, i.e. they must be known constants.

A central attribute in LP is the necessity for allocating resources to activities by choosing the levels of those activities. This attribute is what has originated numerous applications for LP in a considerable number of areas within science and industry.

Nonlinear programming

Nonlinear programming (NP) focuses on problems where a nonlinear function needs to be either minimized or maximized over a set of real unknown values and which is delimited by several nonlinear constraints. The general form of a NP model is as follows:

Find $x = (x_1, x_2, \dots x_n)$ so as to maximize $f(x)$,

subject to $g_i(x) \leq b_i, \quad for\ i = 1,2 \dots, m,$

and $x \geq 0,$

where $f(x)$ and $g_i(x)$ are given functions of the *n* decision variables.

As opposed to LP, there are different types of algorithms depending on the type of NP problem. Frequent NP problems are found in engineering, science, and economics.

Goal programming

Goal programming (GP) is a technique used when multiple and differing objectives are present. Because it is extremely difficult to have one feasible solution that simultaneously optimizes all the objective functions, GP seeks a balanced solution based on the relative weight of each objective. The concept of optimality is not well accepted in multi objective problems due to existing trade-offs among optimization criteria (Ravi Ravindran, 2008), i.e. optimizing one of the objective functions would cause another objective function to move away from its most desirable value. Nonetheless, two methods have been proposed to solve GP problems, namely the weights method, and the preemptive method (Taha, 2007). The former method generates a single objective function consisting of the combined sum of the goals; the latter method optimizes the goals one at a time starting with the highest priority goal and finishing with the lowest priority goal, the quality of a higher-priority goal is never degraded. It is important to mention that, even though none of the methods is superior, these two methods would not generally produce the same solution and their choice would depend on the decision-making preferences of the analyst.

Integer programming

An integer programming (IP) model is a mathematical model in which some or all of the variables are restricted to adopting only integer or discrete values. When the model consists of exclusively integer variables, it is referred as a pure integer model; if the model consists of both continuous and integer values then it is a mixed integer model. In spite of the fact that there are many practical situations where only integer models apply, and that there has been significant research on the topic of IP, a disadvantage of this technique is the lack of consistency in the algorithms for solving integer problems (Taha, 2007); i.e. none of the algorithms is totally reliable in terms of computational efficiency, especially with large numbers of variables.

4.3.1.2 Dynamic programming

Dynamic programming (DP) is a technique used for optimizing multivariable problems; its method consists in a simplification of the general problem into several parts or stages, each comprising a sub problem with only a single variable but commonly linked to other sub problems by common constraints. Contrary to LP, in DP there is not a standard mathematical formulation of the problem because DP is more like a general approach to problem solving and therefore particular equations must be developed to fit each situation. In a DP model, a recursive equation links the different stages of the problem by using the optimal solution of one sub problem as an input to the next sub problem; this guarantees that each stage's optimal feasible solution is also optimal and feasible for the general problem. A key aspect of DP is that decisions in each stage cannot be made in isolation due to the constraints linking the sub problems. According to Hillier and Lieberman (2010), some of the most important characteristics of DP are:

- A DP problem can be divided into stages, with a policy decision required at each stage and which is interrelated to decisions in previous and subsequent stages.
- Each stage has a number of states associated with the beginning of that stage. In general, the states are the various possible conditions in which the system might be at that stage of the problem. The number of states might be either finite or infinite.
- The effect of the policy decision at each stage is to transform the current state to a state associated with the beginning of the next stage. DP problems can be interpreted in terms of networks where, in most cases, the objective corresponds to finding either the shortest or the longest path through the network.
- The solution procedure is designed to find an optimal policy for the overall problem.
- Given the current state, an optimal policy for the remaining stages is independent of the policy decisions adopted in previous stages.
- The solution procedure begins by finding the optimal policy for the last stage.
- A recursive relationship that identifies the optimal policy for stage *n*, given the optimal policy for stage *n+1*, is available.

- The solution procedure starts at the end and moves backward stage by stage, each time finding the optimal policy for that stage, until it finds the optimal policy starting at the initial stage.

The main advantage of DP with respect to mathematical techniques such a LP is the fact that general problem simplification into smaller stages contributes to less computational effort by allowing the optimization of a single variable instead of several variables at the same time. On the contrary, an imperative disadvantage of DP lies in the necessity to develop suitable models to represent specific problematic situations.

4.3.1.3 Queuing theory

Queuing theory (QT) is the representation of a queuing system of any kind in order to analyse waiting times. This technique consists of formulae indicating the way in which a particular system performs, including the average amount of waiting that would occur, under different circumstances. In a basic queuing process, customers, which are generated over time by an input source, enter the queuing system and join a queue. A selection rule known as the queue discipline selects one of the customers in the queue at a certain time. A service mechanism then performs a service for the customer. The customer leaves the system after the service has been terminated. Figure 4.1 below depicts the basic queuing process and its elements.

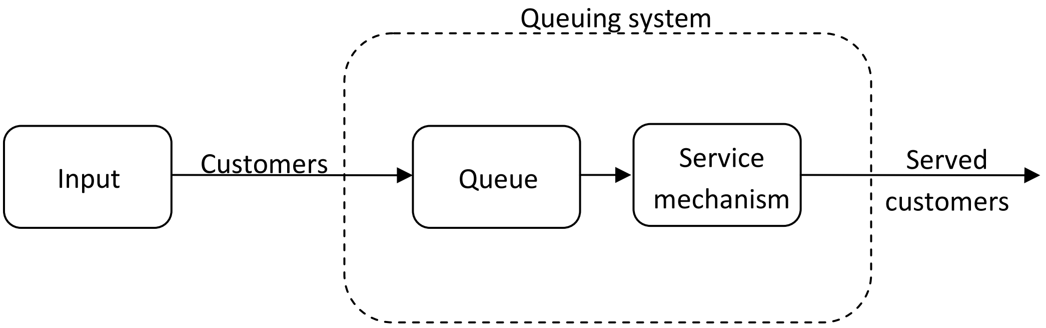

Figure 4.1 – The basic queuing process (from Hillier and Lieberman 2010)

Even though the *customer* and the *service mechanism* are the principal actors in a queuing situation, it can be noticed from figure 4.1 that there are more components involved in the queuing process. The *input source* is the component generating the total number of customers; it can be either limited or unlimited depending on whether the number of customers is finite or infinite. The *queue* is where customers wait to be served; it can also be finite or infinite depending on whether the permissible number of waiting customers is limited or unlimited. The *queue discipline* is the order in which customers are selected from the queue to be served. The *service mechanism* represents the service provided to the customer. An important issue of consideration in QT is the existing trade-off between the cost of the service mechanism and the waiting time for customers; a balanced solution could be obtained either by establishing a service-level/waiting-time criteria or by assessing the costs associated with making customers wait.

Unlike other OR techniques, QT is not an optimization technique; its main objective is to guarantee that waiting customers would get a satisfactory service time by developing a series of algorithms for performance metrics. Output from QT can be used as input to solve design and capacity planning problems and to establish tactical and operational decisions and controls. However, exact analytical results are difficult to obtain for other than small production lines (Papadopoulos and Heavey, 1996); which makes QT of little use for MS design purposes.

4.3.2 Artificial Intelligence approaches

Artificial intelligence (AI) consists in developing the capabilities of computers so they can simulate basic human capabilities, such as expertise and knowledge of the system environment, in the solution of problems. Even though it is a different approach in the analysis and design of MS, AI shares some common characteristics with OR approaches (Phelps, 1986), those are the following:

- Similar applications, i.e. both approaches face similar problems.
- Consideration of models for problem solving.
- Utilization of heuristics when optimal methods are not suitable.
- Use of mathematics.
- Implementation facilitated by computers.
- Employment of inter-disciplinary people.

There are two popular AI techniques, namely search, and rule-based systems; these are described in the following two sections.

4.3.2.1 Search

Essentially, search is a technique which finds solutions by exploring paths. The basic idea of search is that, instead of trying all possible paths to get to a destination or goal, it focuses on the paths that seem to be shorter to the goal; in order to do that, an evaluation function scores the different nodes along the search path according to how close the goal seems to be. Figure 4.2 represents a basic search problem.

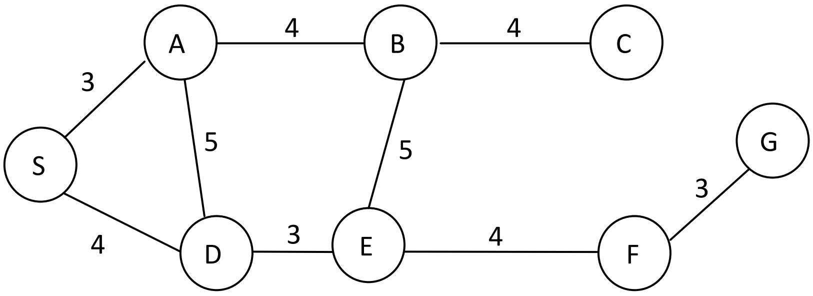

Figure 4.2 –Search; finding a path from the start node S to the goal node G (from Chryssolouris 2006)

There are several search methods being the heuristics deciding on the mechanics of the exploration what differentiates all the available methods. Among those, genetic algorithms, simulated annealing, taboo search, depth-first search, hill climbing, breadth-first search, best-first search, and branch and bound search are among the most popular methods. These methods are not described in this chapter since further detail into the approaches is not the purpose of this chapter.

4.3.2.2 Rule-based systems

Rule-bases systems is a technique consisting of *if* and *then* rules; i.e. rules where if condition 1, condition 2, etc. are true, then take action 1, action 2, etc. This technique consists of two basic components namely a rule-base, and an inference engine (Winston, 1993). On the one hand, the rule-base is a collection of rules containing human expertise in a particular problem domain; most of the rules are interrelated so that implementing an action in the *then* part of one rule, may cause a condition in the *if* part of another rule to become true. On the other hand, the inference engine is a piece of software which makes use of the collection of rules in the rule-base to solve problems; its problem-solving mechanism operates in two different ways referred to as forward chaining and backward chaining. In forward chaining the inference answers the question “which actions should be taken?” and is mainly applied when the purpose is to discover all that can be deduced from a given set of facts. On the contrary, in backward chaining the inference engine answers the question “shall a given action be taken?” and is usually applied when the idea is to verify or deny one particular conclusion.

4.3.3 Simulation approaches

Simulation is reportedly one of the most widely used modelling and analysis techniques in the field of operations and manufacturing (Law and Kelton, 2000); this is mainly due to both its flexibility and the significant advances in computational capabilities that have been occurring over the last three decades (Smith, 2003). Simulation is defined as the technique of building an abstract logical model, generally by means of a computer, that represents a real system and describes the internal behaviour and interactions of its components (Wang and Chatwin, 2005). In a broad sense, the simulation process in a MS context consists in specifying a series of inputs (e.g. design, workload, and operational policy decision variables) and component-interaction rules to a simulator which puts together these data into a model of the MS; the simulator then follows the operation of the model tracking a series of events over the simulation time. At the end of the process the simulator provides an output (e.g. statistical performance measures) by which the model is evaluated; this process is represented in figure 4.3.

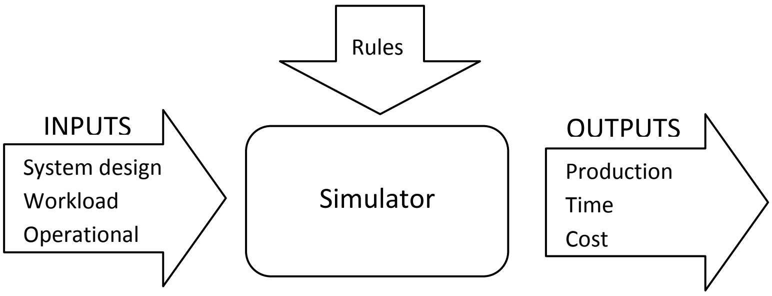

Figure 4.3 – The simulation process (Adapted from Chryssolouris 2006)

There are two types of simulation, namely discrete and continuous. Discrete simulation is characterised by instantaneous changes in the state of the system at random points in time due to the occurrence of discrete events such as the arrival of parts into to the system or the shipment of finished product out of the system. In continuous simulation, the changes in the state of the system occur continuously over time. Differential equations are generally used in continuous simulation to describe the way the system fluctuates over time; this makes continuous simulation relatively more complex than discrete simulation.

Advantages and limitations of simulation

In a broad sense, the advantages of simulation are summarised in its rich modelling expressiveness and its flexibility for representing complex and uncertain interdependencies between the components of a MS together with its ability to represent system's dynamic behaviour (Madan et al., 2005, Wang and Chatwin, 2005, Wu, 1994) . According to Yücesan and Fowler (2000), other advantages of simulation are the following:

- Time compression - the ability to reproduce long periods of real system operation in a shorter time.
- Risk avoidance - the financial and physical risks involved in studying real systems are not present in simulation studies.
- Physical scaling – larger or smaller versions of any system can be analysed.
- Repeatability – either different systems in identical environments or the same system in different environments can be investigated.
- Control – In a simulated environment, every aspect can be monitored and controlled.

Regarding the limitations of simulation, the requirement of expertise and the amount of time required to construct a simulation model are reportedly its most fundamental disadvantages (Wu, 1994); other limitations include the possibility to omit some important details during the construction of the model and the difficulty to find optimal solutions due to the fact that, as opposed to mathematical approaches, simulation models are not expressed in terms of decision variables.

Popular simulation software

According to Wang and Chatwin (2005), some of the most popular simulation packages extensively used for MS applications in recent years are: *SIMAS II*, dedicated to the simulation of industrial mass production installations using automated assembly lines. *WITNESS*, which can model both discrete manufacturing and continuous flow manufacturing; models are built using a building block design, having a modular and hierarchical structure. *SIMUL8*, which is mainly used for discrete simulation, has a graphical model building interface, allowing icons representing logic to be placed and connected by arrows showing entity flow. *Taylor ED*, which is an object-oriented software application used to model and simulate business processes. *ShowFlow*, which is designed to model and simulate logistic, manufacturing, and material handling processes. Finally *ARENA*, which is able to model any environment, including continuous systems; it also has a graphical interface for model building with logic modules connected with arrows representing entity flow.

4.4 EVALUATION OF METHODS

Analytical methods and simulation are very important approaches in the analysis and design of MS in the sense that they both provide valuable information. However, it is important to mention that there is a significant difference between these two approaches in terms of their scope and characteristics. On the one hand analytical methods (AM) are quite limited in the complexity of the system they can describe; basically consisting of mathematical equations, they can specifically provide numerical answers for individual components within a system; therefore their significance in achieving optimal solutions. AM require less building and run time because their data requirement is low, to the detriment of their accuracy. In order to develop reliable models, the time and effort required are unpredictable. The flexibility of AM, in terms of ease to introduce structural changes, is low because little changes would completely affect model’s reliability. On the other hand, simulation approaches are more robust when representing the complexity of MS; their capacity to model not only one but several aspects of a system at the same time constitutes a significant advantage in measuring system’s performance. A high demand for data in simulation models results in considerable building and run times; however the accuracy of results is benefited. The time an effort to develop a reliable simulation model in an industrial context can be assessed accurately if the simulation team is experienced; additionally, the flexibility of simulation approaches is high because changes in parameters can be easily introduced without major consequences.

4.5 CONCLUSION

In this chapter different techniques for the analysis and design of MS have been reviewed. After evaluating the characteristics of the different techniques and realizing the limitations of analytical/mathematical techniques, particularly concerning the difficulty involved in analysing complex systems and their inability to accurately represent the dynamic characteristic of MS, it is not difficult to favour simulation approaches given their superior advantages in the modelling and analysis of MS. Nonetheless, far from declaring the superiority of one type of approach over the other, it is important to understand that the combined application of both approaches can lead to further benefits. For example, whereas simulation can be extremely useful for representing the complexity involved in MS and for generating data about the performance of a MS, analytical approaches can use the results in order to conduct more detailed analyses where optimal responses are required. However, and regardless of the sequence in which these approaches are used, what is important is to realize that the benefits from combining different techniques are higher than the benefits from the consideration of a single technique.

CHAPTER 5

DEVELOPMENT OF THE PROPOSED SIMULATION MODEL

5.1 INTRODUCTION

This chapter details the development process of the simulation model used during the experimental stage of this study. The chapter consists of three sections; the first section provides an overview of the simulation software employed to develop the model; the second section describes all the activities involved in the process of model development, specifically the activities comprised between model conceptualization and model testing; the last section of the chapter lists the operative assumptions under which the proposed simulation model is valid.

5.2 AN OVERVIEW OF THE SIMULATION SOFTWARE EMPLOYED

Simul8 has been selected as the discrete event simulation (DES) software to be used in the present study. Simul8 has been developed to be applied in a variety of areas, especially in business processes and manufacturing. One of the most important characteristic of Simul8 is its simplicity; model building is facilitated by a variety of simple graphical tools and modelling objects. Different objects can be pulled into the model layout enabling quick structuring and understanding. The main modelling objects in Simul8 are: Generators, storage points, work centres, operators, and vehicles. Each object offers the possibility to set a variety of parameters. Despite of the fact that there are only a few built-in modelling objects, it is possible to create new components either by modifying the existing ones or by programming, which increases the flexibility of the software. An important feature in DES software is the quality of animations. In this regard, Simul8 does not disappoint, and provides a good resolution and icon quality. Randomness in the model can be generated either by a variety of built-in standard distributions or by new distributions created by users. With respect to Simul8 utility when generating reports, each modelling element offers the possibility to generate their own report, displaying their output parameters in different graphs to choose from. As opposed to other DES software, results in Simul8 can be obtained at any time during a simulation run. The optimization of results is also possible in Simul8 by means of OptQuest optimization tool.

Even though Simul8 is characterized by putting more emphasis on building models by its pre-designed graphical objects and tools, there is also the possibility to use programming language to develop a model. The programming language used by Simul8 is Visual Logic, which is also easy to learn and use. A great amount of the programming can be assisted by a programming wizard (Hauge and Paige, 2001) . Providing that several users would prefer using the coding environment rather than the graphical environment, Simul8 provides a step-by-step debugging tool which provides excellent advice when it finds logical and syntax errors.

5.2.1 Justification for using Simul8

The main reason why Simul8 was chosen among different DES packages available is because of the author's previous experience with Simul8. Even though the author also has experience with other simulation packages like ProModel or Witness, Simul8 seems to be more versatile software when it comes to modelling MS. In addition, Simul8 has been selected because of the following complementary reasons:

- *Easy to use*. Given that there are not many pre-defined modelling objects, quick modelling and easy understanding are facilitated. This does not mean that Simul8 lacks the capacity to model complex systems; existing objects can be set to a desire level of detail so they can represent any level of complexity. There is also the possibility of creating new objects.

- *Availability of a variety of built-in functions*. Simul8 offers a considerable selection of pre-defined routing rules and loading/unloading disciplines together with an extensive list of probability distributions.
- *Clear and accurate results*. The reporting capabilities offered by Simul8 enable the monitoring of results at different levels and at any time during simulations.
- *Confidence in modelling*. The efficient error detecting features offered by Simul8 make the user feel comfortable about modelling. A debugging tool would assist users throughout the entire modelling process, enabling coding errors to be detected and corrected on time.

Even though the cost of the simulation package was not really a determinant in the selection of Simul8, it is important to mention that costs also constitute an advantage in favour of Simul8. Among other simulation packages available in the market, Simul8 represents a serious alternative when it comes to evaluate the cost-performance relationship.

5.3 SIMULATION MODEL DEVELOPMENT

In the development process of a simulation model, there are three main stages, namely problem definition, model building and testing, and experimentation (Robinson, 1994). As shown by figure 5.1, where the simulation model development process is graphically described, each of the three stages is composed of a series of activities or sub processes.

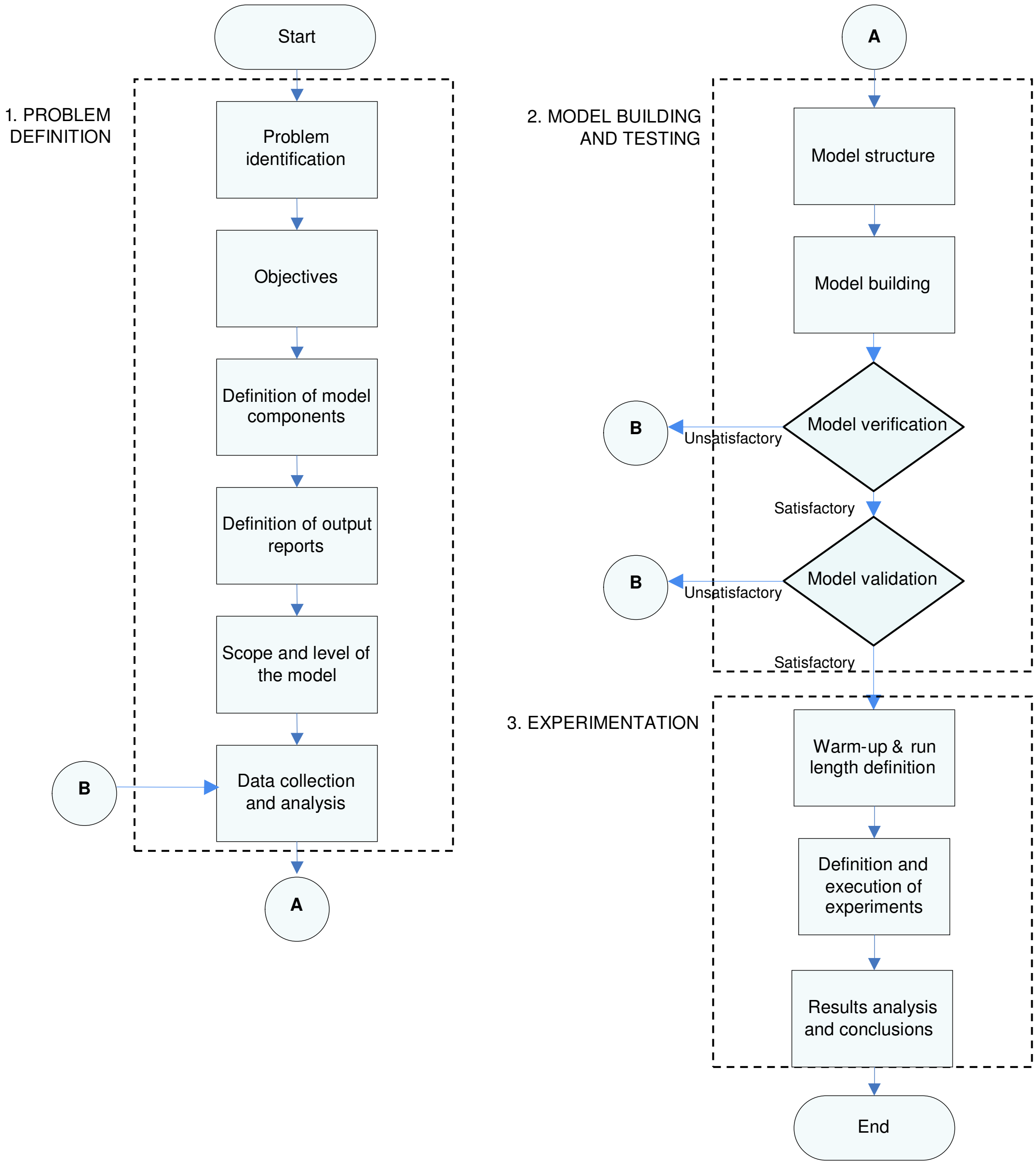

Figure 5.1 – Development process of a simulation model (Adapted from Robinson 1994)

It is the aim of the present chapter to describe the activities concerning to the stages of problem definition and model building and testing. The stage of experimentation is not of concern for this chapter given that it will be described in chapter 6. Looking at figure 5.1, it is important to note that, even though there are several activities involved in the first two stages of the model development process, there are some particular activities that seem to be critical in order to efficiently achieve a reliable simulation model. The activities of data collection and analysis, verification, and validation may have significant implications in the model development process and therefore it is important to pay special attention to them.

These key activities together with the other involved activities are described in the following sections.

5.3.1 Model development phase 1: Problem definition

The first phase of model development is concerned with the understanding of the problem to be represented by the simulation model; after problem understanding, an approach to solve such problem needs to be defined. Problem definition phase consists of 5 steps through which the model is conceptualized.

5.3.1.1 Problem identification

In the context of the present study, the *flexibility* of a MS is determined by the system capacity to maintain an acceptable performance under the influence of different manufacturing disturbances. In order to maintain an acceptable performance, the system may offer a number of varying responses depending on the type of disturbance being faced at a particular period of time. The number of responses offered by the system to a specific type of disturbance depends on a number of physical system capabilities, which in turn are determined by characteristics associated to each component within the system. Each system component provides a response which contributes, to a certain extent, to the *flexibility* of the entire system. In order to define the flexibility of a MS, it is therefore very important to be aware of the range of responses a MS may be able to offer in order to maintain an acceptable performance when the system is subjected to specific disturbances.

5.3.1.2 Objectives

The objective of the proposed simulation model is threefold:

1. *To facilitate the understanding of a MS*. All the interactions occurring between system components are easily represented by means of discrete event simulation.

2. *To define the most suitable system responses under different disturbance scenarios.* The components providing the system with the ability to maintain an acceptable performance under restrictive conditions are identified and the best system operating parameters are defined.

3. *To simplify the experimentation and analysis*. Compared to physical experimentation in MS, time and money restrictions are not really an issue in simulation based experimentation and analysis.

5.3.1.3 Definition of simulation model components

The system components considered in the proposed simulation model are described in table 5.1 below.

Table 5.1 – System components of the proposed simulation model

COMPONENT	DEFINITION
Raw material	The input to be transformed along the manufacturing process
Operators	It is the human component of the manufacturing system. Operators are responsible for the control of machines.
Machines	Machines are the physical devises to process raw materials.
Buffers	Physical space available within the system to store material being processed.
Vehicle	It is the physical device used to transport material between different machines along the system.
Finished product	It is the main output of the system. Once raw material has gone through a number of machines along the system it turns into a finished product.

The components listed in table 5.1 together with the interactions occurring among them provide a number of characteristics to model a representative MS.

5.3.1.4 Definition of output reports

In order to evaluate the efficiency of the modelled system, the simulation model must be able to generate information concerning the following outputs:

- The total number of products generated by the system.
- The time it takes to produce those products.
- The total cost involved in the generation of products.

With the intention of counting on additional information for decision making purposes the model must also be able to report on additional outputs like resource utilization, inventory levels, etc.

5.3.1.5 Scope of the simulation model

To achieve the objectives stated in section 3.3.1.2, the simulation model must be limited to the consideration of the most important components intervening at a shop floor level of a MS. The simulation model needs to include activities and components occurring between the arrival of parts and the delivery of finished products. In the proposed model, raw material initially arrives into an initial buffer from where it is directed to a manufacturing area consisting of different processes. Once material has gone through all the predefined processes, it is then sent to a last station where it is subsequently shipped to the customer in the form of a finished product.

5.3.1.6 Level of detail of the simulation model

Even though the proposed model is a simple representation of a theoretical MS, it needs to consider a certain level of detail; therefore, the variables listed in table 5.2 need to be included in the model.

Table 5.2 – Variables to consider in the proposed simulation model

COMPONENT	VARIABLE
Raw material	Inter-arrival time Arrival pattern (distribution) Cost Processing routes
Operators	Costs per unit Allocate machines Availability percentages Average absence times
Machines	Processing times and distributions Usage costs Efficiencies Repair times Loading/unloading rules
Buffers	Capacities Storage costs Scheduling rules
Vehicle	Loading capacity Speed Loading/unloading time
Finished product	Revenue

From the list of characteristics in table 5.2 it can be noticed that even though there is not a big variety of system components, the model becomes more complex as different characteristics are associated to each component, not to mention the interactions occurring between the different components. Both the list of components above and the related level of detail of each component provide an insight for the next phase in the development process, i.e. the building and testing of the simulation model.

5.3.2 Model development phase 2: Building and testing

When the problem to be approached by means of a simulation model has been defined and understood, the subsequent steps in the development of the model are model structuring, model building, and model validation; these steps are described in detail in the following three sections.

5.3.2.1 Structuring the model

At this stage of model development it is possible to use an activity diagram in order to graphically provide a definition of the components and activities to be included in the simulation model. Figure 5.2 shows an activity diagram for the simulation model under development.

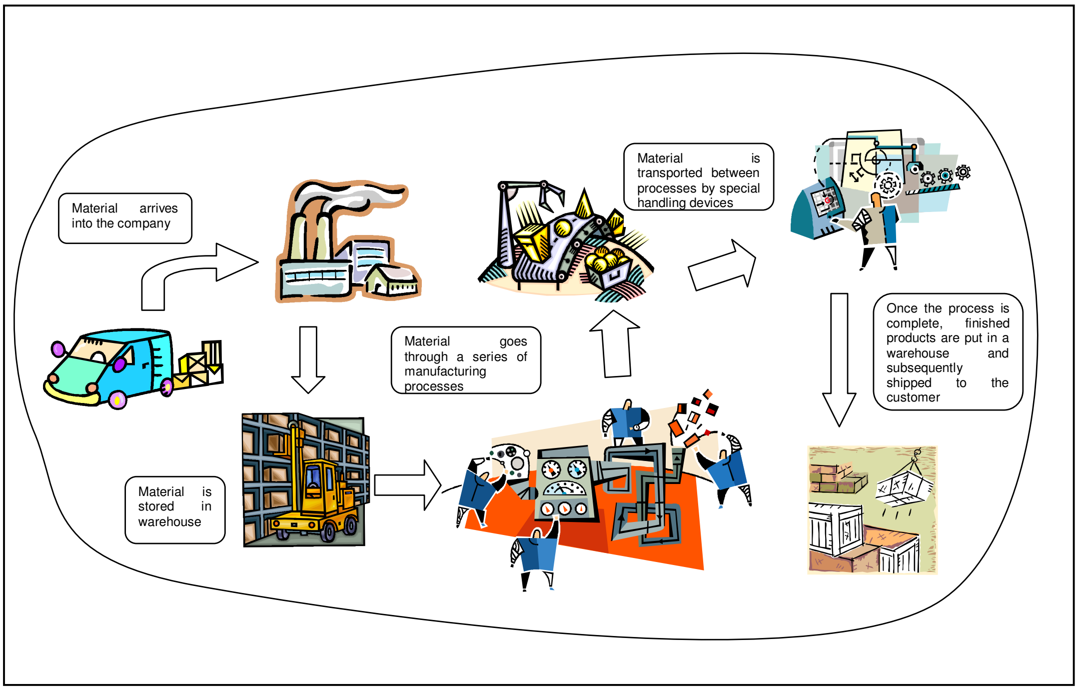

Figure 5.2 – Activity diagram of the simulation model

Once a clear understanding on the components, activities, and interactions to be included in the simulation model has been achieved the next step is to build the model.

5.3.2.2 Model building

Model building consists in coding the model, defining its basic logic, and establishing a final model display. Model coding has been greatly facilitated by the graphical features of the simulation software employed. Coding has been performed iteratively until the model behaved according to its basic logic.

Basic logic

Raw material arrives into the system following a predefined pattern, which is determined by an inter-arrival time and a probability distribution. The arrival pattern needs to be generated by a specific component in the model; such component is also responsible to assign a cost to raw material. After arrival, material is directed into an initial buffer where it is allocated to a specific product line; this initial buffer acts as raw material warehouse. Once material enters into this facility storage, manufacturing costs start to add up. As soon as there are ten material units in any product-line buffer, that material is pulled out of the buffer and loaded into the processing system; this action is performed by a part loading component, which directs material to the related processing route. Each product type follows a specific processing route with different processing times in each of the machines along the route. When a batch of parts arrives into a machine, it is directed into an input buffer. An assigned operator collects the material from the input buffer and loads parts into a predefined machine as soon as the latter becomes available. The operator stays next to a working machine during the whole processing time. As soon as machines finish processing a part, the latter is sent out into an output buffer and the operator is released; after this, machine and operator become available for the next part. Parts held in output buffers are ready to be directed into the following process (work centre). The flow of parts between different processes is assisted by an automated guided vehicle (AGV) with limited loading capacity and speed. After parts have gone through all the manufacturing processes in the route, they are sent to a finished product buffer from where they are subsequently shipped out to customers. Shipment of finished products is the final component in the simulation model and it is also the point where process data is added up into overall system performance. The flow chart in figure 5.3 graphically describes the logic of the proposed simulation model.

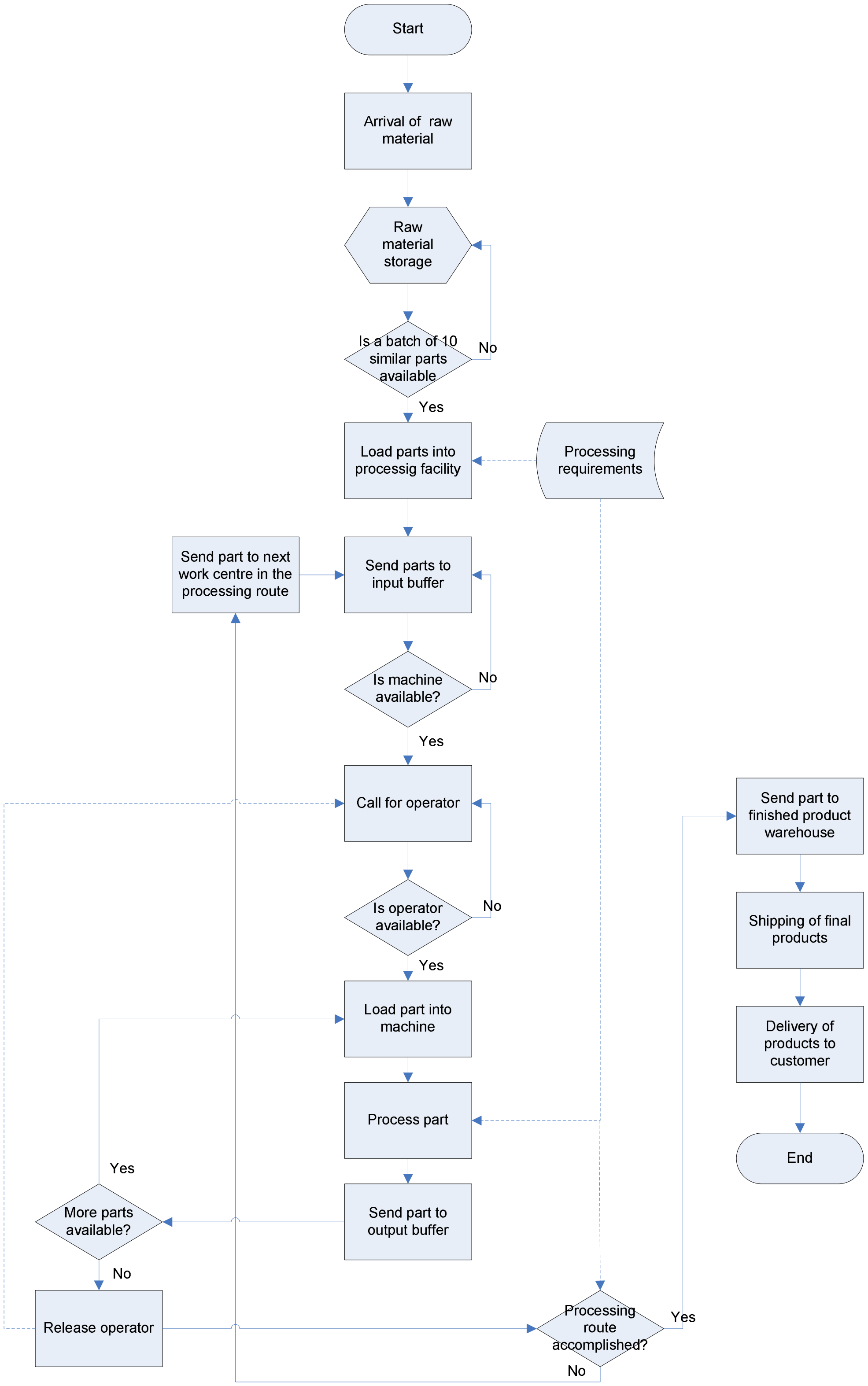

Figure 5.3 – Flow chart of the simulation model logic

Final display

After a series of adjustments the final display of the proposed simulation model looks exactly as shown in figure 5.4.

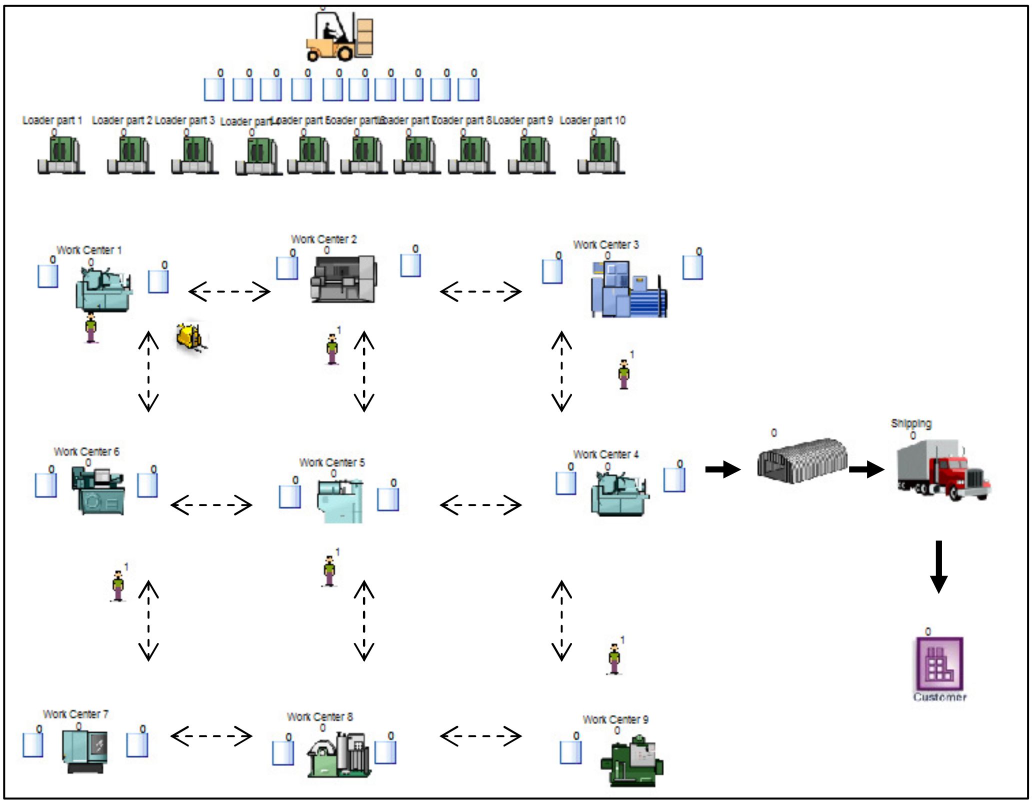

Figure 5.4 – Display of simulation model

A brief description of the display shown in figure 5.4 is as follows: At the top of the display, there is an arrival generator together with an initial buffer for each part and ten part loaders. In the middle section of the display, there is a processing area which consists of 9 work centres representing 9 different processes; each work centre is composed of one input buffer, one machine, and one output buffer. There are 6 operators in charge of the 9 work centres and one AGV which transports parts between the work centres. On the far right side of the display there are the final three model components, i.e. a buffer for finished products, a shipping point, and customers receiving the finished products.

Selection of input probability distributions

In a simulation project involving an existing manufacturing system, data collection usually takes place during the first phase of model development (Robinson, 1994). After a significant amount of data is collected, a probability distribution representing the behaviour of that data is then selected. Nevertheless, the model considered in the present research is a theoretical model and, in consequence, its sources of randomness need to be assumed. Basically, there are three sources of randomness in the proposed model, namely the arrival of parts into the system, machines, and operators. Probability distributions for all the machines and operators in the model have been defined first; an inter arrival distribution has been defined subsequently. Following the example of existing research on the topic, machine processing times are assumed to follow a normal distribution (Chan, 2004, Kannan, 1998). Other random events originating from both machines and operators such as set ups, time between break downs, time to repair machines, time between absences, and time to return, are assumed to follow an exponential distribution (Hauge and Paige, 2001). Refer to appendix 1 for a complete list of assumed operative parameters for the components within the proposed system.

Arrivals into the system are determined by an inter-arrival time, i.e. the number of time units between arrivals generally expressed in terms of time per arrival (Hauge and Paige, 2001). Inter-arrival times are assumed to follow an exponential distribution in view of the fact that it has been demonstrated that inter-arrival times for real world systems closely resemble independent and identically distributed exponential random variables (Law and Kelton, 2000). For examples of similar research considering the exponential distribution as the probability function generating the pattern of arrivals in manufacturing systems see (Mishra and Pandey, 1989, Yao and Buzacott, 1985, Chan, 2004). In the proposed simulation model, an inter-arrival time of 45 minutes average following an exponential distribution has been selected; refer to appendix 2 for details.

5.3.2.3 Model verification and validation

The purpose of both verification and validation is to ensure that the simulation model behaves in accordance to its intended purposes. The difference between both stages lies in their analytical scope. Model verification is a development stage mainly concerned with assuring the correct translation of model physical behaviour into a computer program. Conversely, model validation has a broader scope which is more concerned with the behaviour of the overall model once every intervening component has been considered (Law and Kelton, 2000). Generally, verification and validation are treated as two different stages in the lifecycle of a simulation project; however, in the present research both stages have been covered simultaneously; this has been possible due to the technical features offered by the simulation software employed.

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 has been facilitated by the capabilities of the simulation software, which made possible to interactively check the coding line by line. Visual checks have been 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 has made possible to guarantee that each element within the model behaves 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. The first thing to be verified was that the model would generate an output in accordance to the number of units entered into the system; this is confirmed by figure 5.5 which shows that there is actually a system output.

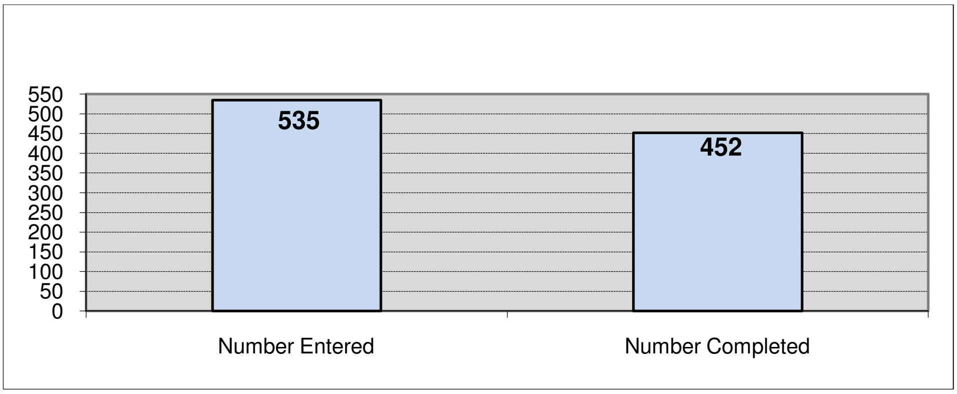

Figure 5.5 – Number of entered parts vs. number of completed parts

From figure 5.5 it can be noticed that, after performing the replications, an average of 535 parts are fed into the system and an average of 452 parts are completed. Additionally, an average number of parts are not completed by the system. Those uncompleted parts, as evidenced by appendix 3, remain within the system as parts waiting in a queue, parts being processed by a machine, or parts being transported between work centres.

The next verification step was to make sure that raw material was always available to be processed by the system. Figure 5.6 shows the average number of parts in each of the raw material buffers.

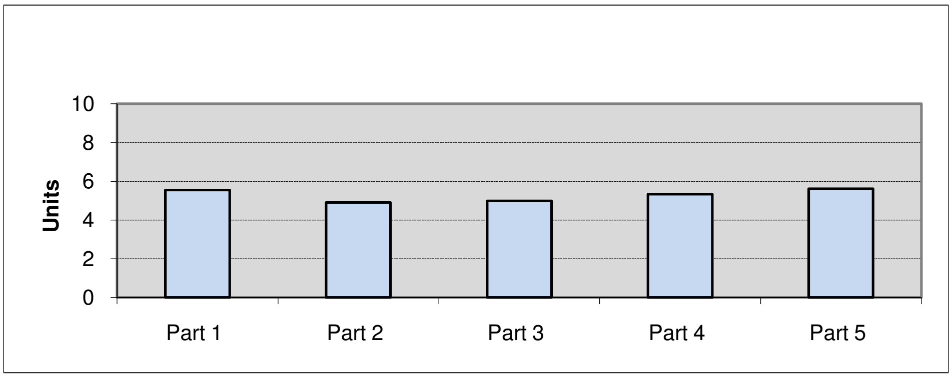

Figure 5.6 – Average queue size in raw material buffer

As it can be noticed, the average number of available material for the production of each of the 5 initial products during a simulation run is enough to guarantee that the system is not going to starve during the operation time. The availability of parts for each of the work centres was also verified as shown by figure 5.7.

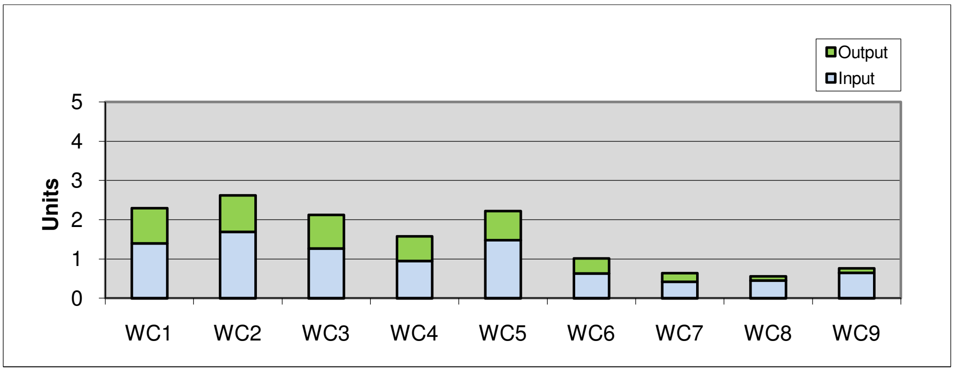

Figure 5.7 – Average buffer size in work centres

Figure 5.7 confirms that each work centre actually receives, processes, and releases parts. Note that, obviously, the concentration of parts is different in each work centre due to the fact that parts have different processing requirements in terms of timing and allocated machines.

Regarding the utilization of resources within the simulated system, figure 5.8 below shows the proportion of time each machine spends waiting, working, changing over, etc.

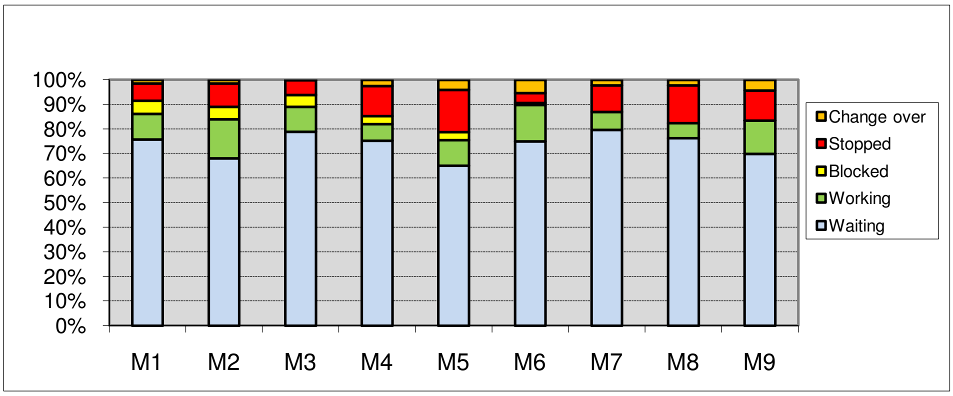

Figure 5.8 – Average machine utilization

In addition to the average utilization percentage for each machine, figure 5.8 also confirms that every machine within the system performs according to pre-specified parameters. Similarly, figure 5.9 shows the average operator utilization percentage during a simulation run.

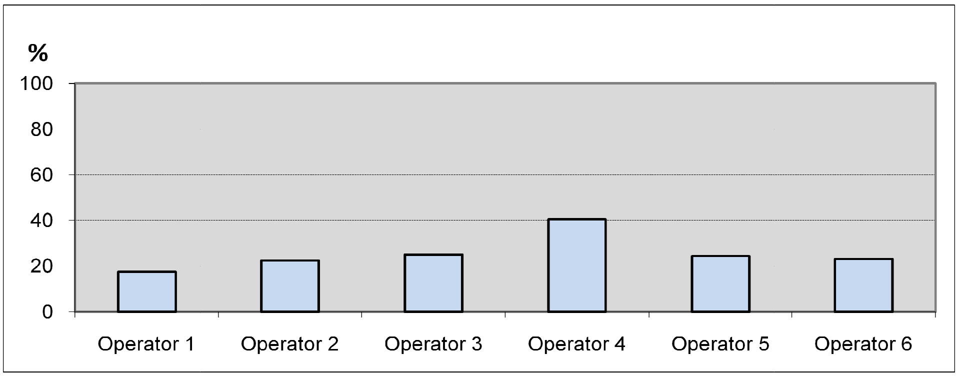

Figure 5.9 – Average operator utilization

Note from figure 5.9 that all of the operators within the model also have a level of intervention in the process, mainly related to loading and running machines.

After analysing some of the most important system outputs, it has been possible to confirm that all the model components perform according to what has been defined during the model coding process.

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 is judged upon the viability of making decisions based on the information provided by the simulation model (Law and Kelton, 2000). Ideally, a model is 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 study, 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 objective techniques and subjective 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 consists in testing the assumed probability distributions in terms of how sensitive the results are to changes in these inputs (Hauge and Paige, 2001). A number of probability distributions, particularly related to machine processing times and set-ups, have been randomly selected to be tested. The sensitivity analysis has confirmed the validity of the assumptions. Please refer to appendix 4 for details on the sensitivity analysis report.

5.4 MODEL ASSUMPTIONS

A series of assumptions have been made for the development and operation of the simulation model described in this chapter, those are the following:

- The MS considered in this chapter is represented at an operational level.
- The modelled MS works 5 days a week on an 8 hours a day basis.
- Raw material arrives into the system one part at a time and following an exponential distribution with a predefined interarrival time. The proportion of material arriving for each type of product is determined by a predefined product mix representing the demand for each product. The cost of raw material is the same regardless of the type of product to be produced.

- The initial model produces 5 different parts. Each part has different processing requirements, i.e. different processing times and different routing throughout the MS. Process routing is fixed for each of the products.
- 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 times and set-up times, the times are different from each other. There is also a different usage cost per minute associated to each machine.
- Machines do not have any automation level, therefore each machine do require an operator in order to run. It is also 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.
- Operators have different abilities and in consequence labour cost is associated to the level of skill. Assuming that operators cannot be always available, different availability percentages and absence times have been set for each operator.
- Buffer capacity is limited. There is not a central buffer but nine input/output buffers in each work centre instead. 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.
- Within buffers, parts are prioritized according to their arrival sequence; specifically according to the FIFO dispatching rule, i.e. parts are dispatched either into a machine or vehicle considering a first come first served rule.
- The material handling devise is totally independent from human resources. The vehicle travels at a constant speed along a fixed route connecting all the work centres in the manufacturing facility. Transportation costs are omitted and no vehicle breakdowns are assumed.

- For simplicity reasons, travelling times for operators have not been considered in the model. Regarding vehicle's travelling time, it is determined based on vehicle speed.
- The modelled MS does not produce defective parts, all the production output is assumed to be within quality specifications.
- A unique shipping time has been assumed regardless of product type. Shipping time does not follow a particular distribution and is determined only by an average time. Revenue per shipped product regardless of its type has been also assumed.
- Because the choice of probability distributions has an important effect on the output of simulation models, results obtained from the model are valid only under the assumed probability distributions (Exponential and normal distributions). Different distributions would yield different results and therefore different conclusions.

5.5 CONCLUSION

In this chapter a series of steps have been taken in order to develop the simulation model to be used during the experimentation stage of the research process. Simul8 has been selected among a number of discrete event simulation packages because of its excellent quality and advantages regarding the modelling of MS. After conceptualizing the simulation model, its main components together with the interactions occurring between the different components have been identified and understood. After developing the simulation model, a number of approaches have been taken in order to guarantee that the model produced reliable data. The simulation model developed throughout this chapter constitutes the basis for experimentation in subsequent chapters.

CHAPTER 6

DESIGN OF EXPERIMENTS AND EXPERIMENTATION

6.1 INTRODUCTION

In this chapter the different experimental design stages of the present study are described. In the first section of the chapter the problem to be explored by means of experimentation is defined. The following section gives details on the selected performance indicators to measure the experiments. Before explaining the experimental factors and experimental scenarios considered in this study, some experimental conditions for the simulation model, such as the warm-up period and run length, are established. Subsequently, the procedure to determine the number of model replications is described. The last part of the chapter provides specific detail on the chosen design and run order for conducting the experiments.

6.2 PROBLEM DEFINITION

On the subject of design and operation of MS, it is important to know which of its components provide the system with the capability to cope with unexpected situations and, ultimately, with a certain level of flexibility. Even though the system in this research considers the basic elements of a conventional system (machines, operators, material handling, etc.), it is still a hypothetical system and therefore it needs to be assumed new and unfamiliar for research purposes. Under such condition, it is necessary to analyze the proposed system in order to find a suitable answer to the research questions stated in chapter 1 and which are reconsidered in this chapter, those are the following:

- How different disturbance scenarios affect the performance of a particular manufacturing system?
- What are the components providing the manufacturing system under consideration with the ability to more efficiently perform under such disrupting circumstances?
- What characteristics make the components in the previous question able to contribute to a better system performance?
- What are the trade-offs, if any, involved in the system's response to disturbances?

Consequently, it is important to conduct experiments with an aim to facilitate the identification of those components that would contribute to a more robust MS by providing the system with the capabilities to more efficiently cope with performance disruptions. Given that this study is intended to investigate manufacturing performance under the influence of specific disturbances so as to determine the level of contribution to system flexibility coming from different components, a number of sequential experiments, each with a specific factor screening objective, are defined in this chapter.

6.3 SELECTION OF THE RESPONSE VARIABLES

MS can be evaluated in terms of either one or several indicators; however, in the field of manufacturing and operations management a significant amount of available research considers only a single performance indicator. In this study, MS performance is evaluated in terms of multiple responses.

According to Miltenburg (1995), MS can be evaluated in terms of different outputs such as cost, quality, delivery time and reliability, innovativeness, etc. Even though quality together with manufacturing cost and lead time are the three most usual indicators to measure manufacturing performance; in this study the indicators cost, lead time, and throughput are considered as the main response variables. Quality has not been considered as a response variable because it is not the intention of the present study to deal with the quality aspects of manufacturing. Would further analysis and decision criteria be required, complementary indicators may be considered. Table 6.1 below provides a definition of the three response variables considered and their relationship with the research objective.

Table 6.1 – Response variables

Response Variable	Units	Definition
Throughput	Number of parts	It measures system productivity by expressing the amount of work done in a particular period of time. Manufacturing flexibility depends upon system capacity to have an acceptable throughput under different disrupting conditions.
Manufacturing cost	Dollars	It is the amount of money expended in material, labour and manufacturing overheads necessary for the fabrication of products. Flexibility is determined in terms of system capacity to maintain low costs despite of unexpected disruptions.
Lead time	Minutes	It is the total time required to manufacture and deliver an item. System flexibility depends on the capacity to maintain low production times and low delivery times even in environments characterized by uncertainty.

In this study the ultimate objective is to evaluate the level of MS flexibility as a result of these three indicators; therefore, the system capability to operate with higher throughputs while keeping low lead times and low operating costs, all this while the system experiences different disturbances, is what in turn determines the level of manufacturing flexibility.

6.4 MODEL RUNNING TIME: WARM-UP PERIOD AND RUN LENGHT

In the proposed simulation model, the total running time is composed of a warming up period, during which the model reaches its normal operating condition, and a run length period, during which the model collects results. Details on both periods are given in the following sections.

6.4.1 Warm up period

In order obtain reliable results out of the simulation model, it is necessary to run the model for a period of time until it reaches a steady state, i.e. a normal operating condition. The required time for the simulation model to reach the steady state is known as warm-up period. In this study, Welch's graphical method has been used to determine the warm up period for the proposed simulation model. As stated by Robinson (1994), this method consists in running the model a number of times with different random number seeds in order to calculate a mean average of a key output for specific periods of time; moving averages are calculated afterwards using the equation 6.1 below:

$$\text{Moving average}_i = \begin{cases} \dfrac{\sum_{s=(i-1)}^{i-1} mean_{i+s}}{2i-1} & \text{if } i = 1,\dots,\text{w} \\ \dfrac{\sum_{s=-w}^{w} mean_{i+s}}{2w+1} & \text{if } i = w+1,\dots,m-w \end{cases} \qquad (6.1)$$

where

i = period for which the moving average is being calculated

mean = mean of the key result, across all the replications, for period i

w = number of periods in the window

m = number of periods in the run

For the proposed simulation model, Welch's method has specified a minimum warm-up period of 50 hours; however, a total warm-up period of 240 hours (equivalent to 30 working days for the simulated system) has been chosen in order to guarantee that all the different scenarios originating from the initial simulation model would achieve their normal operating conditions within the same period of time. Please refer to appendix 5 for details on the calculation of the warm-up period using Welch's method.

6.4.2 Run length

After defining a warm-up period it is necessary to define a period during which the model collects the results. A graphical approach, suggested by Robinson (1994), has been considered to calculate the run length . According to such approach, the proposed simulation model requires a minimum run length period of 220 hours. Similarly to the warm-up period, it has been decided to employ a much longer run length period so that all of the different scenarios originating from the initial model would fit within the same period of time. A final run length period of 500 hours (equalling 2 working months for the simulated system) has been set as the general run length period. Please refer to appendix 6 for details on the approach used to calculate the run length period.

6.5 CHOICE OF EXPERIMENTAL FACTORS

6.5.1 Noise factors; definition of disturbance scenarios

In order to identify the best system response in terms of manufacturing flexibility, a set of factors need to be tested under diverse scenarios. Those scenarios are characterized by a particular disruption occurring in the environment in which the MS operates. Manufacturing disturbances, as they are known, inevitably lead to a loss of system performance. With the purpose of representing different disturbance scenarios, the baseline simulation model described in the previous chapter has been altered in a number of ways. A description of the considered disturbance scenarios together with the parameters entered into the model to represent each scenario is offered in the subsequent sections.

6.5.1.1 Frequent machine breakdowns scenario

The purpose of considering this scenario is to identify a suitable system response under the presence of recurrent failures in machines throughout the MS. When the system does not have the capability to cope with frequent machine breakdowns, it won't be long before in-process inventories will start accumulating in front of the broken down machine first, and eventually, in front of the other machines along the manufacturing process. When the system's capacity to hold in-process inventory is exceeded by the accumulating inventory levels, the evident result is that the whole system will eventually come to a stop and it will not resume operations until the failure is properly fixed.

In the initial or baseline model, machine efficiencies have been randomly determined choosing values from an interval of efficiencies between 83% and 96%.Even though a predefined frequency of machine breakdowns is already considered in the baseline simulation model, such frequency is moderated compared to the higher frequency of machine breakdowns needed in this scenario. From table 6.2 it can be noticed that, in order to simulate a higher occurrence of machine breakdowns, the efficiencies of each of the machines have been decreased with respect to the efficiencies in the baseline model.

Table 6.2 – Comparison of machine efficiencies

	Baseline model		**Disturbance scenario**	
Machine	**Efficiency**	**Avg. Repair time**	**Efficiency**	**Avg. Repair time**
1	93%	23	70%	23
2	91%	26	65%	26
3	94%	30	69%	30
4	88%	28	64%	28
5	83%	29	68%	29
6	96%	27	66%	27
7	89%	20	62%	20
8	85%	30	60%	30
9	88%	21	63%	21

min	**83%**	20	**60%**	20
max	**96%**	30	**70%**	30

In the current disturbance scenario, new efficiencies ranging from 60% to 70% have been randomly assigned to each of the machines within the system. Compared to the initial interval of machine efficiencies in the baseline model, the new interval of efficiencies significantly produces a higher frequency of machine breakdowns with respect to the baseline model.

Note from table 6.2 that, because the variable of interest is the frequency of breakdowns and not the time it takes for the machine to be fixed, average repair times have not been altered in this scenario.

6.5.1.2 Frequent operator unavailability scenario

Human operators are very important resources for MS, but they are especially significant for systems with a low level of automation. When systems are highly dependent upon human operators, any level of absenteeism would inevitably have an effect upon the system. Occasionally, human operators get sick, tired or even have personal issues preventing them from going to work on an ordinary day. If the system is not prepared to cope with the temporary unavailability of operators, its performance can be significantly affected. The aim of this scenario is to represent a working environment where the unavailability of operators is slightly higher than the unavailability of operators in the baseline model. There is a direct relationship between this scenario and the previous scenario given that both, operator unavailability and machine breakdowns, are characterized by the unavailability of a specific resource during a period of time; however, even though it may seem that both scenarios are quite similar and therefore it may seem as a duplicated scenario, the truth is that both scenarios have different aims. While in the machine breakdown scenario what is tested is the frequency of resource unavailability, this scenario examines the impact caused by the duration of the resource unavailability together with the effect of machine dependability upon operators.

In the baseline model, availability percentages have been determined assuming that each operator is absent at least once every 30 days (1/30); this means a mean availability of 96% per operator. The availability percentage of each operator has been randomly assigned considering the mean availability of 96% as the lowest availability and 97% as the highest availability. Moreover, an average absence time of 480 min (8 hours) per operator has also been assumed in the baseline model; in the same way, average absence times for each operator have been randomly chosen from an interval between 480 and 600 minutes.

Regarding the calculation of availability percentages in this disturbance scenario, the values for each operator have been randomly chosen from an interval between 91% and 95%.Table 6.3 shows the availabilities and absence times considered in this scenario with respect to the baseline simulation model.

Table 6.3 – Comparison of operator availabilities

Operator	**Baseline model**		**Disturbance scenario**	
	Availability %	Average absence time	Availability %	Average absence time
1	96%	530 min	95%	530 min
2	96%	600 min	94%	600 min
3	97%	495 min	93%	495 min
4	97%	480 min	91%	480 min
5	96%	510 min	93%	510 min
6	96%	550 min	94%	550 min
min	**96%**	480 min	**91%**	480 min
max	**97%**	600 min	**95%**	600 min

Note from table 6.3 that the difference between the availability interval in the baseline model (96% - 97%) and the availability interval of the disturbance scenario (91% - 95%) is not a significant variation; this is due to the fact that if lower availability percentages had been considered for the disturbance scenario, the model would have got frequently blocked which in turn would have lead to significant variations between simulation runs. Note as well that the average absence time for each operator in the model was intentionally unaltered in the disturbance scenario.

6.5.1.3 Irregular pattern of raw-material-arrivals scenario

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. Disruptions in the pattern of arrivals lead to a system working intermittently, i.e. a system that is combining periods of inactivity and periods of operation. Depending on whether the system involves the production of a few or several parts, together with the availability of safety stocks, the impact of irregular arrivals can negatively affect the utilization of resources and consequently system's delivery time and throughput. As opposed to the arrival pattern described earlier for the baseline model, the arrival pattern for this scenario needs to reflect both varying arrivals between time intervals and a higher variation between arrivals. In order to simulate such condition in the arrival pattern, a different inter-arrival distribution is considered in this scenario. The variation in the arrival pattern in this scenario with respect to the arrival pattern in the baseline model is contrasted in figures 6.1 and 6.2 below.

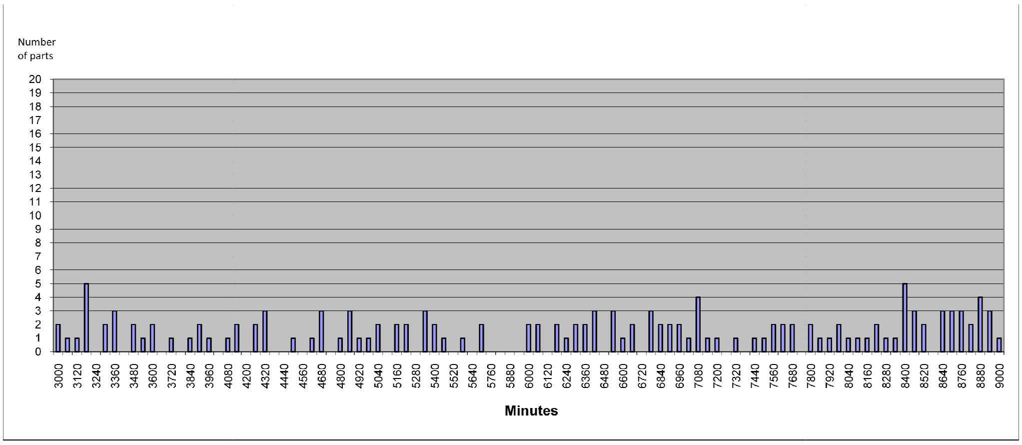

Figure 6.1 – Pattern of material arrivals per time interval in the baseline model

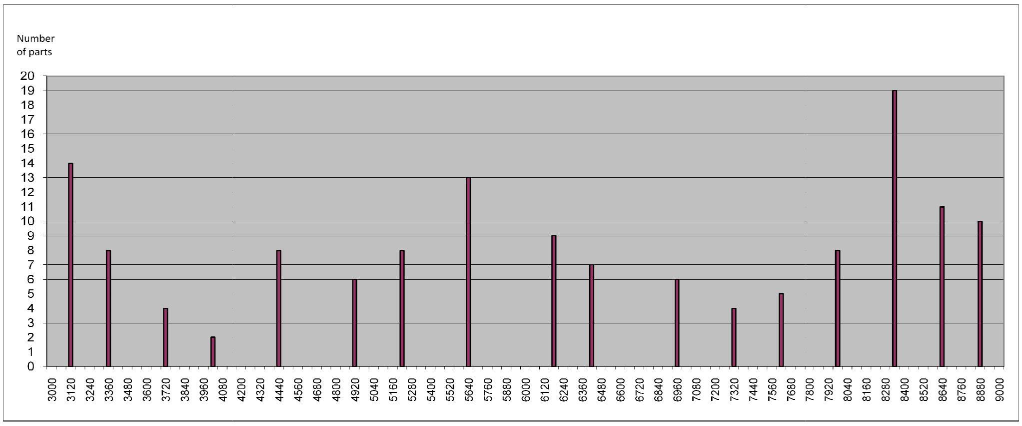

Figure 6.2 – Pattern of material arrivals per time interval in the disturbance scenario

In order to generate the pattern of arrivals in figure 6.2 a gamma distribution has been used. Similarly to the exponential distribution used in the baseline model, the gamma distribution is also continuous distribution with a shape that varies greatly with the values of its parameters, i.e. shape (α) and scale (β) (Hauge and Paige, 2001). Reportedly, the gamma distribution has the widest range of shapes for modelling time between events (e.g. interarrival time, time between failure, etc.) and time to complete tasks (e.g. customer service, machine repair, etc (Robinson, 1994). The parameters used in the gamma distribution generating the interarrival times in this scenario are a shape parameter of α=10 minutes and a scale parameter of β=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. Note that the pattern of arrivals used in the baseline model and the pattern of arrivals used in this disturbance scenario generate approximately the same number of parts within the same time interval.

6.5.1.4 Increased arrivals of raw material scenario

Even though this scenario is related to the previous one in the sense that both simulate one aspect regarding the arrival of raw materials into the system; in this scenario, as opposed to the previous 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. There are several reasons why material arrivals may unexpectedly increase; it may be due to external causes such as a sudden increase in demand for products or it may also due to internal causes such as logistics errors. Figure 6.3 shows the difference between arrivals of raw material in the baseline model and arrivals of material in the disturbance scenario.

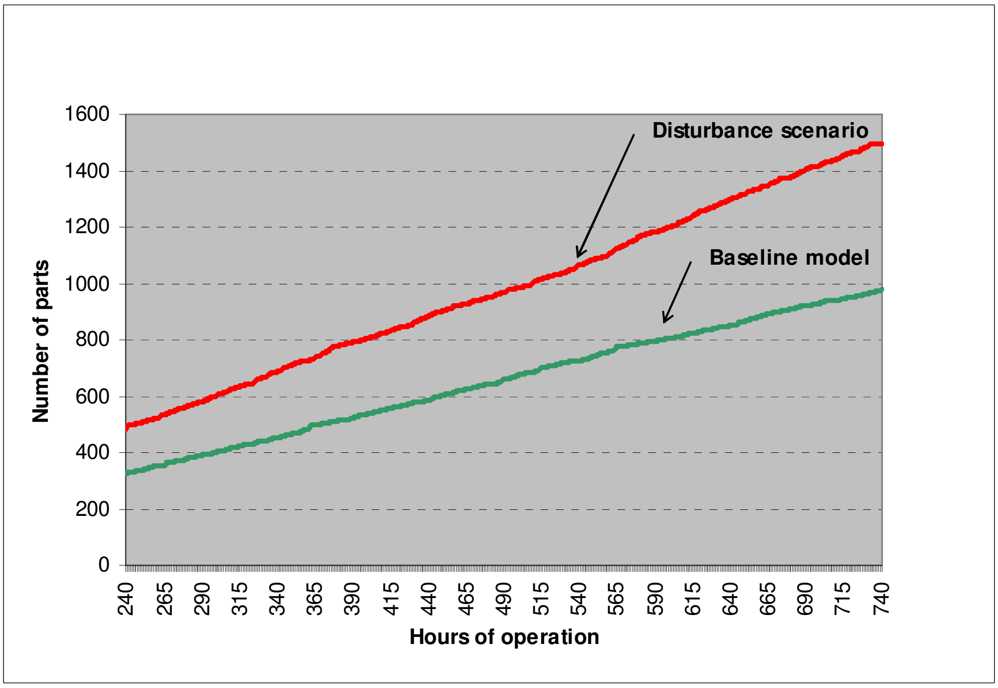

Figure 6.3 – Number of raw material arrivals

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.

6.5.1.5 Increased product variety scenario

The baseline model involves the production of five different parts. In order to represent a situation where the system needs to produce a wider range of products, under this scenario, the range of parts produced by the system has been increased to ten parts, each with 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%. For a MS some of the implications of dealing with a wider product range could be lower utilization of resources due to more frequent changeovers. Increased product variety also demands more capabilities from human and technological resources. In terms of human resources, the production of a wider variety of products demands skilled operators able to handle a range of different processes. In terms of technology, product variety demands machines with better processing capabilities and material handling systems able to efficiently transport different parts between work centres throughout the manufacturing facility. Table 6.4 compares the increased product variety in this scenario with respect to the product variety in the baseline model.

Table 6.4 – 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	0%	13%
7	0%	14%
8	0%	11%
9	0%	12%
10	0%	10%
TOTAL	**100%**	**100%**

Please refer to appendix 7 for the additional processing routes and times considered in this scenario. Note from table 6.4 that only product mix has been modified, with respect to the baseline model, in order to accommodate the new product range. Routings and times for the original five products defined in the baseline model are still valid in this scenario.

6.5.1.6 High variation in product mix scenario

Just as in the previous section this scenario is also related to changes in the product portfolio but, instead of investigating a wider choice of products, this scenario considers the demand variation existing between products. When a MS fabricates different products, each going through a different stage of their life cycles, it is usual to have some highly demanded products and, at the same time, some other products whose demand is not very significant, particularly those in the later stages of their life cycle. This disproportion in the demand for different products leads to problems in the MS; most of which are related to idle times especially caused by changeovers. To simulate this scenario, the same five original products defined in the baseline model are considered but 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 6.5 illustrate a comparison between the original product mix and the mix considered in this scenario.

Table 6.5 – Comparison of product mixes

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 above that the range in the product mix for the disturbance scenario is considerably larger than the range in the baseline model.

6.5.2 Design factors

Having taken into consideration existing research on the topic of manufacturing systems, a cause-and-effect diagram has been used to identify all those possible components that have an important influence on the responses throughput, cost, and lead time. The cause-and-effect diagram in figure 6.4 shows the different factors having an effect on manufacturing performance.

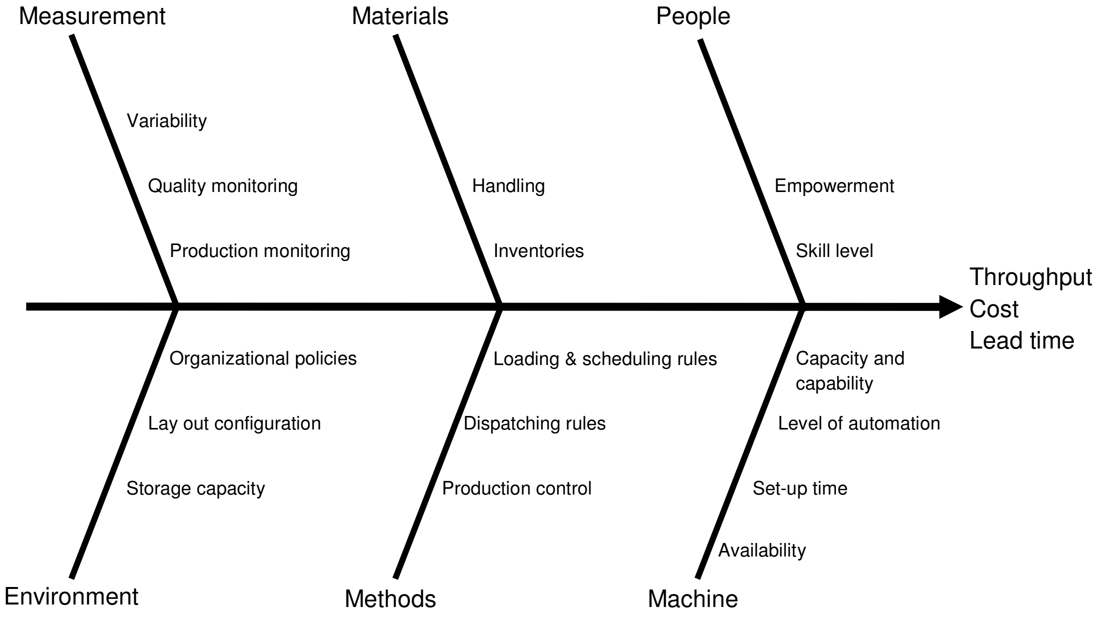

Figure 6.4 – Cause-and-effect diagram: factors affecting performance measures

From the diagram above it can be noticed how each main aspect is divided into further characteristics, all of those influencing the chosen response variables to a certain extent. Even though there are a variety of factors that influence the selected response variables, it would be very complicated, in terms of accurateness and required time, to investigate all the involved factors within the same experimental design. Taking into consideration that the present study has a special interest in the concept of manufacturing flexibility, as seen from a uniformity dimension perspective, characteristics related to those operational system aspects determining the performance of a MS, and which were previously identified in chapter 3, are of particular significance. Therefore, system aspects related to the human labour, the work centre and the material handling subsystems are considered as the design factors. Six factors of particular interest in this research are the following:

1. **Skill level of operators.** It is related to the capacity of the operators to perform different activities within the manufacturing process. The skill level is determined by the number of different machines a single operator is able to control.

2. **System capacity to hold in-process inventories.** It is concerned with the number of parts that can be temporarily held within the system; in this case, the number of parts held in the raw materials warehouse and in both input and output buffers at work centres.

3. **Number of automated guided vehicles.** It is determined by the total number of material handling devices within the system.

4. **Speed of automated guided vehicles.** It is the distance covered by material handling vehicles during a specific period of time.

5. **Loading capacity of automated guided vehicles.** It is the maximum number of parts a material handling device can transport between work centres.

6. **Duration of set-ups in machines.** The time it takes for a machine to switch from fabricating one type of product to fabricating a completely different product.

As shown in figure 6.5 not only are the factors above influential to the response variables but also they are controllable and measurable. According to Coleman and Montgomery (1993) such features make the selected factors suitable control variables for experimentation.

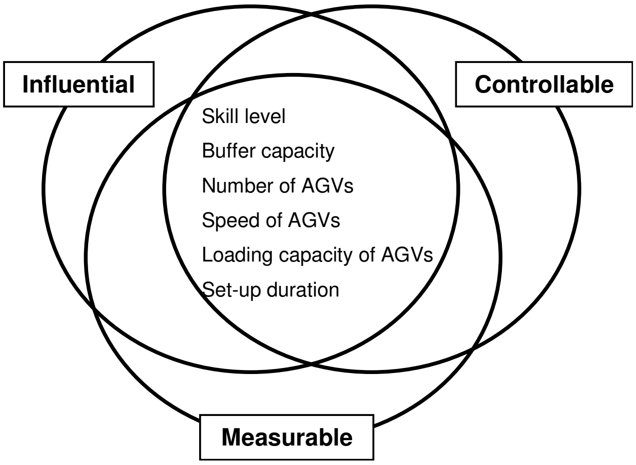

Figure 6.5 – Venn diagram: Design factors

In addition to the design factors above, there are other factors involved in the experimental design, for example some of factors within the *methods* and *environment* categorizations in figure 6.4. Those additional factors are classified in table 6.6 below.

Table 6.6 – Other factors involved in the experimental design

CLASSIFICATION	DEFINITION	FACTORS
Held constant factors	Factors to be held at a specific level.	• Dispatching rule (FIFO) • Cost of materials, labour and machine-time • Types of material, machines, vehicles and operators • Revenue per unit
Allowed to vary factors	Factors with an assumed small effect.	• Processing times * It is important to mention that these factors vary within a predefined interval.

Table 6.6 (continued)

Controllable nuisance factors	Their levels are set by the experimenter though they are of no particular interest for the research.	• Working days • Working hours
Noise factors	These factors vary naturally; they are controlled for the purposes of the experimentation process.	Each of the disturbance scenarios considered in this research represent a specific noise factor: • Frequency of machine breakdowns • Frequency of operator unavailability • Customer's preferences (product variety and product mix) • Demand fluctuations (increase in arrival of materials and irregular arrival of material)

Even though additional factors may have an influence on the responses, they are not of direct interest for this research.

6.5.2.1 Choice of factor levels and range

Consistent with Montgomery (2009), since the objective of the experiment is to identify those factors exerting major influence on the response variables, it is recommended to keep a low number of factor levels, with a relatively large range between levels. Two levels, low and high, have been set for each of the six considered factors. It is important to state that factor levels are measured and controlled at the desired levels by means of the simulation software employed. Tables 6.7 to 6.13 below include the ranges and factor levels selected for each experimental scenario.

Table 6.7 – Baseline simulation model: Factor levels

F	DESCRIPTION	LEVEL 1	LEVEL 2
X1	Operator skills	4 unskilled operators and 2 semi-skilled operators.	3 semi-skilled operator and 3 skilled operators
X2	Buffer capacity	Buffer capacity of up to 10 parts; cost per item per minute $0.010.	Buffer capacity of up to 15 parts; cost per item per minute $0.015.
X3	Number of vehicles	1 AGV.	4 AGVs.
X4	Vehicle speed	Vehicle speed 5.	Vehicle speed 60.
X5	Loading capacity	2 parts loading capacity. (load/unload = 0.5 min)	10 pieces loading capacity (load/unload =1.2 min)
X6	Machine set-ups duration	Set-up time between 11 and 15 minutes.	Set-up time between 20 and 29 minutes.

Table 6.8 – Frequent machine breakdowns scenario: Factor levels

F	DESCRIPTION	LEVEL 1	LEVEL 2
X1	Operator skills	4 unskilled operators and 2 semi-skilled operators.	3 semi-skilled operator and 3 skilled operators
X2	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.
X3	Number of vehicles	1 AGV.	4 AGVs.
X4	Vehicle speed	Vehicle speed 5.	Vehicle speed 60.
X5	Loading capacity	3 parts loading capacity. (load/unload = 0.5 min)	10 pieces loading capacity (load/unload = 1.2 min)
X6	Machine set-ups duration	Set-up time between 1 and 5 minutes.	Set-up time between 20 and 29 minutes.

Table 6.9 – Frequent operator unavailability scenario: Factor levels

F	DESCRIPTION	LEVEL 1	LEVEL 2
X1	Operator skills	4 unskilled operators and 2 semi-skilled operators.	2 semi-skilled operator and 4 skilled operators.
X2	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.
X3	Number of vehicles	1 AGV.	5 AGVs.
X4	Vehicle speed	Vehicle speed 5.	Vehicle speed 80.
X5	Loading capacity	4 parts loading capacity. (load/unload = 0.5 min)	10 pieces loading capacity (load/unload = 1.2 min)
X6	Machine set-ups duration	Set-up time between 6 and 10 minutes.	Set-up time between 20 and 29 minutes.

Table 6.10 – Irregular pattern of raw material arrivals scenario: Factor levels

F	DESCRIPTION	LEVEL 1	LEVEL 2
X1	Operator skills	4 unskilled operators and 2 semi-skilled operators.	1 semi-skilled operator and 5 skilled operators
X2	Buffer capacity	Buffer capacity of up to 10 parts; cost per item per minute $0.010.	Buffer capacity of up to 21 parts; cost per item per minute $0.030.
X3	Number of vehicles	1 AGV.	5 AGVs.
X4	Vehicle speed	Vehicle speed 5.	Vehicle speed 60.
X5	Loading capacity	6 parts loading capacity. (load/unload = 1.2 min)	10 pieces loading capacity (load/unload = 1.2 min)
X6	Machine set-ups duration	Set-up time between 1 and 5 minutes.	Set-up time between 20 and 29 minutes.

Table 6.11 – Increased arrivals of raw material scenario: Factor levels

F	DESCRIPTION	LEVEL 1	LEVEL 2
X1	Operator skills	4 unskilled operators and 2 semi-skilled operators.	2 semi-skilled operator and 4 skilled operators
X2	Buffer capacity	Buffer capacity of up to 10 parts; cost per item per minute $0.010.	Buffer capacity of up to 33 parts; cost per item per minute $0.030.
X3	Number of vehicles	1 AGV.	5 AGVs.
X4	Vehicle speed	Vehicle speed 5.	Vehicle speed 10.
X5	Loading capacity	3 parts loading capacity. (load/unload = 0.5 min)	10 pieces loading capacity (load/unload = 1.2 min)
X6	Machine set-ups duration	Set-up time between 1 and 5 minutes.	Set-up time between 20 and 29 minutes.

Table 6.12 – Increased product variety scenario: Factor levels

F	DESCRIPTION	LEVEL 1	LEVEL 2
X1	Operator skills	4 unskilled operators and 2 semi-skilled operators.	6 skilled operators.
X2	Buffer capacity	Buffer capacity of up to 10 parts; cost per item per minute $0.010.	Buffer capacity of up to 20 parts; cost per item per minute $0.020.
X3	Number of vehicles	1 AGV.	4 AGVs.
X4	Vehicle speed	Vehicle speed 5.	Vehicle speed 15.
X5	Loading capacity	2 parts loading capacity. (load/unload = 0.5 min)	10 pieces loading capacity (load/unload = 1.2 min)
X6	Machine set-ups duration	Set-up time between 1 and 5 minutes.	Set-up time between 20 and 29 minutes.

Table 6.13 – High variation in product mix scenario: Factor levels

F	DESCRIPTION	LEVEL 1	LEVEL 2
X1	Operator skills	4 unskilled operators and 2 semi-skilled operators.	3 semi-skilled operator and 3 skilled operators
X2	Buffer capacity	Buffer capacity of up to 10 parts; cost per item per minute $0.010.	Buffer capacity of up to 20 parts; cost per item per minute $0.020.
X3	Number of vehicles	1 AGV.	5 AGVs.
X4	Vehicle speed	Vehicle speed 5.	Vehicle speed 60.
X5	Loading capacity	3 parts loading capacity. (load/unload = 0.5 min)	10 pieces loading capacity (load/unload = 1.2 min)
X6	Machine set-ups duration	Set-up time between 6 and 10 minutes.	Set-up time between 20 and 29 minutes.

For further details on the method used to define ranges and factor levels please refer to appendix 8.

6.6 DETERMINATION OF THE NUMBER OF REPLICATIONS

In order for an experiment to be statistically reliable it must be based on a number of replications. A replication, in the context of discrete event simulation, is a single run of a simulation model generated from a specific seed number. There are different methods to determine the number of replications for a simulation model. The process to determine the number of replications for the model considered in this study is described next. In the first place, a maximum error estimate has been calculated out of a series of initial replications of the simulation model. This was achieved by equation (6-1) below

$$E = t_{1-\alpha/2,n-1}\frac{S(x)}{\sqrt{n}} \qquad (6\text{-}1)$$

where:

E = the maximum error estimate.

$S(x)$ = the standard deviation of the results from the initial replications.

n = the number of initial replications.

$t_{1-\alpha/2,\, n-1}$ = the standard deviate in the t-distribution.

Confidence intervals for the mean results could be constructed afterwards using the equation (6-2)

$$\mu = (\overline{x} - E, \overline{x} + E) \tag{6-2}$$

where:

$\overline{x}$ = average of the results from the initial replications.

The last step consisted in determining the number of replications required to a desired error, this was achieved by using equation (6-3) below

$$n^{*} \geq n\left(\frac{E}{E^{*}}\right)^{2} \tag{6-3}$$

where:

n* = the total number of required replications.

n = the number of initial replications.

E* = the desired error.

For further details on this method please refer to Saad (1994) who provides an extensive explanation on the method together with a practical example of the calculation process to determine the number of replications.

Table 6.14 below shows the necessary number of replications determined for the baseline simulation model and for each disturbance scenario.

Table 6.14 – Number of necessary replications for each simulation scenario

SIMULATION SCENARIO	NUMBER OF REPLICATIONS
Baseline model	200
Frequent machine breakdowns	250
Frequent operator unavailability	250
Irregular pattern of raw material arrivals	350
Increased arrivals of raw material	250
Increased product variety	350
High variation in product mix	250

Please refer to appendix 9 for details on the calculation procedure to determine the number of replications in the table above.

6.7 CHOICE OF EXPERIMENTAL DESIGN

Factorial designs are recommended when there are a number of factors in the experiment whose corresponding effects on either one or several responses need to be investigated. According to Montgomery (2009), the importance of this factorial designs lies in the fact that all the possible combinations of factor levels are considered. Additionally, and as opposed to other types of experimental designs, factorial designs do consider the effect of factor interactions. Mason *et al.* (2003) suggest that in the presence of interactions, complete factorial experimental designs should be considered in order to avoid wrong conclusions. In this study, the type of experimental design has been selected according to the screening objective of the experiment, i.e. to identify those factors with an influential effect on pre-defined response variables. Consequently, a 2^6 full factorial design has been selected as the experimental design. The statistical model for the selected design includes:

- 6 main effects
- 15 two factor interactions
- 20 three factor interactions
- 15 four factor interactions
- 6 five factor interaction
- 1 six factor interaction

In this type of design the assumption is that, because there are only two levels, the response is linear along the range between the lower and upper levels.

6.7.1 Sample size

A 2^6 full factorial design involves a total of 64 experimental settings; taking into consideration that the present research intends to investigate 6 different scenarios, with each scenario involving a 2^6 full factorial design; the total of experimental settings adds up to 384 experimental trials; no to mention that each experimental setting requires to be replicated a considerable number of times (refer to section 6.6). The complexity of the simulation model together with the characteristics of the experimental design would demand a significant amount of time to perform the experiments; for this reason an unreplicated factorial has been considered. Montgomery (2009) states that a single replicate strategy is reportedly helpful when there are many factors involved and the available time for experimentation is restricted.

6.7.2 Run order for experimental trials

Randomization and blocking are both strategies in experimental designs to reduce or eliminate the effects of nuisance factors (Montgomery, 2009). Given that in this study all the experiments are conducted by means of the simulation software employed, i.e. the experiments are not influenced by environmental conditions in the way physical experiments are, neither randomization nor blocking strategies are necessary. Table 6.15 includes each of the 64 experimental settings necessary in a 2^6 full factorial arrangement.

Table 6.15 – Model matrix for the 2^6 full factorial experiments

RUN	LABEL	DESIGN FACTORS					
		X1	X2	X3	X4	X5	X6
1	(1)	-1	-1	-1	-1	-1	-1
2	a	+1	-1	-1	-1	-1	-1
3	b	-1	+1	-1	-1	-1	-1
4	ab	+1	+1	-1	-1	-1	-1
5	c	-1	-1	+1	-1	-1	-1
6	ac	+1	-1	+1	-1	-1	-1
7	bc	-1	+1	+1	-1	-1	-1
8	abc	+1	+1	+1	-1	-1	-1
9	d	-1	-1	-1	+1	-1	-1
10	ad	+1	-1	-1	+1	-1	-1
11	bd	-1	+1	-1	+1	-1	-1
12	abd	+1	+1	-1	+1	-1	-1
13	cd	-1	-1	+1	+1	-1	-1
14	acd	+1	-1	+1	+1	-1	-1
15	bcd	-1	+1	+1	+1	-1	-1
16	abcd	+1	+1	+1	+1	-1	-1
17	e	-1	-1	-1	-1	+1	-1
18	ae	+1	-1	-1	-1	+1	-1
19	be	-1	+1	-1	-1	+1	-1
20	abe	+1	+1	-1	-1	+1	-1
21	ce	-1	-1	+1	-1	+1	-1
22	ace	+1	-1	+1	-1	+1	-1
23	bce	-1	+1	+1	-1	+1	-1
24	abce	+1	+1	+1	-1	+1	-1
25	de	-1	-1	-1	+1	+1	-1
26	ade	+1	-1	-1	+1	+1	-1
27	bde	-1	+1	-1	+1	+1	-1
28	abde	+1	+1	-1	+1	+1	-1
29	cde	-1	-1	+1	+1	+1	-1
30	acde	+1	-1	+1	+1	+1	-1
31	bcde	-1	+1	+1	+1	+1	-1
32	abcde	+1	+1	+1	+1	+1	-1
33	f	-1	-1	-1	-1	-1	+1
34	af	+1	-1	-1	-1	-1	+1
35	bf	-1	+1	-1	-1	-1	+1
36	abf	+1	+1	-1	-1	-1	+1
37	cf	-1	-1	+1	-1	-1	+1
38	acf	+1	-1	+1	-1	-1	+1
39	bcf	-1	+1	+1	-1	-1	+1
40	abcf	+1	+1	+1	-1	-1	+1
41	df	-1	-1	-1	+1	-1	+1
42	adf	+1	-1	-1	+1	-1	+1
43	bdf	-1	+1	-1	+1	-1	+1
44	abdf	+1	+1	-1	+1	-1	+1
45	cdf	-1	-1	+1	+1	-1	+1
46	acdf	+1	-1	+1	+1	-1	+1
47	bcdf	-1	+1	+1	+1	-1	+1
48	abcdf	+1	+1	+1	+1	-1	+1
49	ef	-1	-1	-1	-1	+1	+1
50	aef	+1	-1	-1	-1	+1	+1
51	bef	-1	+1	-1	-1	+1	+1
52	abef	+1	+1	-1	-1	+1	+1
53	cef	-1	-1	+1	-1	+1	+1
54	acef	+1	-1	+1	-1	+1	+1
55	bcef	-1	+1	+1	-1	+1	+1
56	abcef	+1	+1	+1	-1	+1	+1
57	def	-1	-1	-1	+1	+1	+1
58	adef	+1	-1	-1	+1	+1	+1
59	bdef	-1	+1	-1	+1	+1	+1
60	abdef	+1	+1	-1	+1	+1	+1
61	cdef	-1	-1	+1	+1	+1	+1
62	acdef	+1	-1	+1	+1	+1	+1
63	bcdef	-1	+1	+1	+1	+1	+1
64	abcdef	+1	+1	+1	+1	+1	+1

Design factors:
X1 *: Operator skills*
X2 *: Buffer capacity*
X3 *: Number of AGVs*
X4 *: AGV's speed*
X5 *: AGV's loading capacity*
X6 *: Machine set-up duration*

In the table above, the *run* column indicates the order of the experiments though, for the reason stated in the previous paragraph, it doesn't necessarily has to be followed when conducting the experiments. The *label* column indicates the factors set at the high level in a particular run. The columns *X1* to *X6* represent each of the design factors which are set at low (-1) or high (+1) level.

6.8 CONCLUSION

This chapter has covered three main issues regarding the methodology of the present research. First, the problem to be approached through experimentation has been identified. Second, all the experimental scenarios together with the intervening factors and response variables have been defined. Third, experimental parameters for the simulation model have been established in conjunction with a description of the method under which experiments are carried out. The succeeding chapter presents the results of the experimental settings defined in this chapter together with a statistical analysis to validate the assumptions under which the experiments are conducted.

CHAPTER 7

EXPERIMENTAL RESULTS AND STATISTICAL ANALYSIS

7.1 INTRODUCTION

In this chapter the results of the previously defined experimental scenarios are presented and analysed. The chapter is divided in six sections related to each of the six different disturbance scenarios defined in the preceding chapter. Each section presents both the results of the experiments and a statistical analysis of such results. The results of the experiments are expressed in terms of the three selected performance measures. The analytical part consists of a preliminary data analysis and a formal statistical analysis. In the preliminary data analysis potential data problems and possible significant factors are identified. In the formal statistical analysis the experimental assumptions and the significant factors, in terms of the response variables, are confirmed.

7.2 FREQUENT MACHINE BREAKDOWNS SCENARIO

7.2.1 Experimental results and exploratory data analysis

After conducting the series of experiments defined in chapter 6, the model matrix presented in table 6.15 has been extended in order for it to include the results of the experiments. Table 7.1 shows the results, in terms of the three response variables, for the present disturbance scenario.

Table 7.1 - Experimental results; machine breakdowns scenario

		EXPERIMENTAL FACTOR						Machine breakdowns		
RUN	LABEL	X1	X2	X3	X4	X5	X6	Parts	Time	Cost
1	(1)	-1	-1	-1	-1	-1	-1	666	1,586	$38,134
2	a	+1	-1	-1	-1	-1	-1	667	1,456	$41,403
3	b	-1	+1	-1	-1	-1	-1	668	1,639	$59,111
4	ab	+1	+1	-1	-1	-1	-1	667	1,460	$59,431
5	c	-1	-1	+1	-1	-1	-1	667	1,566	$38,212
6	ac	+1	-1	+1	-1	-1	-1	667	1,417	$41,280
7	bc	-1	+1	+1	-1	-1	-1	668	1,602	$58,421
8	abc	+1	+1	+1	-1	-1	-1	667	1,417	$58,636
9	d	-1	-1	-1	+1	-1	-1	667	1,540	$38,110
10	ad	+1	-1	-1	+1	-1	-1	667	1,388	$41,180
11	bd	-1	+1	-1	+1	-1	-1	667	1,579	$58,321
12	abd	+1	+1	-1	+1	-1	-1	667	1,386	$58,352
13	cd	-1	-1	+1	+1	-1	-1	666	1,540	$38,156
14	acd	+1	-1	+1	+1	-1	-1	667	1,386	$41,201
15	bcd	-1	+1	+1	+1	-1	-1	667	1,577	$58,273
16	abcd	+1	+1	+1	+1	-1	-1	667	1,386	$58,373
17	e	-1	-1	-1	-1	+1	-1	668	1,590	$38,168
18	ae	+1	-1	-1	-1	+1	-1	667	1,477	$41,462
19	be	-1	+1	-1	-1	+1	-1	667	1,651	$59,222
20	abe	+1	+1	-1	-1	+1	-1	667	1,477	$59,614
21	ce	-1	-1	+1	-1	+1	-1	667	1,572	$38,215
22	ace	+1	-1	+1	-1	+1	-1	667	1,419	$41,268
23	bce	-1	+1	+1	-1	+1	-1	668	1,613	$58,568
24	abce	+1	+1	+1	-1	+1	-1	667	1,419	$58,625
25	de	-1	-1	-1	+1	+1	-1	667	1,538	$38,055
26	ade	+1	-1	-1	+1	+1	-1	667	1,390	$41,188
27	bde	-1	+1	-1	+1	+1	-1	667	1,583	$58,329
28	abde	+1	+1	-1	+1	+1	-1	667	1,389	$58,376
29	cde	-1	-1	+1	+1	+1	-1	667	1,538	$38,145
30	acde	+1	-1	+1	+1	+1	-1	667	1,388	$41,179
31	bcde	-1	+1	+1	+1	+1	-1	667	1,577	$58,220
32	abcde	+1	+1	+1	+1	+1	-1	667	1,387	$58,326
33	f	-1	-1	-1	-1	-1	+1	667	1,827	$41,883
34	af	+1	-1	-1	-1	-1	+1	667	1,598	$45,152
35	bf	-1	+1	-1	-1	-1	+1	667	1,925	$66,880
36	abf	+1	+1	-1	-1	-1	+1	667	1,593	$64,701
37	cf	-1	-1	+1	-1	-1	+1	667	1,845	$42,366
38	acf	+1	-1	+1	-1	-1	+1	667	1,586	$45,543
39	bcf	-1	+1	+1	-1	-1	+1	667	1,950	$67,695
40	abcf	+1	+1	+1	-1	-1	+1	667	1,583	$64,928
41	df	-1	-1	-1	+1	-1	+1	667	1,805	$42,027
42	adf	+1	-1	-1	+1	-1	+1	667	1,568	$45,563
43	bdf	-1	+1	-1	+1	-1	+1	667	1,943	$67,928
44	abdf	+1	+1	-1	+1	-1	+1	667	1,560	$64,839
45	cdf	-1	-1	+1	+1	-1	+1	667	1,835	$42,466
46	acdf	+1	-1	+1	+1	-1	+1	667	1,561	$45,573
47	bcdf	-1	+1	+1	+1	-1	+1	667	1,935	$67,712
48	abcdf	+1	+1	+1	+1	-1	+1	667	1,561	$64,884
49	ef	-1	-1	-1	-1	+1	+1	667	1,791	$41,288
50	aef	+1	-1	-1	-1	+1	+1	667	1,603	$44,974

Table 7.1 (continued)

		EXPERIMENTAL FACTOR						Machine breakdowns		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
51	*bef*	-1	+1	-1	-1	+1	+1	667	1,908	$66,364
52	*abef*	+1	+1	-1	-1	+1	+1	667	1,600	$64,585
53	*cef*	-1	-1	+1	-1	+1	+1	667	1,866	$42,526
54	*acef*	+1	-1	+1	-1	+1	+1	667	1,586	$45,531
55	*bcef*	-1	+1	+1	-1	+1	+1	667	1,944	$67,512
56	*abcef*	+1	+1	+1	-1	+1	+1	667	1,585	$64,901
57	*def*	-1	-1	-1	+1	+1	+1	667	1,762	$41,747
58	*adef*	+1	-1	-1	+1	+1	+1	666	1,569	$45,474
59	*bdef*	-1	+1	-1	+1	+1	+1	668	1,932	$67,627
60	*abdef*	+1	+1	-1	+1	+1	+1	667	1,563	$64,856
61	*cdef*	-1	-1	+1	+1	+1	+1	666	1,859	$42,577
62	*acdef*	+1	-1	+1	+1	+1	+1	667	1,563	$45,550
63	*bcdef*	-1	+1	+1	+1	+1	+1	668	1,937	$67,713
64	*abcdef*	+1	+1	+1	+1	+1	+1	667	1,562	$64,849

In table 7.1, just as it was mentioned in the previous chapter, the column *Run* specifies the standard order, which is a non-randomized run order. The column *Label*, indicates the factor set at the high level within a run (e.g. for run 37, the label column indicates that factors c and f are set at the high level, whereas the rest of the factors are set at the low level). Columns *X1* to *X6* represent each of the experimental factors, i.e. *X1=operator skills*, *X2=buffer capacity*, *X3=number of AGVs*, *X4=vehicle's speed*, *X5=vehicle's loading capacity*, and *X6=machine set-up duration*; and indicate whether the factor is set at low (-1) or high (+1) level. The last three columns on the far right side of table 7.1 include the results of the experiments, in terms of the three selected performance indicators, for each of the experimental settings in the design. Note that the same description of this table of results applies for the rest of the scenarios.

The response data in table 7.1 has been plotted in different ways to identify any trends or anomalies that may be a problem when representing the data by standard linear response models. Please refer to appendix 10 for the exploratory data analysis of the results in terms of the three selected responses.

7.2.2 Statistical analysis of the results

In accordance with the previous chapter, a single replicate of a 2^6 design has been used to conduct the experiments. According to Montgomery (2009), a method for analysing this kind of design consists in examining a normal probability plot of the estimates of the effects, in which those points lying along a straight line are the apparently negligible effects with mean 0 and variance σ^2, whereas those points falling far from the straight line will be the significant effects with nonzero means. The preliminary model contains the significant effects and the negligible effects are combined as an estimate of error.

7.2.2.1 Statistical analysis of the response number of completed parts

After calculating the effect estimates and sum of squares (see appendix 11), a normal probability plot of the estimates of the effects has been generated. The normal plot of the effects in figure 7.1 shows that the significant effects are *A*, *B*, and the *AE*, *ABC*, and *BEF* interactions.

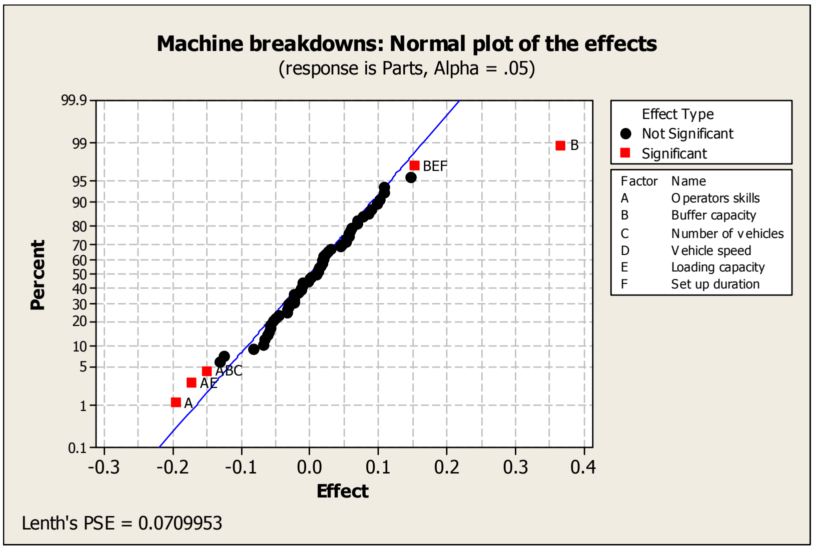

Figure 7.1 - Normal plot of the effects for number of parts; machine breakdowns scenario

Taking into consideration the significant factors and interactions, a simplified theoretical model has been created. The simplified model contains 12 terms and its relevant analysis of variance is shown in table 7.2 below.

Table 7.2 - ANOVA table for the response number of parts; machine breakdowns scenario

```
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%
```

The analysis of variance confirms the significance of the previously mentioned effects and interactions. However, before accepting the model, the residuals need to be analysed in order to confirm that the assumptions of normality and equality of variance are satisfied. The previous analysis indicates that significant effects (*) for the response number of completed parts are *A*, *B*, and the *AE*, *ABC*, and *BEF.* If this is true the estimated number of parts is given by equation 7.1 below.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_{15}X_1X_5+\beta_{123}X_1X_2X_3+\beta_{256}X_2X_5X_6 \tag{7.1}$$

Where

β_0 = average response

$\beta_{(1\ldots n)}$ = coefficients of the effect estimates

and $X_{1\ldots}X_6$ are coded variables taking on values between -1 and +1

Using the results of the response number of completed parts together with the equation above, residuals have been calculated. See appendix 12 for the related table of residuals.

A normal probability plot of the residuals in figure 7.2 confirms the normality assumption by displaying all the residuals lying along a straight line. In figure 7.3 the equality of variance assumption is confirmed by a plot of residuals versus the predicted number of completed parts, which displays a random spread of the data points.

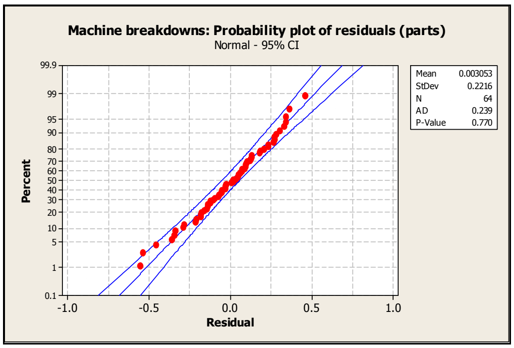

Figure 7.2 - Normal probability plot of the residuals for no. of parts; machine breakdowns

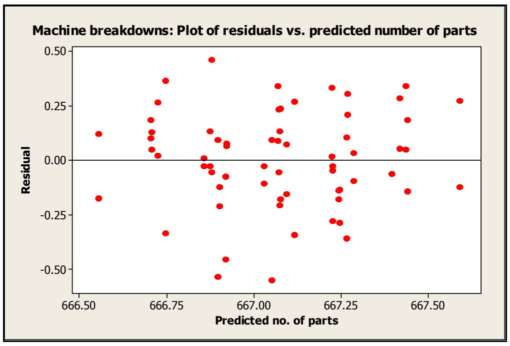

Figure 7.3 - Plot of residuals vs. predicted no. of parts; machine breakdowns

After ensuring that there are no serious violations of the model assumptions, it is possible to draw reliable conclusions. The significant design factors are plotted in figure 7.4. It can be noticed that the findings in the preliminary data analysis are correct since the factors *skill level of operators* and *buffer capacity* are the most significant when it comes to generating a higher throughput. The interactions between all the factors are plotted in figure 7.5.

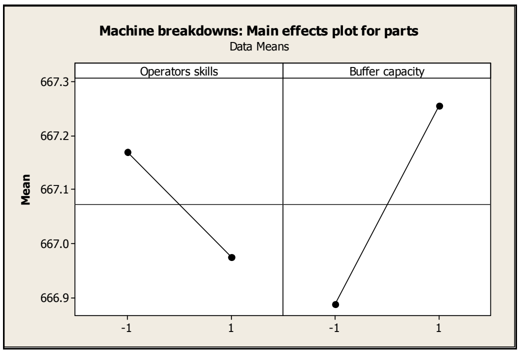

Figure 7.4 - Main effects plot for no. of parts; machine breakdowns

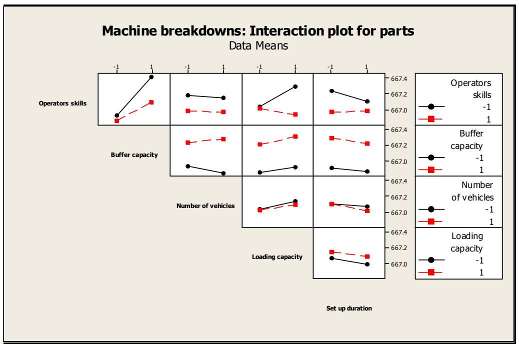

Figure 7.5 - Interaction plot for no. of parts; machine breakdowns

From figure 7.4 it can be concluded that, in order to maximize the number of completed parts, and if only these factors were considered, the skill level of operators needs to be kept at the lowest level, whereas the buffer capacity needs to be kept at the highest level. However, figure 7.5 indicates that because there are interacting factors, in order to maximize the number of parts it is also necessary to keep the loading capacity of AGVs at the highest level and the duration of machine set-ups at the lowest level. Appendix 11 shows that the skills of the operators together with the capacity of the buffers have a combined percent contribution to the response number of completed parts of nearly 40%. The other factors show very insignificant percent contributions.

7.2.2.2 Statistical analysis of the response manufacturing cost

Note that the procedure to identify significant factors and their levels is similar to the procedure described in the response number of completed parts; however, from this section on, supportive figures and tables have been included in the appendices section in order to present only a more informative narrative.

Due to the fact that the response variables cost and time have not had enough model replications to guarantee a normal distribution of the data (see appendix 9), the normality assumption is likely to be violated if results are used as they are. In order to avoid this, the original set of data has been transformed so as to reflect a more normal distribution in these two complementary responses. See appendix 13 for the calculation of the effect estimates and sum of squares for the response cost following a log transformation.

The normal plot of the effects in figure 7.6 shows that the significant effects are *A*, *B*, *C*, *F*, and the *AB*, *AC*, *AF*, *BC*, *BF*, *CF*, *DF*, *ABF*, *CDF*, and *BDF* interactions.

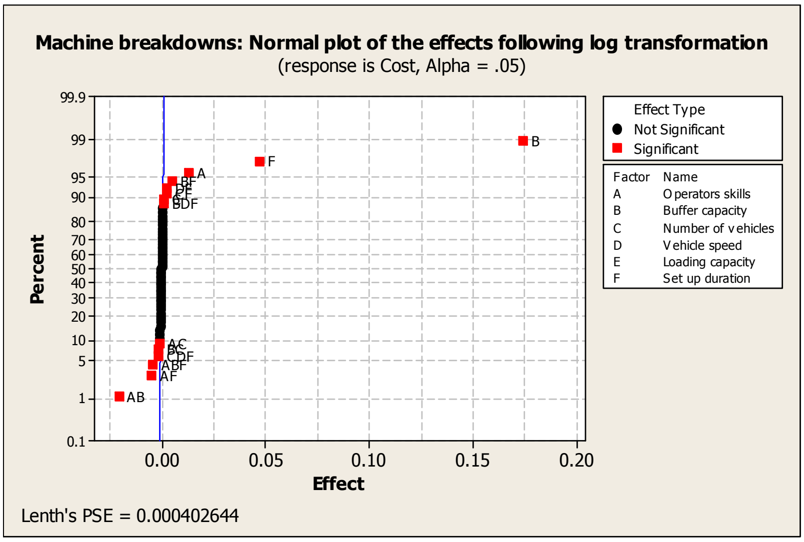

Figure 7.6 - Normal plot of the effects for cost; machine breakdowns

The significance of the effects is confirmed by the analysis of variance in appendix 14.

If the effects of the previously named factors and interactions are significant then the estimated cost is given by the equation 7.2.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_6X_6+\beta_{12}X_1X_2+\beta_{13}X_1X_3+\beta_{16}X_1X_6+\beta_{23}X_2X_3+ \beta_{26}X_2X_6+\beta_{36}X_3X_6+\beta_{46}X_4X_6+\beta_{126}X_1X_2X_6+\beta_{246}X_2X_4X_6+\beta_{346}X_3X_4X_6 \quad (7.2)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 15. Figures 7.7 and 7.8 show the main effect plot and interaction plot respectively.

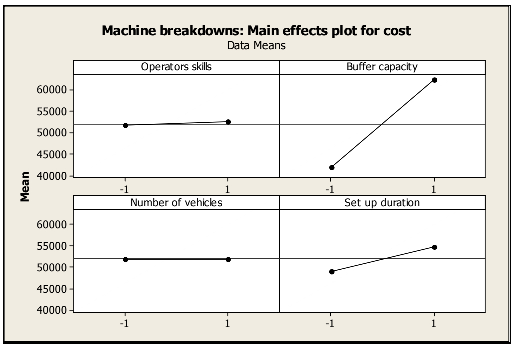

Figure 7.7 - Main effects plot for cost; machine breakdowns

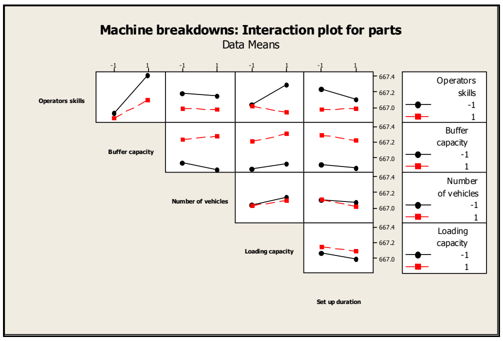

Figure 7.8 - Interaction plot for cost; machine breakdowns

From figure 7.7 it can be noticed that, in order to minimize the total cost, there are two significant factors, namely low buffer capacity and low duration of machine set-ups. According to appendix 13, the combined percent contribution to the response cost from these two factors is of approximately 97%. Additionally, figure 7.7 shows that low operator skills and high number of vehicles are important factors although their related effect on the response is hardly significant, i.e. a combined percent contribution of 0.5% according to appendix 13. Figure 7.8 shows no significant interaction with other factors.

7.2.2.3 Statistical analysis of the response time in the system

Refer to appendix 16 for the calculation of the effect estimates and sum of squares for the response average time in the system. The normal plot of the effects in figure 7.9 shows that the significant effects are *A*, *B*, *D*, *F*, and the *AB*, *AC*, *AD*, *AF*, *BF*, *CD*, *CF*, *DF*, *ABC*, *ABF*, *ACF*, and *CDF* interactions.

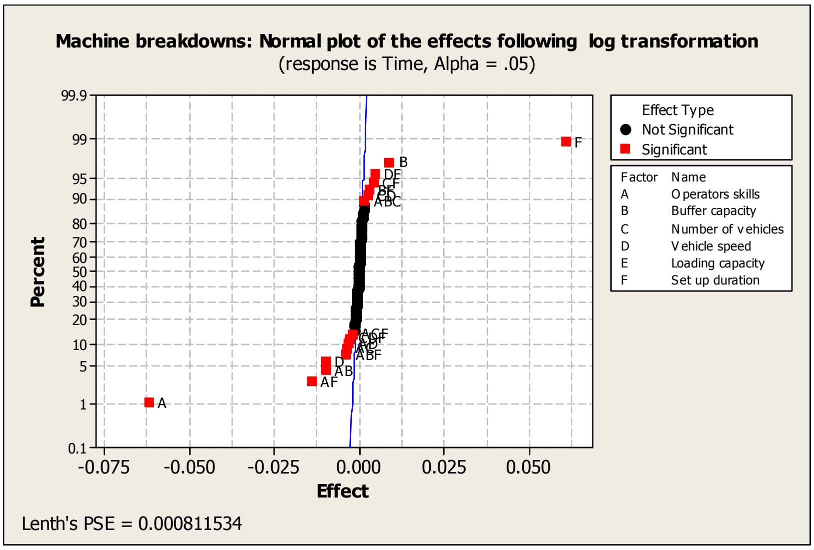

Figure 7.9 - Normal plot of the effects for time; machine breakdowns

The significance of the effects is confirmed by the analysis of variance in appendix 17. If the effects of the previously cited factors and interactions are significant, then the estimated time in the system is given by the equation 7.3.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_4X_4+\beta_6X_6+\beta_{12}X_1X_2+\beta_{13}X_1X_3+\beta_{14}X_1X_4+ \beta_{16}X_1X_6+\beta_{24}X_2X_4+\beta_{26}X_2X_6+\beta_{34}X_3X_4+\beta_{36}X_3X_6+\beta_{123}X_1X_2X_3+ \beta_{126}X_1X_2X_6+\beta_{136}X_1X_3X_6+\beta_{346}X_3X_4X_6 \qquad (7.3)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 18.

Figure 7.10 and 7.11 show the main effect plot and interaction plot respectively.

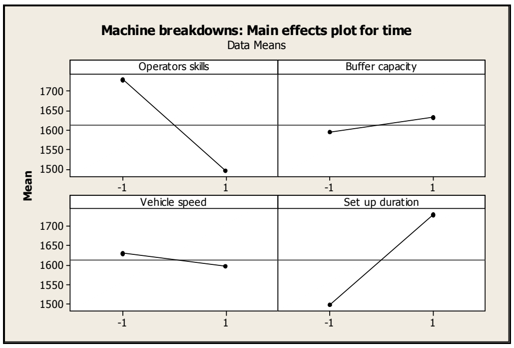

Figure 7.10 - Main effects plot for time; machine breakdowns

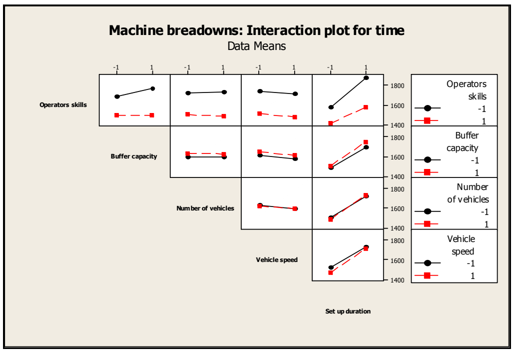

Figure 7.11 - Interaction plot for time; machine breakdowns

From figure 7.10 above, it can be concluded that in order to minimize the average time in the system, high operator skills and low set-up duration in machines are the most significant factors with a combined percent contribution of approximately 93% according to appendix 16. Even though figure 7.10 also shows low buffer capacity and high vehicle speed as main factors, it is important to mention that these are actually factors with little impact on the response time, each with a percent contribution of only 1% according to appendix 16.

7.3 FREQUENT OPERATOR UNAVAILABILITY SCENARIO

7.3.1 Experimental results and exploratory data analysis

The results of this experimental scenario are shown in table 7.3.

Table 7.3 - Experimental results; operator unavailability scenario

		EXPERIMENTAL FACTOR						Operator unavailability		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
1	*(1)*	-1	-1	-1	-1	-1	-1	663	1,486	$36,046
2	*a*	+1	-1	-1	-1	-1	-1	667	1,347	$39,450
3	*b*	-1	+1	-1	-1	-1	-1	666	1,584	$57,071
4	*ab*	+1	+1	-1	-1	-1	-1	667	1,348	$56,281
5	*c*	-1	-1	+1	-1	-1	-1	662	1,481	$36,254
6	*ac*	+1	-1	+1	-1	-1	-1	668	1,306	$39,405
7	*bc*	-1	+1	+1	-1	-1	-1	667	1,553	$56,595
8	*abc*	+1	+1	+1	-1	-1	-1	667	1,307	$55,626
9	*d*	-1	-1	-1	+1	-1	-1	663	1,421	$35,919

Table 7.3 (continued)

		EXPERIMENTAL FACTOR						Operator unavailability		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
10	*ad*	+1	-1	-1	+1	-1	-1	667	1,277	$39,322
11	*bd*	-1	+1	-1	+1	-1	-1	666	1,523	$56,325
12	*abd*	+1	+1	-1	+1	-1	-1	667	1,277	$55,385
13	*cd*	-1	-1	+1	+1	-1	-1	663	1,448	$36,120
14	*acd*	+1	-1	+1	+1	-1	-1	668	1,273	$39,307
15	*bcd*	-1	+1	+1	+1	-1	-1	667	1,521	$56,245
16	*abcd*	+1	+1	+1	+1	-1	-1	668	1,275	$55,309
17	*e*	-1	-1	-1	-1	+1	-1	665	1,478	$35,822
18	*ae*	+1	-1	-1	-1	+1	-1	666	1,375	$39,513
19	*be*	-1	+1	-1	-1	+1	-1	666	1,605	$57,354
20	*abe*	+1	+1	-1	-1	+1	-1	667	1,374	$56,614
21	*ce*	-1	-1	+1	-1	+1	-1	663	1,480	$36,235
22	*ace*	+1	-1	+1	-1	+1	-1	668	1,307	$39,359
23	*bce*	-1	+1	+1	-1	+1	-1	667	1,558	$56,604
24	*abce*	+1	+1	+1	-1	+1	-1	667	1,309	$55,601
25	*de*	-1	-1	-1	+1	+1	-1	663	1,423	$35,828
26	*ade*	+1	-1	-1	+1	+1	-1	667	1,281	$39,302
27	*bde*	-1	+1	-1	+1	+1	-1	666	1,528	$56,390
28	*abde*	+1	+1	-1	+1	+1	-1	668	1,280	$55,393
29	*cde*	-1	-1	+1	+1	+1	-1	663	1,449	$36,096
30	*acde*	+1	-1	+1	+1	+1	-1	667	1,277	$39,305
31	*bcde*	-1	+1	+1	+1	+1	-1	667	1,524	$56,256
32	*abcde*	+1	+1	+1	+1	+1	-1	668	1,277	$55,340
33	*f*	-1	-1	-1	-1	-1	+1	663	1,587	$37,954
34	*af*	+1	-1	-1	-1	-1	+1	667	1,412	$41,336
35	*bf*	-1	+1	-1	-1	-1	+1	666	1,719	$60,895
36	*abf*	+1	+1	-1	-1	-1	+1	667	1,410	$58,869
37	*cf*	-1	-1	+1	-1	-1	+1	663	1,626	$38,508
38	*acf*	+1	-1	+1	-1	-1	+1	667	1,391	$41,696
39	*bcf*	-1	+1	+1	-1	-1	+1	668	1,729	$61,305
40	*abcf*	+1	+1	+1	-1	-1	+1	667	1,391	$58,852
41	*df*	-1	-1	-1	+1	-1	+1	663	1,550	$37,827
42	*adf*	+1	-1	-1	+1	-1	+1	667	1,369	$41,669
43	*bdf*	-1	+1	-1	+1	-1	+1	667	1,707	$61,251
44	*abdf*	+1	+1	-1	+1	-1	+1	668	1,366	$58,806
45	*cdf*	-1	-1	+1	+1	-1	+1	664	1,603	$38,421
46	*acdf*	+1	-1	+1	+1	-1	+1	667	1,365	$41,631
47	*bcdf*	-1	+1	+1	+1	-1	+1	666	1,707	$61,221
48	*abcdf*	+1	+1	+1	+1	-1	+1	667	1,365	$58,708
49	*ef*	-1	-1	-1	-1	+1	+1	663	1,611	$38,316
50	*aef*	+1	-1	-1	-1	+1	+1	665	1,432	$41,146
51	*bef*	-1	+1	-1	-1	+1	+1	667	1,733	$60,983
52	*abef*	+1	+1	-1	-1	+1	+1	667	1,429	$58,972
53	*cef*	-1	-1	+1	-1	+1	+1	666	1,625	$38,522
54	*acef*	+1	-1	+1	-1	+1	+1	667	1,392	$41,636
55	*bcef*	-1	+1	+1	-1	+1	+1	667	1,738	$61,388
56	*abcef*	+1	+1	+1	-1	+1	+1	668	1,394	$58,922
57	*def*	-1	-1	-1	+1	+1	+1	664	1,546	$38,055
58	*adef*	+1	-1	-1	+1	+1	+1	667	1,370	$41,586
59	*bdef*	-1	+1	-1	+1	+1	+1	667	1,709	$61,264
60	*abdef*	+1	+1	-1	+1	+1	+1	667	1,368	$58,783

Table 7.3 (continued)

RUN	LABEL	EXPERIMENTAL FACTOR X1	X2	X3	X4	X5	X6	Operator unavailability Parts	Time	Cost
61	*cdef*	-1	-1	+1	+1	+1	+1	665	1,598	$38,484
62	*acdef*	+1	-1	+1	+1	+1	+1	668	1,367	$41,642
63	*bcdef*	-1	+1	+1	+1	+1	+1	666	1,703	$61,052
64	*abcdef*	+1	+1	+1	+1	+1	+1	668	1,367	$58,716

Please refer to appendix 19 for the exploratory data analysis of the results in terms of the three selected responses.

7.3.2 Statistical analysis of the results

7.3.2.1 Statistical analysis of the response number of completed parts

See appendix 20 for the calculation of the effect estimates and sum of squares for the response number of completed parts. The normal plot of the effects in figure 7.12 shows that the significant effects are *A*, *B*, *C*, and the *AB* and *AE* interactions.

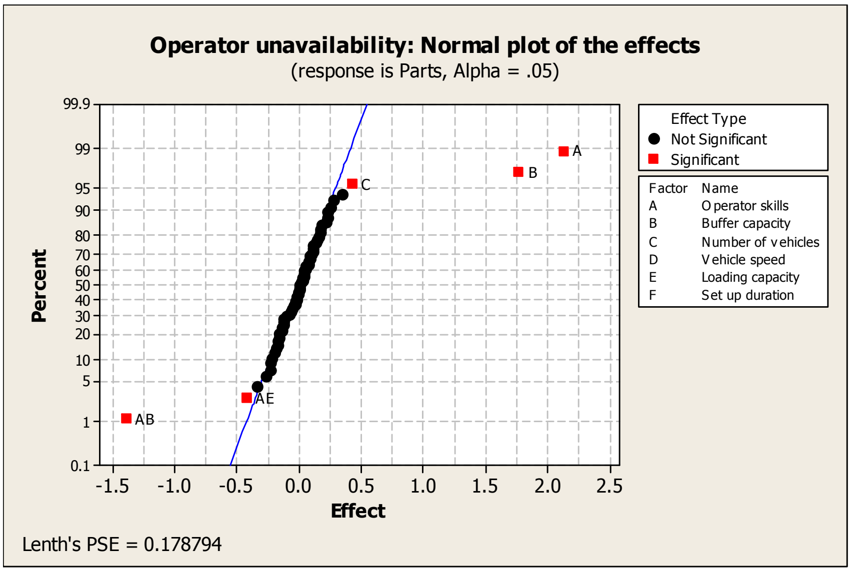

Figure 7.12 - Normal plot of the effects for no. of parts; operator unavailability scenario

The significance of the effects is confirmed by the analysis of variance in appendix 21.

If the effects of the previously named factors and interactions are significant, then the estimated number of completed parts is given by the equation 7.4.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_{12}X_1X_2+\beta_{15}X_1X_5 \qquad (7.4)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 22. Figure 7.13 and 7.14 show the main effect plot and interaction plot respectively.

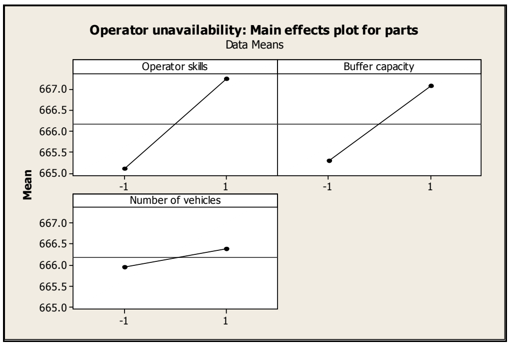

Figure 7.13 - Main effects plot for parts; operator unavailability

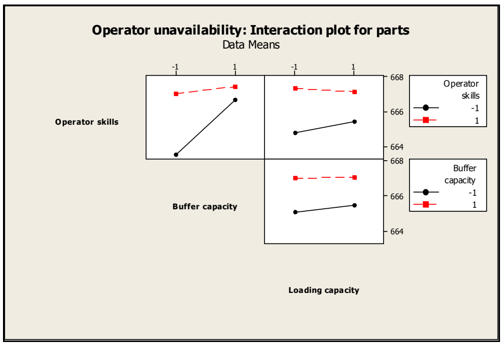

Figure 7.14 - Interaction plot for parts; operator unavailability

Figure 7.13 indicates that two factors are very significant for maximizing the number of completed parts; these are high operator skills and high buffer capacity. Both factors, according to appendix 20, have a combined percent contribution of approximately 68%. The same figure shows that a third slightly less significant factor is a high number of vehicles; however, its percent contribution to the response is only of 1.7% according to appendix 20. Figure 7.14 indicates that, due the existence of a significant interaction, it is important to keep loading capacity of AGVs at the lowest level.

7.3.2.2 Statistical analysis of the response manufacturing cost

See appendix 23 for the calculation of the effect estimates and sum of squares for the response manufacturing cost. The normal plot of the effects in figure 7.15 shows that the significant effects are *A, B*, *F*, and the *AB*, *AF*, and *BF* interactions.

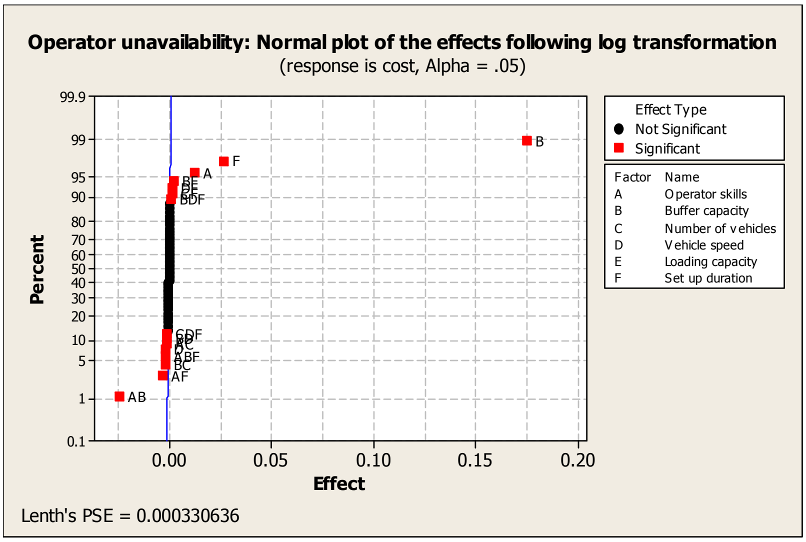

Figure 7.15 - Normal plot of the effects for cost; operator unavailability

The significance of effects is confirmed by the analysis of variance in appendix 24. If the effects of the previously named factors and interactions are significant, then the estimated cost is given by the equation 7.5.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_6X_6+\beta_{12}X_1X_2+\beta_{16}X_1X_6+\beta_{26}X_2X_6 \qquad (7.5)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 25. Figure 7.16 and 7.17 show the main effect plot and interaction plot respectively.

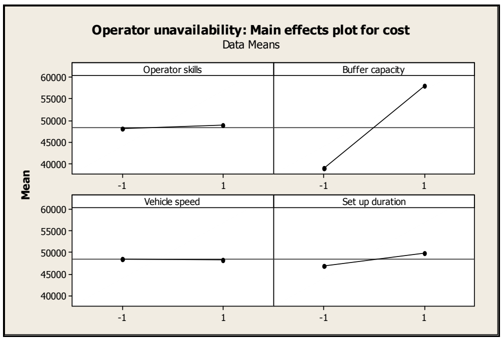

Figure 7.16 - Main effects plot for cost; operator unavailability

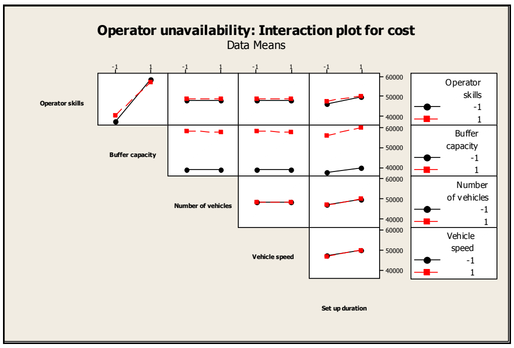

Figure 7.17 - Interaction plot for cost; operator unavailability

From figure 7.16 above, it can be noticed that, in order to minimize the average cost, there is only one highly influential factor, which is a low buffer capacity. As shown by appendix 23, such factor alone has a percent contribution of 95%. Low operator skills, high vehicle speed, and low duration of machine set-ups - having a combined percent contribution of 2.7% - cannot be considered very influential factors. Figure 7.17 shows no evidence of a significant interaction.

7.3.2.3 Statistical analysis of the response average time in the system

See appendix 26 for the calculation of the effect estimates and sum of squares for the response average time in the system. The normal plot of the effects in figure 7.18 shows that the significant effects are *A*, *B*, *D*, *F*, and the *AB*, *AC*, *AF*, *CD*, and *DF* interactions.

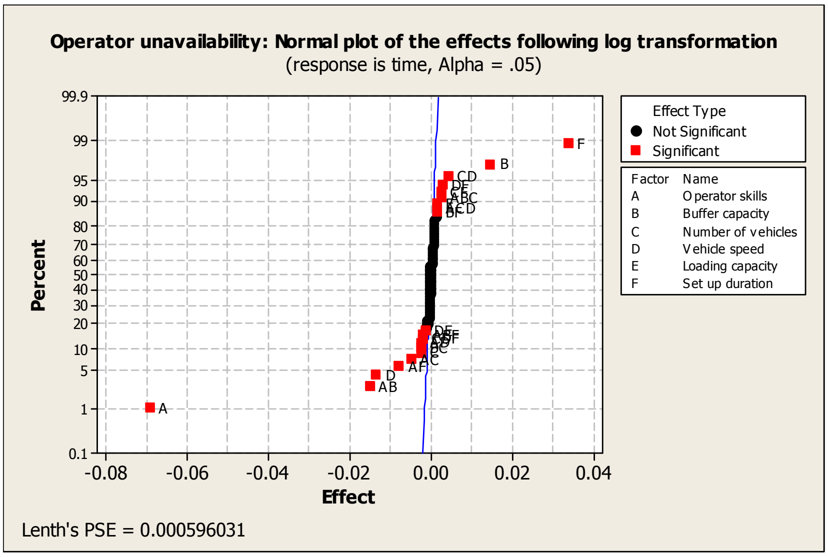

Figure 7.18 - Normal plot of the effects for time; operator unavailability

The significance of effects is confirmed by the analysis of variance in appendix 27. If the effects of the previously named factors and interactions are significant, then the estimated time in the system is given by the equation 7.6.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_4X_4+\beta_6X_6+\beta_{12}X_1X_2+\beta_{13}X_1X_3+\beta_{16}X_1X_6+\beta_{34}X_3X_4+\beta_{46}X_4X_6 \qquad (7.6)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 28. Figure 7.19 and 7.20 show the main effect plot and interaction plot respectively.

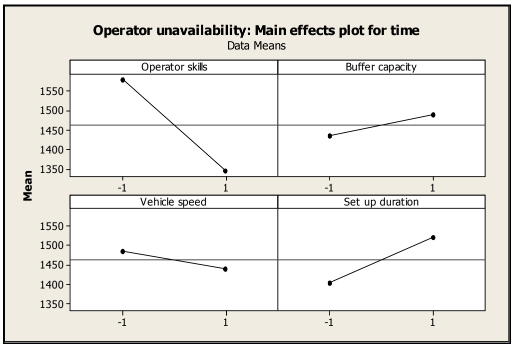

Figure 7.19 - Main effects plot for time; operator unavailability

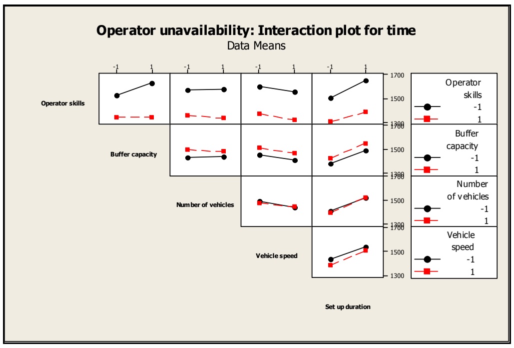

Figure 7.20 - Interaction plot for time; operator unavailability

From figure 7.19 it can be noticed that, the factors with a higher influence in minimizing time in the system are high operator skills together with low set-up machine duration; both factors with a combined percent contribution of approximately 88% according to appendix 26. Other less important influential factors are low buffer capacity and high vehicle speed with a combined percent contribution of approximately 6%. As shown by figure 7.20, no significant interaction involving other factors occurs.

7.4 IRREGULAR PATTERN OF RAW-MATERIAL ARRIVALS SCENARIO

7.4.1 Experimental results and exploratory data analysis

The results of this experimental scenario are shown in table 7.4.

Table 7.4 - Experimental results; irregular pattern of raw-material arrivals scenario

		EXPERIMENTAL FACTOR						Irregular arrivals		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
1	*(1)*	-1	-1	-1	-1	-1	-1	784	1,309	$39,644
2	*a*	+1	-1	-1	-1	-1	-1	779	1,261	$43,548
3	*b*	-1	+1	-1	-1	-1	-1	784	1,383	$60,479
4	*ab*	+1	+1	-1	-1	-1	-1	787	1,258	$62,158
5	*c*	-1	-1	+1	-1	-1	-1	787	1,279	$39,901
6	*ac*	+1	-1	+1	-1	-1	-1	788	1,161	$43,634
7	*bc*	-1	+1	+1	-1	-1	-1	787	1,312	$59,210
8	*abc*	+1	+1	+1	-1	-1	-1	788	1,161	$60,320
9	*d*	-1	-1	-1	+1	-1	-1	783	1,257	$39,686
10	*ad*	+1	-1	-1	+1	-1	-1	789	1,132	$43,622
11	*bd*	-1	+1	-1	+1	-1	-1	786	1,286	$58,996
12	*abd*	+1	+1	-1	+1	-1	-1	788	1,131	$60,041
13	*cd*	-1	-1	+1	+1	-1	-1	782	1,253	$39,599
14	*acd*	+1	-1	+1	+1	-1	-1	788	1,129	$43,573
15	*bcd*	-1	+1	+1	+1	-1	-1	786	1,280	$58,826
16	*abcd*	+1	+1	+1	+1	-1	-1	788	1,128	$59,971
17	*e*	-1	-1	-1	-1	+1	-1	781	1,327	$39,675
18	*ae*	+1	-1	-1	-1	+1	-1	778	1,261	$43,785
19	*be*	-1	+1	-1	-1	+1	-1	786	1,389	$60,728
20	*abe*	+1	+1	-1	-1	+1	-1	787	1,257	$62,125
21	*ce*	-1	-1	+1	-1	+1	-1	786	1,279	$39,862
22	*ace*	+1	-1	+1	-1	+1	-1	788	1,161	$43,626
23	*bce*	-1	+1	+1	-1	+1	-1	787	1,309	$59,167
24	*abce*	+1	+1	+1	-1	+1	-1	788	1,161	$60,321
25	*de*	-1	-1	-1	+1	+1	-1	782	1,249	$39,473
26	*ade*	+1	-1	-1	+1	+1	-1	789	1,132	$43,622
27	*bde*	-1	+1	-1	+1	+1	-1	786	1,287	$59,016
28	*abde*	+1	+1	-1	+1	+1	-1	788	1,131	$60,043
29	*cde*	-1	-1	+1	+1	+1	-1	783	1,252	$39,602
30	*acde*	+1	-1	+1	+1	+1	-1	788	1,129	$43,576
31	*bcde*	-1	+1	+1	+1	+1	-1	786	1,283	$58,885
32	*abcde*	+1	+1	+1	+1	+1	-1	788	1,128	$59,972
33	*f*	-1	-1	-1	-1	-1	+1	775	1,605	$44,222
34	*af*	+1	-1	-1	-1	-1	+1	776	1,378	$48,117
35	*bf*	-1	+1	-1	-1	-1	+1	786	1,636	$68,725
36	*abf*	+1	+1	-1	-1	-1	+1	788	1,369	$68,272
37	*cf*	-1	-1	+1	-1	-1	+1	777	1,627	$44,929
38	*acf*	+1	-1	+1	-1	-1	+1	786	1,343	$49,691
39	*bcf*	-1	+1	+1	-1	-1	+1	787	1,712	$71,075
40	*abcf*	+1	+1	+1	-1	-1	+1	788	1,342	$68,902
41	*df*	-1	-1	-1	+1	-1	+1	776	1,543	$44,030

Table 7.4 (continued)

		EXPERIMENTAL FACTOR						Irregular arrivals		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
42	*adf*	+1	-1	-1	+1	-1	+1	782	1,335	$49,553
43	*bdf*	-1	+1	-1	+1	-1	+1	786	1,689	$71,021
44	*abdf*	+1	+1	-1	+1	-1	+1	788	1,322	$68,943
45	*cdf*	-1	-1	+1	+1	-1	+1	776	1,605	$44,829
46	*acdf*	+1	-1	+1	+1	-1	+1	787	1,321	$49,842
47	*bcdf*	-1	+1	+1	+1	-1	+1	788	1,706	$71,302
48	*abcdf*	+1	+1	+1	+1	-1	+1	787	1,322	$68,947
49	*ef*	-1	-1	-1	-1	+1	+1	774	1,528	$43,192
50	*aef*	+1	-1	-1	-1	+1	+1	776	1,379	$48,070
51	*bef*	-1	+1	-1	-1	+1	+1	786	1,633	$68,637
52	*abef*	+1	+1	-1	-1	+1	+1	787	1,368	$68,214
53	*cef*	-1	-1	+1	-1	+1	+1	777	1,632	$44,924
54	*acef*	+1	-1	+1	-1	+1	+1	786	1,344	$49,694
55	*bcef*	-1	+1	+1	-1	+1	+1	789	1,711	$71,066
56	*abcef*	+1	+1	+1	-1	+1	+1	788	1,342	$68,901
57	*def*	-1	-1	-1	+1	+1	+1	774	1,540	$43,329
58	*adef*	+1	-1	-1	+1	+1	+1	783	1,331	$49,561
59	*bdef*	-1	+1	-1	+1	+1	+1	784	1,684	$70,689
60	*abdef*	+1	+1	-1	+1	+1	+1	788	1,322	$68,940
61	*cdef*	-1	-1	+1	+1	+1	+1	775	1,605	$44,813
62	*acdef*	+1	-1	+1	+1	+1	+1	787	1,322	$49,871
63	*bcdef*	-1	+1	+1	+1	+1	+1	788	1,697	$71,077
64	*abcdef*	+1	+1	+1	+1	+1	+1	787	1,322	$68,947

Please refer to appendix 29 for an exploratory data analysis of the results in terms of the three selected responses.

7.4.2 Statistical analysis of the results

7.4.2.1 Statistical analysis of the response number of completed parts

See appendix 30 for the calculation of the effect estimates and sum of squares for the response number of completed parts. The normal plot of the effects in figure 7.21 shows that the significant effects are *A*, *B*, *C*, *D*, *F*, and the *AB*, *AC*, *AD*, *AF*, *BC*, BD, *BF*, *CD*, *CF*, *ABC*, *ABD*, *ABF*, *BCD*, *ABCD*, and *ABCF* interactions.

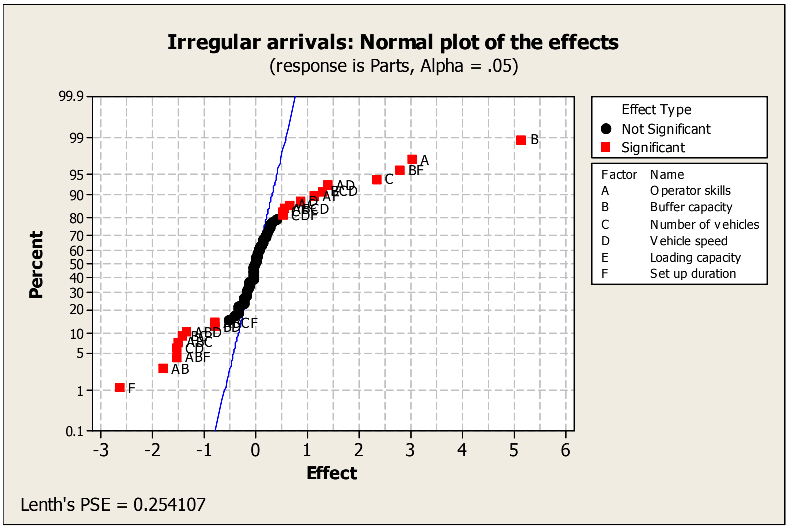

Figure 7.21 - Normal plot of the effects for no. of parts; irregular arrival of material

The significance of the effects is confirmed by the analysis of variance in appendix 31. If the effects of the previously named factors and interactions are significant, then the estimated number of completed parts is given by the equation 7.7.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_6X_6+\beta_{12}X_1X_2+\beta_{13}X_1X_3+ \quad (7.7)$$
$$\beta_{14}X_1X_4+\beta_{16}X_1X_6+\beta_{23}X_2X_3+\beta_{24}X_2X_4+\beta_{26}X_2X_6+\beta_{34}X_3X_4+\beta_{36}X_3X_6+$$
$$\beta_{123}X_1X_2X_3+\beta_{124}X_1X_2X_4+\beta_{126}X_1X_2X_6+\beta_{234}X_2X_3X_4+\beta_{1234}X_1X_2X_3X_4+\beta_{1236}X_1X_2X_3X_6$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 32. Figure 7.22 and 7.23 show the main effect plot and interaction plot respectively.

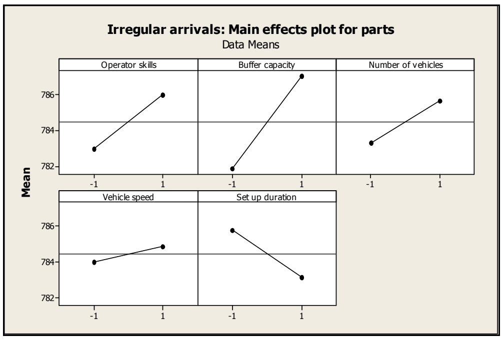

Figure 7.22 - Main effects plot for parts; irregular arrival of material

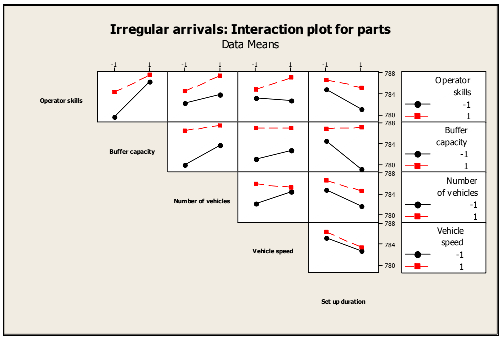

Figure 7.23 - Interaction plot for parts; irregular arrival of material

From figure 7.22 it can be concluded that, to maximize the number of parts, four very influential factors are high operators skills, high buffer capacity, high number of vehicles, and low duration of machine set-ups; all these with a combined percent contribution of approximately 61% according to appendix 30. Although high vehicle speed appears in figure 7.22 as a fifth main factor the true is that its contribution of only 1% could be considered negligible. Figure 7.23 shows no important interaction involving another factor.

7.4.2.2 Statistical analysis of the response manufacturing cost

See appendix 33 for the calculation of the effect estimates and sum of squares for the response manufacturing cost. The normal plot of the effects in figure 7.24 shows that the significant effects are *A*, *B*, *F*, and the *AB*, *AF*, *BF*, *CF*, *DF*, and *ABF* interactions.

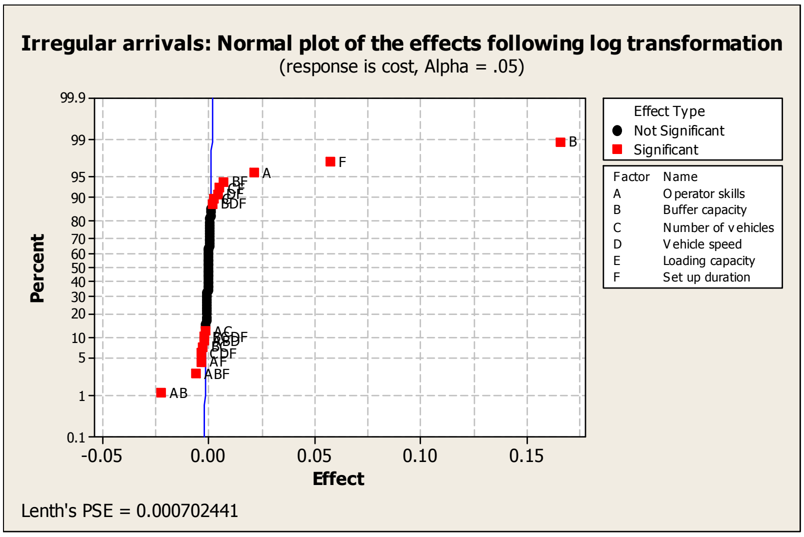

Figure 7.24 - Normal plot of the effects for cost; irregular arrival of material

The significance of the effects is confirmed by the analysis of variance in appendix 34. If the effects of the previously named factors and interactions are significant, then the estimated cost is given by the equation 7.8.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_6X_6+\beta_{12}X_1X_2+\beta_{16}X_1X_6+\beta_{26}X_2X_6+ \beta_{36}X_3X_6+\beta_{46}X_4X_6+\beta_{126}X_1X_2X_6 \quad (7.8)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 35. Figure 7.25 and 7.26 show the main effect plot and interaction plot respectively.

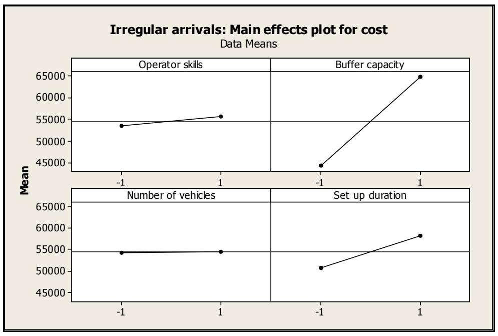

Figure 7.25 - Main effects plot for cost; irregular arrival of material

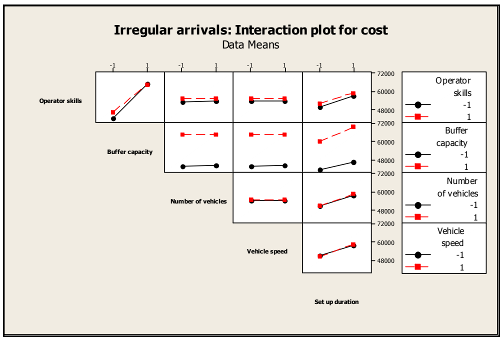

Figure 7.26 - Interaction plot for cost; irregular arrival of material

Figure 7.25 evidences the existence of two significant factors to minimize cost, namely low buffer capacity and low duration of machine set-ups. According to appendix 33, the combined percent contribution of these two factors is of approximately 96%. Although low operator skills and low number of vehicles appear also as important factors, their significance in achieving minimum cost is not important since their combined percent contribution is of approximately 1.5 %. Figure 7.26 shows no significant interaction in this response.

7.4.2.3 Statistical analysis of the response average time in the system

See appendix 36 for the calculation of the effect estimates and sum of squares for the response average time in the system. The normal plot of the effects in figure 7.27 shows that the significant effects are *A*, *B*, *C*, *D*, *F*, and the *AB*, *AC*, *AD*, *AF*, *CD*, *CF*, *DF*, and *CDF* interactions.

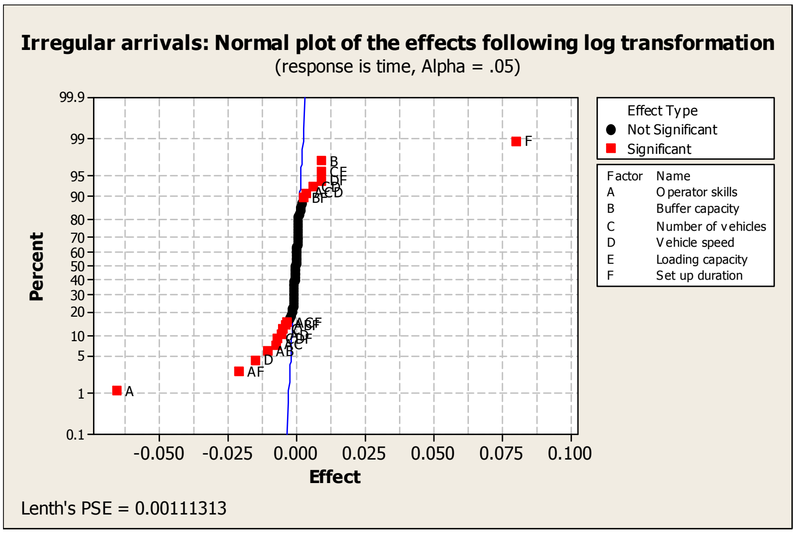

Figure 7.27 - Normal plot of the effects for time; irregular arrival of material

The significance of the effects is confirmed by the analysis of variance in appendix 37. If the effects of the previously named factors and interactions are significant, then the estimated time in the system is given by the equation 7.9.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_6X_6+\beta_{12}X_1X_2+\beta_{13}X_1X_3+ \beta_{14}X_1X_4+\beta_{16}X_1X_6+\beta_{34}X_3X_4+\beta_{36}X_3X_6+\beta_{46}X_4X_6+\beta_{346}X_3X_4X_6 \quad (7.9)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 38. Figure 7.28 and 7.29 show the main effect plot and interaction plot respectively.

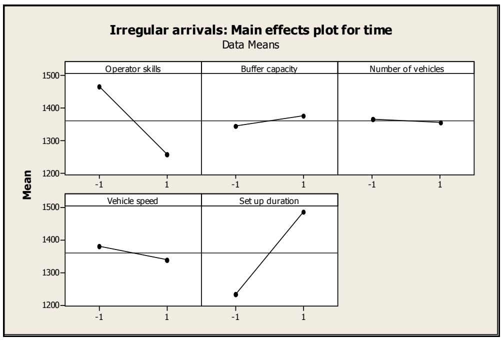

Figure 7.28 - Main effects plot for time; irregular arrival of material

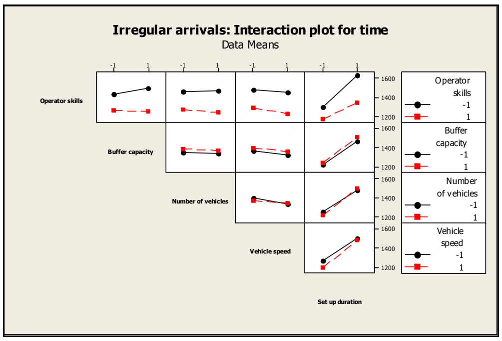

Figure 7.29 - Interaction plot for time; irregular arrival of material

According to the figure 7.28 above, high operator skills and low duration of machine set-ups are the most important factors to achieve a minimum time in the system, both factors with a combined percent contribution of approximately 89% according to appendix 36. Other much less important factors to achieve minimum time in the system are low buffer capacity, high number of vehicles, and high vehicle speed; all with a combined percent contribution of approximately 3%. Figure 7.29 confirms that there is not a significant interaction in this response.

7.5 INCREASED ARRIVALS OF RAW-MATERIAL SCENARIO

7.5.1 Experimental results and exploratory data analysis

The results of this experimental scenario are shown in table 7.5.

Table 7.5 - Experimental results, increased arrivals of material scenario

		EXPERIMENTAL FACTOR						Increased arrivals		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
1	*(1)*	-1	-1	-1	-1	-1	-1	993	1,082	$47,735
2	*a*	+1	-1	-1	-1	-1	-1	999	1,015	$52,376
3	*b*	-1	+1	-1	-1	-1	-1	1000	1,187	$71,279
4	*ab*	+1	+1	-1	-1	-1	-1	1000	1,027	$71,371
5	*c*	-1	-1	+1	-1	-1	-1	993	1,078	$48,019
6	*ac*	+1	-1	+1	-1	-1	-1	1000	956	$52,063
7	*bc*	-1	+1	+1	-1	-1	-1	999	1,132	$69,665
8	*abc*	+1	+1	+1	-1	-1	-1	1000	956	$69,397
9	*d*	-1	-1	-1	+1	-1	-1	996	1,053	$47,741
10	*ad*	+1	-1	-1	+1	-1	-1	1000	962	$52,094
11	*bd*	-1	+1	-1	+1	-1	-1	1000	1,132	$69,928
12	*abd*	+1	+1	-1	+1	-1	-1	1000	961	$69,692
13	*cd*	-1	-1	+1	+1	-1	-1	999	1,064	$48,130
14	*acd*	+1	-1	+1	+1	-1	-1	1000	938	$51,999
15	*bcd*	-1	+1	+1	+1	-1	-1	999	1,114	$69,389
16	*abcd*	+1	+1	+1	+1	-1	-1	1000	938	$69,121
17	*e*	-1	-1	-1	-1	+1	-1	992	1,123	$48,057
18	*ae*	+1	-1	-1	-1	+1	-1	998	1,045	$52,571
19	*be*	-1	+1	-1	-1	+1	-1	1000	1,210	$71,632
20	*abe*	+1	+1	-1	-1	+1	-1	1000	1,053	$71,848
21	*ce*	-1	-1	+1	-1	+1	-1	996	1,078	$48,047
22	*ace*	+1	-1	+1	-1	+1	-1	1000	960	$52,083
23	*bce*	-1	+1	+1	-1	+1	-1	1000	1,132	$69,568

Table 7.5 (continued)

		EXPERIMENTAL FACTOR						Increased arrivals		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
24	*abce*	+1	+1	+1	-1	+1	-1	1000	960	$69,427
25	*de*	-1	-1	-1	+1	+1	-1	994	1,070	$47,831
26	*ade*	+1	-1	-1	+1	+1	-1	999	982	$52,194
27	*bde*	-1	+1	-1	+1	+1	-1	999	1,147	$70,184
28	*abde*	+1	+1	-1	+1	+1	-1	1000	983	$70,156
29	*cde*	-1	-1	+1	+1	+1	-1	998	1,064	$48,104
30	*acde*	+1	-1	+1	+1	+1	-1	1000	941	$52,040
31	*bcde*	-1	+1	+1	+1	+1	-1	999	1,117	$69,385
32	*abcde*	+1	+1	+1	+1	+1	-1	1000	941	$69,174
33	*f*	-1	-1	-1	-1	-1	+1	993	1,340	$52,973
34	*af*	+1	-1	-1	-1	-1	+1	1000	1,121	$56,648
35	*bf*	-1	+1	-1	-1	-1	+1	996	1,456	$81,757
36	*abf*	+1	+1	-1	-1	-1	+1	1001	1,116	$76,959
37	*cf*	-1	-1	+1	-1	-1	+1	996	1,350	$53,563
38	*acf*	+1	-1	+1	-1	-1	+1	1000	1,095	$57,282
39	*bcf*	-1	+1	+1	-1	-1	+1	995	1,510	$83,750
40	*abcf*	+1	+1	+1	-1	-1	+1	1001	1,094	$77,152
41	*df*	-1	-1	-1	+1	-1	+1	994	1,321	$53,226
42	*adf*	+1	-1	-1	+1	-1	+1	1000	1,087	$56,843
43	*bdf*	-1	+1	-1	+1	-1	+1	996	1,510	$84,054
44	*abdf*	+1	+1	-1	+1	-1	+1	1000	1,079	$76,619
45	*cdf*	-1	-1	+1	+1	-1	+1	995	1,333	$53,449
46	*acdf*	+1	-1	+1	+1	-1	+1	1001	1,084	$57,464
47	*bcdf*	-1	+1	+1	+1	-1	+1	995	1,509	$84,016
48	*abcdf*	+1	+1	+1	+1	-1	+1	1001	1,085	$77,283
49	*ef*	-1	-1	-1	-1	+1	+1	996	1,299	$51,801
50	*aef*	+1	-1	-1	-1	+1	+1	998	1,129	$56,065
51	*bef*	-1	+1	-1	-1	+1	+1	997	1,421	$80,090
52	*abef*	+1	+1	-1	-1	+1	+1	1001	1,128	$76,590
53	*cef*	-1	-1	+1	-1	+1	+1	993	1,375	$53,586
54	*acef*	+1	-1	+1	-1	+1	+1	1000	1,096	$57,239
55	*bcef*	-1	+1	+1	-1	+1	+1	996	1,510	$83,624
56	*abcef*	+1	+1	+1	-1	+1	+1	1001	1,096	$77,097
57	*def*	-1	-1	-1	+1	+1	+1	993	1,248	$51,821
58	*adef*	+1	-1	-1	+1	+1	+1	998	1,086	$56,191
59	*bdef*	-1	+1	-1	+1	+1	+1	999	1,444	$81,618
60	*abdef*	+1	+1	-1	+1	+1	+1	1001	1,082	$76,170
61	*cdef*	-1	-1	+1	+1	+1	+1	994	1,372	$53,666
62	*acdef*	+1	-1	+1	+1	+1	+1	1001	1,087	$57,506
63	*bcdef*	-1	+1	+1	+1	+1	+1	995	1,510	$83,775
64	*abcdef*	+1	+1	+1	+1	+1	+1	1001	1,087	$77,250

Please refer to appendix 39 for an exploratory data analysis of the results in terms of the three selected responses.

7.5.2 Statistical analysis of the results

7.5.2.1 Statistical analysis of the response number of completed parts

See appendix 40 for the calculation of the effect estimates and sum of squares for the response number of completed parts. The normal plot of the effects in figure 7.30 shows that the significant effects are *A*, *B*, *F*, and the *AB*, *AF*, and *BC* interactions.

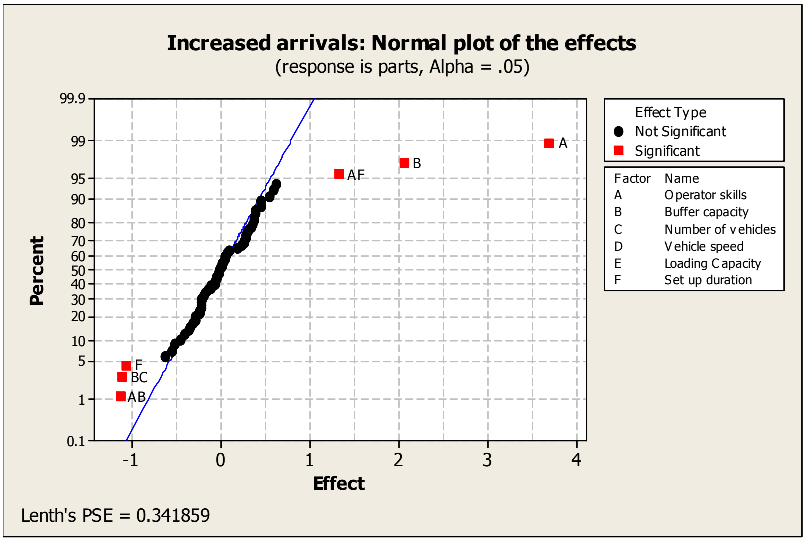

Figure 7.30 - Normal plot of the effects for no. of parts; increased arrival of material

The significance of the effects is confirmed by the analysis of variance in appendix 41. If the effects of the previously named factors and interactions are significant, then the estimated number of completed parts is given by the equation 7.10.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_6X_6+\beta_{12}X_1X_2+\beta_{16}X_1X_6+\beta_{23}X_2X_3 \qquad (7.10)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 42. Figure 7.31 and 7.32 show the main effect plot and interaction plot respectively.

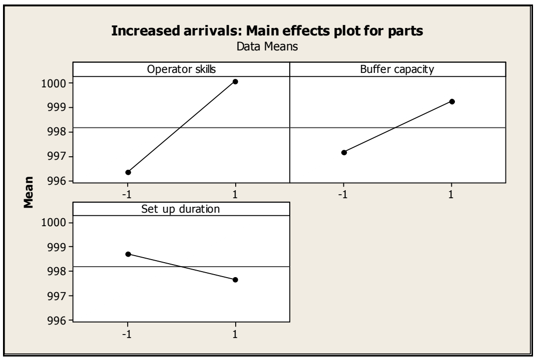

Figure 7.31 - Main effects plot for parts; increased arrival of material

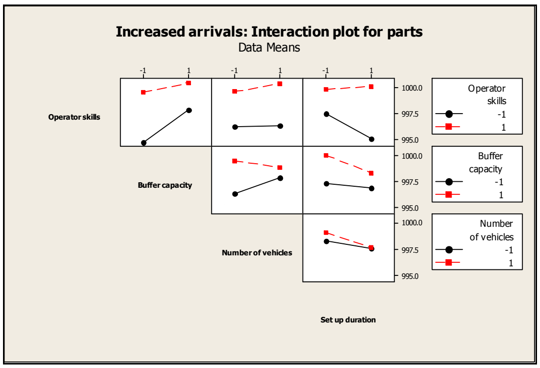

Figure 7.32 - Interaction plot for parts; increased arrival of material

Figure 7.31 indicates that there are three important factors in achieving the maximum number of completed parts; the most important factor is high operator skills, the following important factor is high buffer capacity, and the last important factor is low duration in machine set-ups. These three factors have a combined percent contribution of approximately 67% according to appendix 40. However, figure 7.31 shows that another important interacting factor to achieve maximum number of parts is a low number of AGVs in the system.

7.5.2.2 Statistical analysis of the response manufacturing cost

See appendix 43 for the calculation of the effect estimates and sum of squares for the response manufacturing cost. The normal plot of the effects in figure 7.33 shows that the significant effects are A, B, F, and the AB, AF, BF, and ABF interactions.

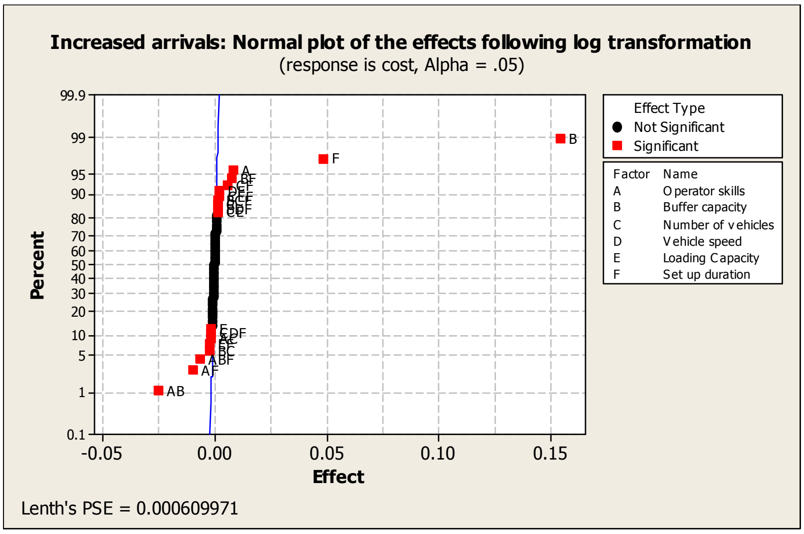

Figure 7.33 - Normal plot of the effects for cost; increased arrival of material

The significance of the effects is confirmed by the analysis of variance in appendix 44. If the effects of the previously named factors and interactions are significant, then the estimated cost is given by the equation 7.11.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_6X_6+\beta_{12}X_1X_2+\beta_{16}X_1X_6+\beta_{26}X_2X_6+\beta_{126}X_1X_2X_6 \qquad (7.11)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 45. Figure 7.34 and 7.35 show the main effect plot and interaction plot respectively.

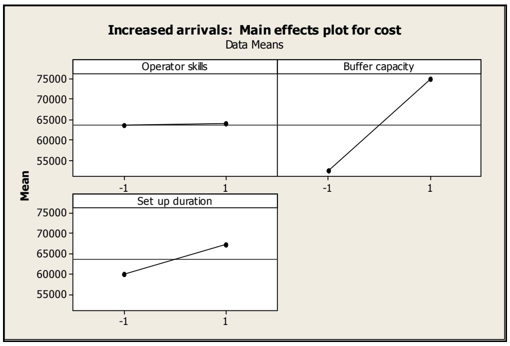

Figure 7.34 - Main effects plot for cost; increased arrival of material

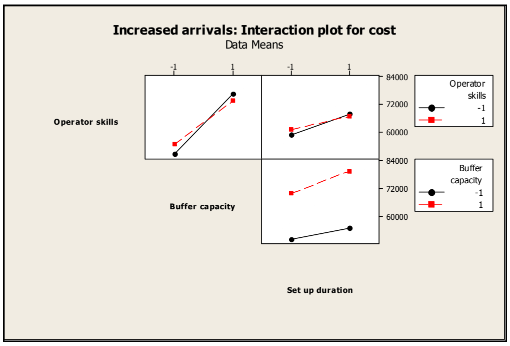

Figure 7.35 - Interaction plot for cost; increased arrival of material

As shown by figure 7.34, there are two important factors in terms of achieving minimum cost, namely low buffer capacity and low duration of machine set-ups; both factors with a combined percent contribution of approximately 97% according to appendix 43. Low operator skills, with a percent contribution not even close to 1%, can be considered negligible. As evidenced by figure 7.35, there is not significant interaction in the response cost.

7.5.2.3 Statistical analysis of the response average time in the system

See appendix 46 for the calculation of the effect estimates and sum of squares for the response average time in the system. The normal plot of the effects in figure 7.36 shows that the significant effects are *A*, *B*, *C*, *D*, *F*, and the *AB*, *AC*, *AF*, *CD*, *CF*, *DF*, and *ABF* interactions.

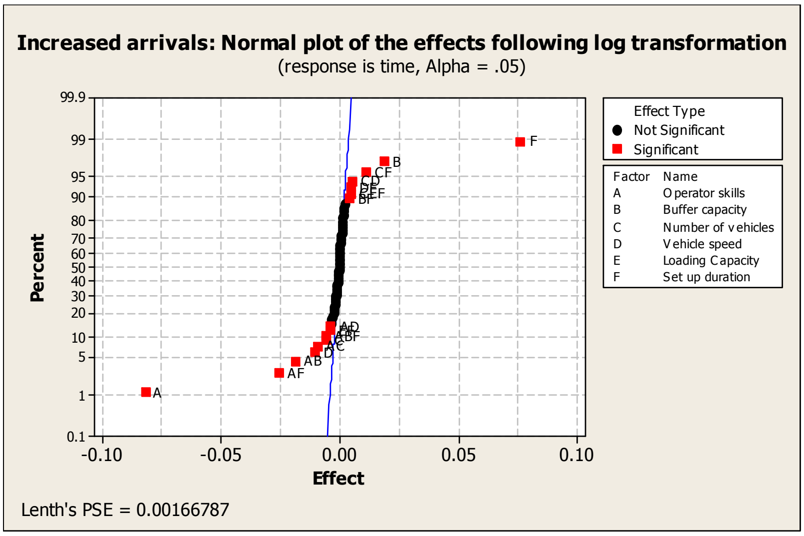

Figure 7.36 - Normal plot of the effects for time; increased arrival of material

The significance of the effects is confirmed by the analysis of variance in appendix 47. If the effects of the previously named factors and interactions are significant, then the estimated time in the system is given by the equation 7.12.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_6X_6+\beta_{12}X_1X_2+\beta_{13}X_1X_3+ \quad (7.12)$$
$$\beta_{16}X_1X_6+\beta_{34}X_3X_4+\beta_{36}X_3X_6+\beta_{46}X_4X_6+\beta_{126}X_1X_2X_6$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 48. Figure 7.37 and 7.38 show the main effect plot and interaction plot respectively.

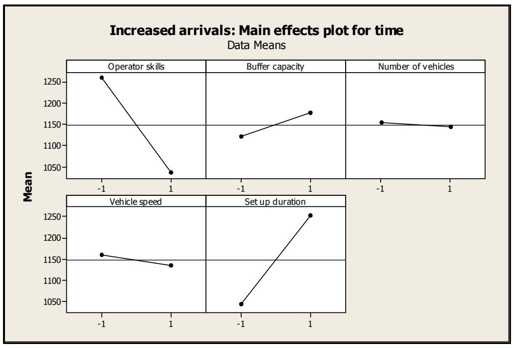

Figure 7.37 - Main effects plot for time; increased arrival of material

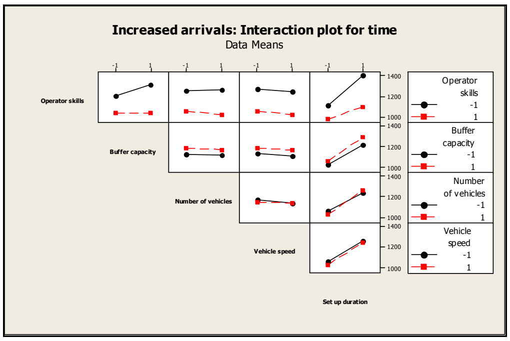

Figure 7.38 - Interaction plot for time; increased arrival of material

According to figure 7.37, the three most important factors for achieving minimum time in the system are, in order of importance, high operator skills, low duration of machine set-ups, and low buffer capacity; all with percent contributions of 46%, 40%, and 2% respectively (see appendix 46). Other two not very significant factors are high number of vehicles and high vehicle speed with a combined percent contribution of nearly 1%. Figure 7.38 reports no significant interaction in the response time in the system.

7.6 INCREASED PRODUCT VARIETY SCENARIO

7.6.1 Experimental results and exploratory data analysis

The results of this experimental scenario are shown in table 7.6.

Table 7.6 - Experimental results; increased product variety scenario

		EXPERIMENTAL FACTOR						Product variety		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
1	*(1)*	-1	-1	-1	-1	-1	-1	665	2,478	$42,582
2	*a*	+1	-1	-1	-1	-1	-1	665	2,369	$46,138
3	*b*	-1	+1	-1	-1	-1	-1	668	2,566	$59,845
4	*ab*	+1	+1	-1	-1	-1	-1	668	2,393	$61,699
5	*c*	-1	-1	+1	-1	-1	-1	667	2,476	$42,658
6	*ac*	+1	-1	+1	-1	-1	-1	667	2,319	$45,939
7	*bc*	-1	+1	+1	-1	-1	-1	667	2,525	$59,328
8	*abc*	+1	+1	+1	-1	-1	-1	667	2,318	$60,736
9	*d*	-1	-1	-1	+1	-1	-1	666	2,441	$42,436
10	*ad*	+1	-1	-1	+1	-1	-1	668	2,301	$45,890
11	*bd*	-1	+1	-1	+1	-1	-1	668	2,512	$59,363
12	*abd*	+1	+1	-1	+1	-1	-1	667	2,299	$60,637
13	*cd*	-1	-1	+1	+1	-1	-1	667	2,462	$42,643
14	*acd*	+1	-1	+1	+1	-1	-1	667	2,292	$45,839
15	*bcd*	-1	+1	+1	+1	-1	-1	668	2,504	$59,243
16	*abcd*	+1	+1	+1	+1	-1	-1	667	2,292	$60,531
17	*e*	-1	-1	-1	-1	+1	-1	663	2,526	$42,560
18	*ae*	+1	-1	-1	-1	+1	-1	666	2,390	$46,106
19	*be*	-1	+1	-1	-1	+1	-1	667	2,570	$59,714
20	*abe*	+1	+1	-1	-1	+1	-1	667	2,390	$61,421
21	*ce*	-1	-1	+1	-1	+1	-1	666	2,490	$42,645
22	*ace*	+1	-1	+1	-1	+1	-1	667	2,320	$45,887
23	*bce*	-1	+1	+1	-1	+1	-1	667	2,531	$59,322
24	*abce*	+1	+1	+1	-1	+1	-1	667	2,320	$60,697
25	*de*	-1	-1	-1	+1	+1	-1	663	2,471	$42,387
26	*ade*	+1	-1	-1	+1	+1	-1	667	2,310	$45,862
27	*bde*	-1	+1	-1	+1	+1	-1	668	2,514	$59,276
28	*abde*	+1	+1	-1	+1	+1	-1	667	2,310	$60,674
29	*cde*	-1	-1	+1	+1	+1	-1	666	2,469	$42,623
30	*acde*	+1	-1	+1	+1	+1	-1	668	2,294	$45,850
31	*bcde*	-1	+1	+1	+1	+1	-1	668	2,518	$59,345
32	*abcde*	+1	+1	+1	+1	+1	-1	667	2,293	$60,524
33	*f*	-1	-1	-1	-1	-1	+1	665	2,754	$46,822
34	*af*	+1	-1	-1	-1	-1	+1	665	2,488	$49,294
35	*bf*	-1	+1	-1	-1	-1	+1	665	2,918	$66,468
36	*abf*	+1	+1	-1	-1	-1	+1	668	2,497	$65,499
37	*cf*	-1	-1	+1	-1	-1	+1	664	2,808	$46,615
38	*acf*	+1	-1	+1	-1	-1	+1	668	2,460	$49,563
39	*bcf*	-1	+1	+1	-1	-1	+1	666	2,976	$67,385
40	*abcf*	+1	+1	+1	-1	-1	+1	668	2,457	$65,186
41	*df*	-1	-1	-1	+1	-1	+1	663	2,734	$45,930
42	*adf*	+1	-1	-1	+1	-1	+1	666	2,448	$49,347
43	*bdf*	-1	+1	-1	+1	-1	+1	664	2,976	$67,613
44	*abdf*	+1	+1	-1	+1	-1	+1	668	2,441	$65,193
45	*cdf*	-1	-1	+1	+1	-1	+1	663	2,816	$46,965
46	*acdf*	+1	-1	+1	+1	-1	+1	668	2,441	$49,647
47	*bcdf*	-1	+1	+1	+1	-1	+1	667	2,988	$67,752
48	*abcdf*	+1	+1	+1	+1	-1	+1	668	2,442	$65,328
49	*ef*	-1	-1	-1	-1	+1	+1	665	2,680	$45,432
50	*aef*	+1	-1	-1	-1	+1	+1	666	2,488	$48,822
51	*bef*	-1	+1	-1	-1	+1	+1	666	2,859	$65,249

Table 7.6 (continued)

		EXPERIMENTAL FACTOR						Product variety		
RUN	LABEL	X1	X2	X3	X4	X5	X6	Parts	Time	Cost
52	*abef*	+1	+1	-1	-1	+1	+1	668	2,477	$64,637
53	*cef*	-1	-1	+1	-1	+1	+1	664	2,811	$46,549
54	*acef*	+1	-1	+1	-1	+1	+1	668	2,460	$49,474
55	*bcef*	-1	+1	+1	-1	+1	+1	665	2,991	$67,505
56	*abcef*	+1	+1	+1	-1	+1	+1	668	2,460	$65,141
57	*def*	-1	-1	-1	+1	+1	+1	663	2,758	$45,958
58	*adef*	+1	-1	-1	+1	+1	+1	666	2,440	$49,079
59	*bdef*	-1	+1	-1	+1	+1	+1	666	2,926	$66,820
60	*abdef*	+1	+1	-1	+1	+1	+1	668	2,439	$64,917
61	*cdef*	-1	-1	+1	+1	+1	+1	664	2,828	$46,755
62	*acdef*	+1	-1	+1	+1	+1	+1	667	2,444	$49,517
63	*bcdef*	-1	+1	+1	+1	+1	+1	668	2,991	$67,763
64	*abcdef*	+1	+1	+1	+1	+1	+1	668	2,442	$65,204

Please refer to appendix 49 for an exploratory data analysis of the results in terms of the three selected responses.

7.6.2 Statistical analysis of the results

7.6.2.1 Statistical analysis of the response number of completed parts

See appendix 50 for the calculation of the effect estimates and sum of squares for the response number of completed parts. The normal plot of the effects in figure 7.39 shows that the significant effects are *A*, *B*, *C*, *F*, and the *AB*, *AF*, *BC*, *EF*, *ABC*, *ABD*, *ACD*, *AEF*, *BCF*, *BDF* and *ABCF* interactions.

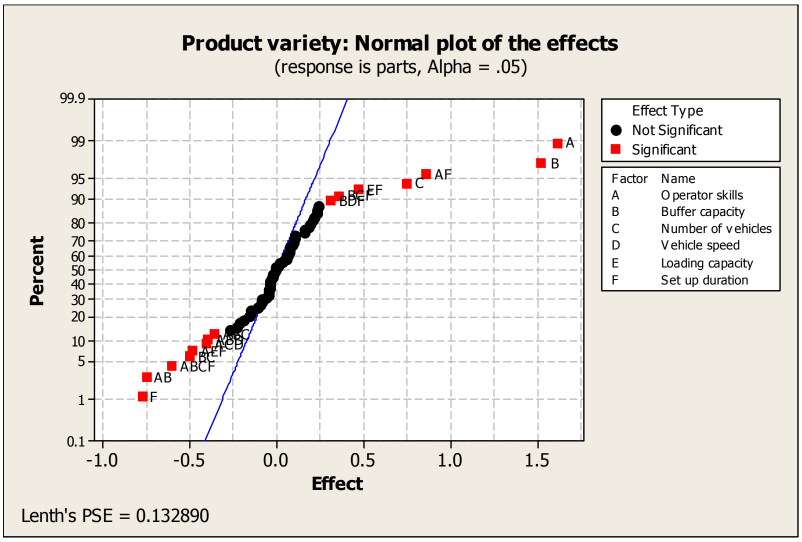

Figure 7.39 - Normal plot of the effects for no. of parts; increased product variety

The significance of the effects is confirmed by the analysis of variance in appendix 51. If the effects of the previously named factors and interactions are significant, then the estimated number of completed parts is given by the equation 7.13.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_6X_6+\beta_{12}X_1X_2+\beta_{16}X_1X_6+\beta_{23}X_2X_3+ \beta_{56}X_5X_6+\beta_{123}X_1X_2X_3+\beta_{124}X_1X_2X_4+\beta_{134}X_1X_3X_4+\beta_{156}X_1X_5X_6+ \beta_{236}X_2X_3X_6+\beta_{246}X_2X_4X_6+\beta_{1236}X_1X_2X_3X_6 \quad (7.13)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 52. Figure 7.40 and 7.41 show the main effect plot and interaction plot respectively.

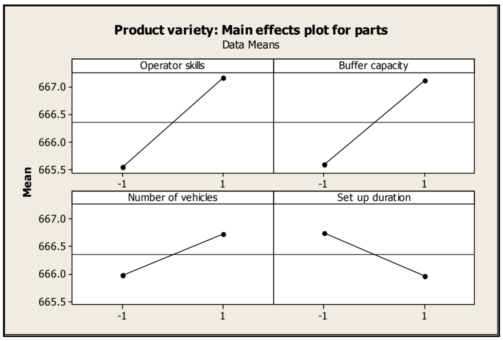

Figure 7.40 - Main effects plot for parts; increased product variety

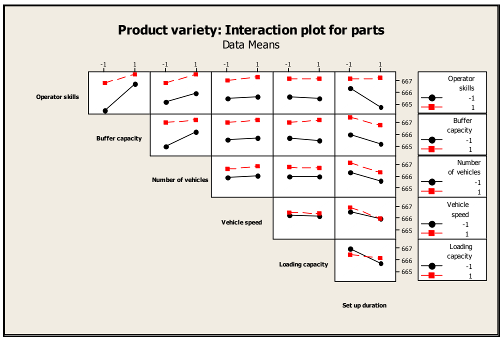

Figure 7.41 - Interaction plot for parts; increased product variety

Figure 7.40 indicates that to achieve a maximum number of completed parts, there are 4 significant factors that need to be considered. The first and most significant factor is 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 are low duration of machine set-ups and high number of vehicles with percent contributions of 6% and 5.6% respectively. See appendix 50 for percent contributions. No evidence of an important interaction is shown in figure 7.41.

7.6.2.2 Statistical analysis of the response manufacturing cost

See appendix 53 for the calculation of the effect estimates and sum of squares for the response manufacturing cost. The normal plot of the effects in figure 7.42 shows that the significant effects are *A*, *B*, *F*, and the *AB*, *AF*, *BF*, *CF*, and *ABF* interactions.

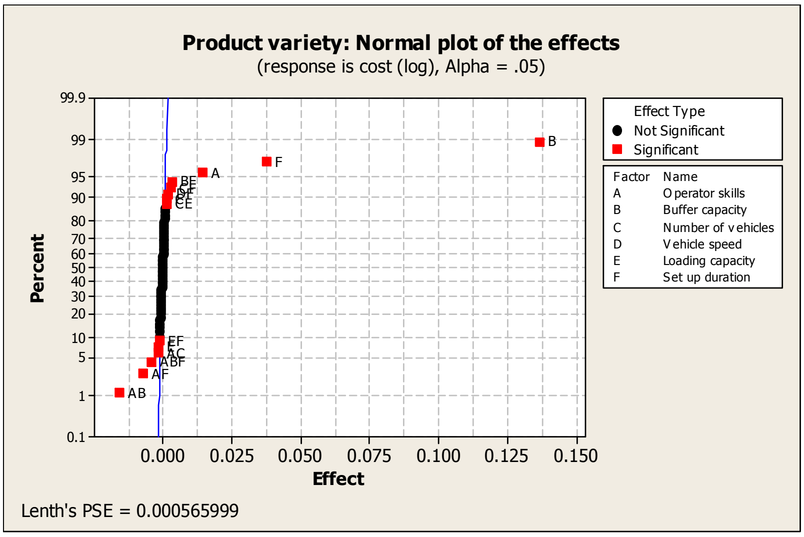

Figure 7.42 - Normal plot of the effects for cost; increased product variety

The significance of the effects is confirmed by the analysis of variance in appendix 54. If the effects of the previously named factors and interactions are significant, then the estimated cost is given by the equation 7.14.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_6X_6+\beta_{12}X_1X_2+\beta_{16}X_1X_6+\beta_{26}X_2X_6+\beta_{36}X_3X_6+\beta_{126}X_1X_2X_6 \qquad (7.14)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 55. Figure 7.43 and 7.44 show the main effect plot and interaction plot respectively.

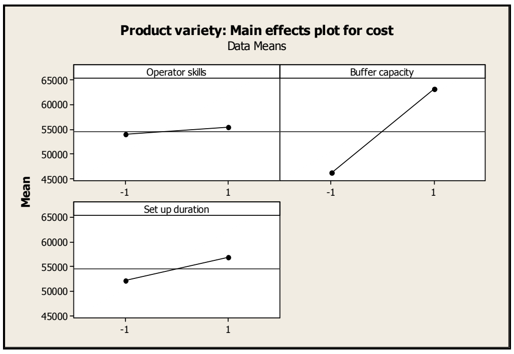

Figure 7.43 - Main effects plot for cost; increased product variety

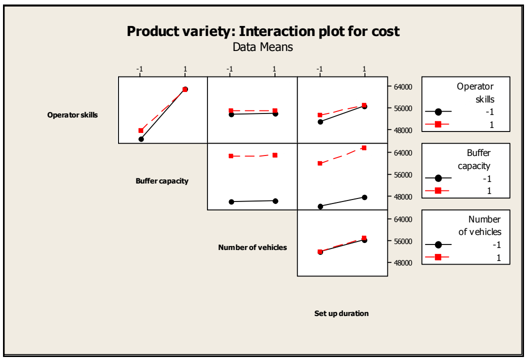

Figure 7.44 - Interaction plot for cost; increased product variety

As evidenced by figure 7.43, there are two main factors for achieving minimum cost; the most significant factor is low buffer capacity, and the second important factor is low duration of machine set-ups; both factors having a combined percent contribution of approximately 97% according to appendix 53. Figure 7.43 also shows low operator skills as a factor of minimum cost; however, its influence is little compared to the first to factors since its percent contribution is of only 1%. Figure 7.44 shows no significant interaction in the response cost.

7.6.2.3 Statistical analysis of the response average time in the system

See appendix 56 for the calculation of the effect estimates and sum of squares for the response average time in the system. The normal plot of the effects in figure 7.45 shows that the significant effects are *A*, *B*, *D*, *F*, and the *AB*, *AC*, *AD*, *AF*, *BF*, *CF*, *DF*, *EF*, *ABF*, *ACE*, and *CEF* interactions

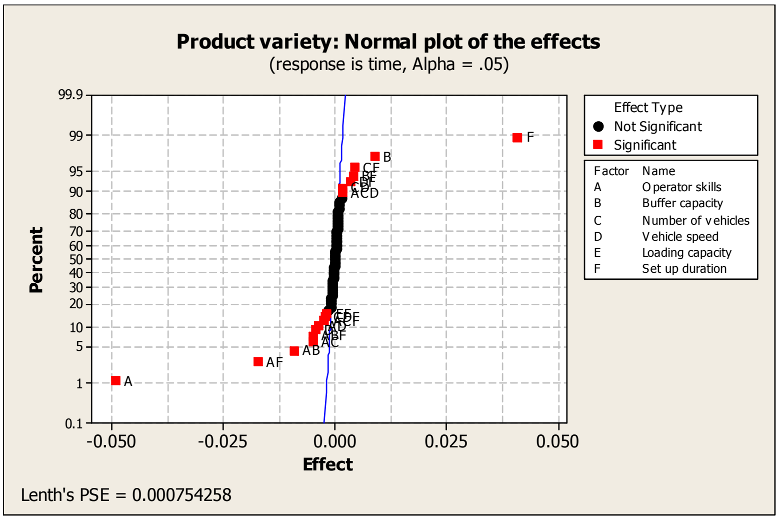

Figure 7.45 - Normal plot of the effects for time; increased product variety

The significance of the effects is confirmed by the analysis of variance in appendix 57. If the effects of the previously named factors and interactions are significant, then the estimated time in the system is given by the equation 7.15.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_4X_4+\beta_6X_6+\beta_{12}X_1X_2+\beta_{13}X_1X_3+\beta_{16}X_1X_6+\beta_{26}X_2X_6+\beta_{36}X_3X_6+\beta_{46}X_4X_6+\beta_{126}X_1X_2X_6 \qquad (7.15)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 58. Figure 7.46 and 7.47 show the main effect plot and interaction plot respectively.

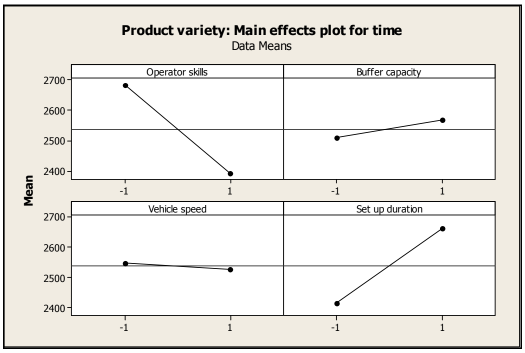

Figure 7.46 - Main effects plot for time; increased product variety

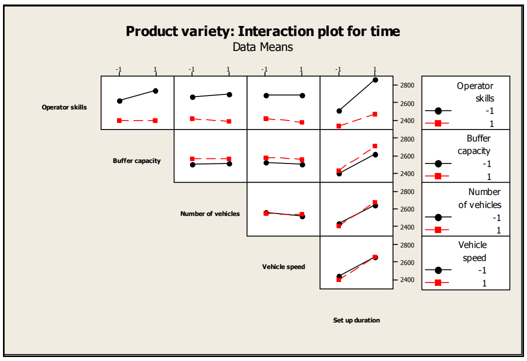

Figure 7.47 - Interaction plot for time; increased product variety

From the figure 7.46 above it can be concluded that, in order to minimize the average time in the system, the factors high operator skills and low duration of machine set-ups play a central role with a combined percent contribution of approximately 87% (see appendix 56); additionally, the factors low buffer capacity and high vehicle speed are also important factors although not as significant as the first two given that their combined percent contribution is slightly over 2%. Figure 7.47 shows no significant interaction in the response time in the system.

7.7 HIGH VARIATION IN PRODUCT MIX SCENARIO

7.7.1 Experimental results and exploratory data analysis

The results of this experimental scenario are shown in table 7.7.

Table 7.7 - Experimental results; high variation in product mix scenario

		EXPERIMENTAL FACTOR						**Variation in product mix**		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
1	*(1)*	-1	-1	-1	-1	-1	-1	668	1,411	$34,879
2	*a*	+1	-1	-1	-1	-1	-1	668	1,334	$37,402
3	*b*	-1	+1	-1	-1	-1	-1	668	1,452	$44,328
4	*ab*	+1	+1	-1	-1	-1	-1	668	1,337	$45,656
5	*c*	-1	-1	+1	-1	-1	-1	667	1,396	$34,884
6	*ac*	+1	-1	+1	-1	-1	-1	668	1,286	$37,196
7	*bc*	-1	+1	+1	-1	-1	-1	668	1,433	$44,176
8	*abc*	+1	+1	+1	-1	-1	-1	668	1,287	$45,153
9	*d*	-1	-1	-1	+1	-1	-1	668	1,354	$34,737
10	*ad*	+1	-1	-1	+1	-1	-1	668	1,259	$37,142
11	*bd*	-1	+1	-1	+1	-1	-1	669	1,396	$43,990
12	*abd*	+1	+1	-1	+1	-1	-1	668	1,258	$44,997
13	*cd*	-1	-1	+1	+1	-1	-1	668	1,371	$34,898
14	*acd*	+1	-1	+1	+1	-1	-1	668	1,256	$37,115
15	*bcd*	-1	+1	+1	+1	-1	-1	669	1,399	$43,995
16	*abcd*	+1	+1	+1	+1	-1	-1	668	1,256	$44,950
17	*e*	-1	-1	-1	-1	+1	-1	668	1,423	$34,902
18	*ae*	+1	-1	-1	-1	+1	-1	668	1,358	$37,466
19	*be*	-1	+1	-1	-1	+1	-1	668	1,469	$44,426
20	*abe*	+1	+1	-1	-1	+1	-1	668	1,356	$45,802
21	*ce*	-1	-1	+1	-1	+1	-1	667	1,395	$34,879
22	*ace*	+1	-1	+1	-1	+1	-1	668	1,290	$37,238
23	*bce*	-1	+1	+1	-1	+1	-1	668	1,434	$44,163

Table 7.7 (continued)

				EXPERIMENTAL FACTOR				Variation in product mix		
RUN	**LABEL**	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**Parts**	**Time**	**Cost**
24	*abce*	+1	+1	+1	-1	+1	-1	668	1,290	$45,157
25	*de*	-1	-1	-1	+1	+1	-1	667	1,355	$34,709
26	*ade*	+1	-1	-1	+1	+1	-1	668	1,262	$37,145
27	*bde*	-1	+1	-1	+1	+1	-1	668	1,398	$43,917
28	*abde*	+1	+1	-1	+1	+1	-1	668	1,261	$44,981
29	*cde*	-1	-1	+1	+1	+1	-1	668	1,370	$34,859
30	*acde*	+1	-1	+1	+1	+1	-1	668	1,257	$37,132
31	*bcde*	-1	+1	+1	+1	+1	-1	668	1,403	$43,987
32	*abcde*	+1	+1	+1	+1	+1	-1	668	1,258	$44,961
33	*f*	-1	-1	-1	-1	-1	+1	668	1,488	$36,139
34	*af*	+1	-1	-1	-1	-1	+1	669	1,378	$38,722
35	*bf*	-1	+1	-1	-1	-1	+1	668	1,529	$46,146
36	*abf*	+1	+1	-1	-1	-1	+1	668	1,377	$47,226
37	*cf*	-1	-1	+1	-1	-1	+1	669	1,496	$36,495
38	*acf*	+1	-1	+1	-1	-1	+1	668	1,351	$38,878
39	*bcf*	-1	+1	+1	-1	-1	+1	668	1,533	$46,417
40	*abcf*	+1	+1	+1	-1	-1	+1	668	1,350	$47,206
41	*df*	-1	-1	-1	+1	-1	+1	669	1,447	$36,323
42	*adf*	+1	-1	-1	+1	-1	+1	668	1,329	$38,844
43	*bdf*	-1	+1	-1	+1	-1	+1	669	1,503	$46,305
44	*abdf*	+1	+1	-1	+1	-1	+1	668	1,325	$47,097
45	*cdf*	-1	-1	+1	+1	-1	+1	669	1,469	$36,464
46	*acdf*	+1	-1	+1	+1	-1	+1	668	1,325	$38,817
47	*bcdf*	-1	+1	+1	+1	-1	+1	669	1,512	$46,362
48	*abcdf*	+1	+1	+1	+1	-1	+1	668	1,324	$47,076
49	*ef*	-1	-1	-1	-1	+1	+1	668	1,483	$35,942
50	*aef*	+1	-1	-1	-1	+1	+1	669	1,390	$38,595
51	*bef*	-1	+1	-1	-1	+1	+1	668	1,533	$45,983
52	*abef*	+1	+1	-1	-1	+1	+1	668	1,391	$47,148
53	*cef*	-1	-1	+1	-1	+1	+1	669	1,494	$36,443
54	*acef*	+1	-1	+1	-1	+1	+1	668	1,353	$38,864
55	*bcef*	-1	+1	+1	-1	+1	+1	669	1,539	$46,439
56	*abcef*	+1	+1	+1	-1	+1	+1	668	1,353	$47,181
57	*def*	-1	-1	-1	+1	+1	+1	669	1,443	$36,195
58	*adef*	+1	-1	-1	+1	+1	+1	668	1,330	$38,817
59	*bdef*	-1	+1	-1	+1	+1	+1	669	1,502	$46,216
60	*abdef*	+1	+1	-1	+1	+1	+1	668	1,328	$47,084
61	*cdef*	-1	-1	+1	+1	+1	+1	669	1,467	$36,389
62	*acdef*	+1	-1	+1	+1	+1	+1	668	1,326	$38,835
63	*bcdef*	-1	+1	+1	+1	+1	+1	668	1,514	$46,327
64	*abcdef*	+1	+1	+1	+1	+1	+1	668	1,326	$47,089

Please refer to appendix 59 for an exploratory data analysis of the results in terms of the three selected responses.

7.7.2 Statistical analysis of the results

7.7.2.1 Statistical analysis of the response number of completed parts

See appendix 60 for the calculation of the effect estimates and sum of squares for the response number of completed parts. The normal plot of the effects in figure 7.48 shows that the significant effects are *A*, *F*, and the *AB*, *AD*, *AF*, *BF*, *ABF*, *ACD*, *ADE*, and *ACDF* interactions.

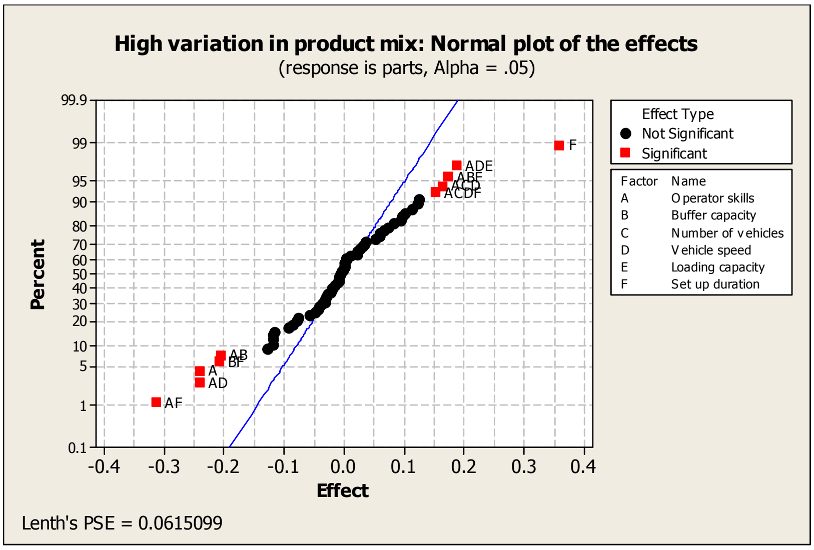

Figure 7.48 - Normal plot of the effects for no. of parts; high variation in product mix

The significance of the effects is confirmed by the analysis of variance in appendix 61. If the effects of the previously named factors and interactions are significant, then the estimated number of completed parts is given by the equation 7.16.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_6X_6+\beta_{12}X_1X_2+\beta_{14}X_1X_4+\beta_{16}X_1X_6+\beta_{26}X_2X_6+ \beta_{126}X_1X_2X_6+\beta_{134}X_1X_3X_4+\beta_{145}X_1X_4X_5+\beta_{1346}X_1X_3X_4X_6 \quad (7.16)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 62.

Figure 7.49 and 7.50 show the main effect plot and interaction plot respectively.

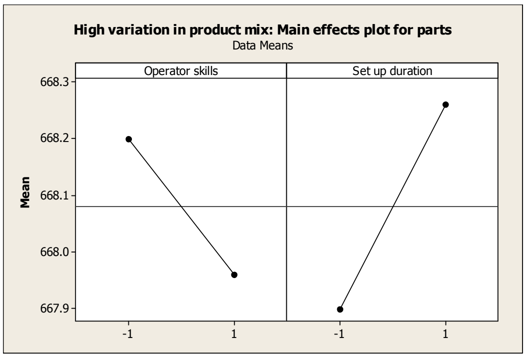

Figure 7.49 - Main effects plot for parts; high variation in product mix

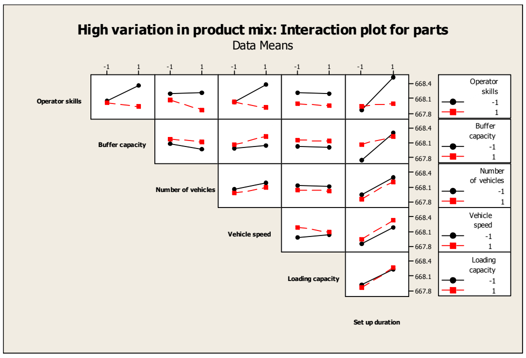

Figure 7.50 - Interaction plot for parts; high variation in product mix

According to figure 7.49, the only two significant factors for achieving a maximum number of completed parts are high duration of machine set-ups and low operator skills. According to appendix 60, these two factors have a combined percent contribution of approximately 24%. However, figure 7.50 shows the existence of an important factor interaction where high vehicle speed also determines a maximum number of parts.

7.7.2.2 Statistical analysis of the response manufacturing cost

See appendix 63 for the calculation of the effect estimates and sum of squares for the response manufacturing cost. The normal plot of the effects in figure 7.51 shows that the significant effects are *A*, *B*, *F*, and the *AB* interaction.

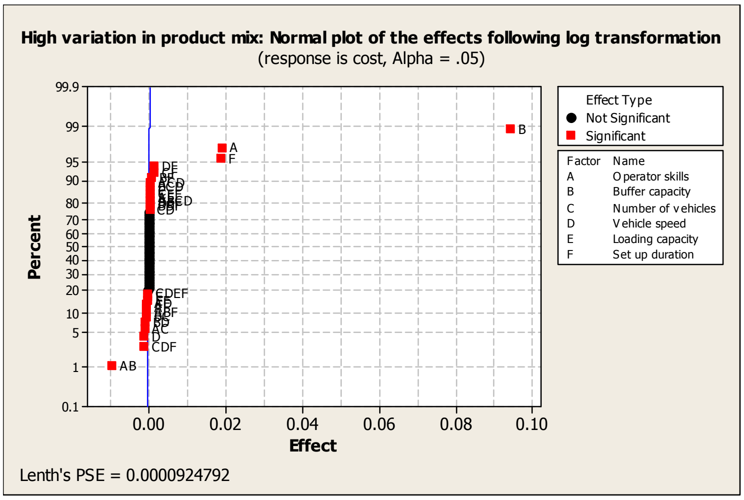

Figure 7.51 - Normal plot of the effects for cost; high variation in product mix

The significance of the effects is confirmed by the analysis of variance in appendix 64. If the effects of the previously named factors and interactions are significant, then the estimated cost is given by the equation 7.17.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_6X_6+\beta_{12}X_1X_2 \qquad (7.17)$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 65. Figure 7.52 and 7.53 show the main effect plot and interaction plot respectively.

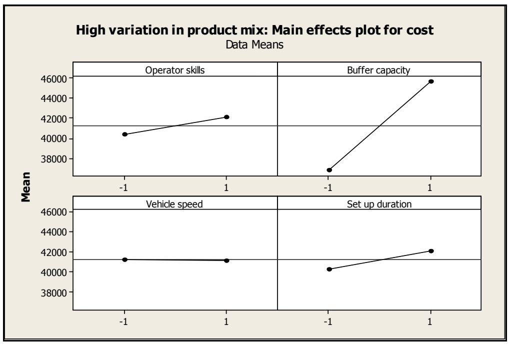

Figure 7.52 - Main effects plot for cost; high variation in product mix

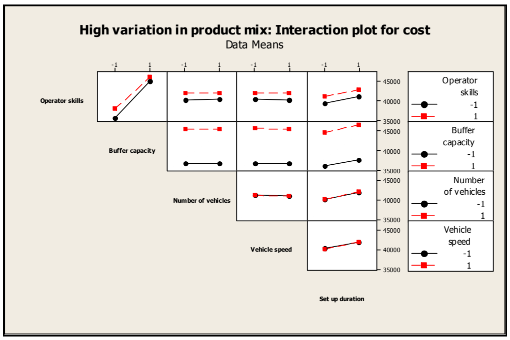

Figure 7.53 - Interaction plot for cost; high variation in product mix

Figure 7.52 shows the existence of four major factors in terms of minimum cost; low buffer capacity is the most influential factor with a percent contribution of 92% (see appendix 63); low operator skills and low duration of machine set-ups are factors with a significantly lower influence, each with a percent contribution of 4%; the influence of the fourth factor, high vehicle speed, can be considered negligible. In this response there is no evidence of a significant interaction as shown by figure 7.53.

7.7.2.3 Statistical analysis of the response average time in the system

See appendix 66 for the calculation of the effect estimates and sum of squares for the response average time in the system. The normal plot of the effects in figure 7.54 shows that the significant effects are *A*, *B*, *C*, *D*, *F*, and the *AB*, *CD*, *AC*, *AF*, *DF*, *AD*, *CF*, and, *CDF* interactions.

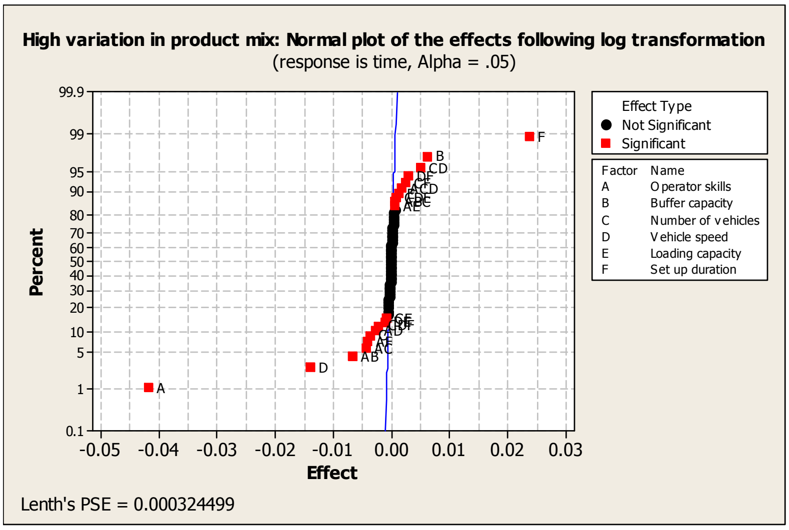

Figure 7.54 - Normal plot of the effects for time; high variation in product mix

The significance of the effects is confirmed by the analysis of variance in appendix 67.

If the effects of the previously named factors and interactions are significant, then the estimated time in the system is given by the equation 7.18.

$$\hat{y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_6X_6+\beta_{12}X_1X_2+\beta_{13}X_1X_3+ \quad (7.18)$$
$$\beta_{14}X_1X_4+\beta_{16}X_1X_6+\beta_{34}X_3X_4+\beta_{36}X_3X_6+\beta_{46}X_4X_6+\beta_{346}X_3X_4X_6$$

The validity of the initial assumption is confirmed by the plots of residuals in appendix 68. Figure 7.55 and 7.56 show the main effect plot and interaction plot respectively.

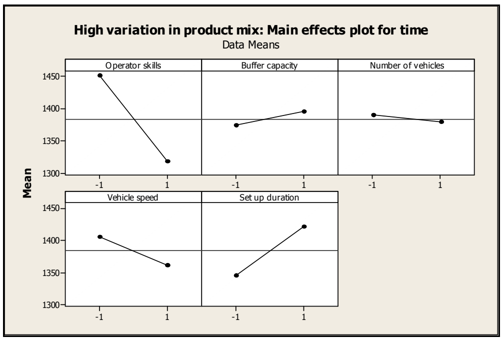

Figure 7.55 - Main effects plot for time; high variation in product mix

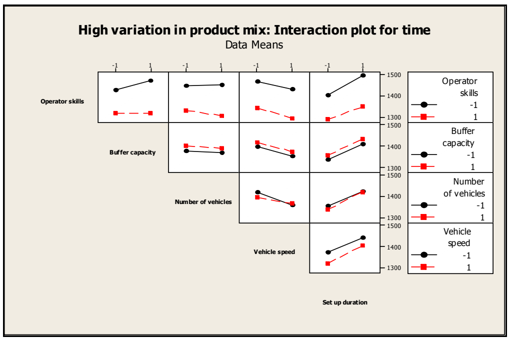

Figure 7.56 - Interaction plot for time; high variation in product mix

Although figure 7.55 shows the existence of five significant factors in terms of minimum time, only three factors are really significant for the response; those are high operator skills, low duration of machine set-ups, and high vehicle speed. According to appendix 66, these three factors have a combined percent contribution of approximately 92%. The other two factors, low buffer capacity and high number of vehicles, have only a little effect on the response given that their combined percent contribution is of approximately 1.5%. Figure 7.56 shows no evidence of an important interaction occurring in the response time in the system.

7.8 SUMMARY OF FINDINGS

After analysing the results of the experiments, the following findings emerged in this chapter:

1. **In a scenario characterized by frequent machine breakdowns:**
    - To maximize the number of completed parts, low skilled operators and high buffer capacity are the most influential factors. Additionally, high loading capacity in vehicles is also important.
    - To minimize total cost, low buffer capacity and low duration in machine set-ups are the most significant factors.
    - To minimize the average time in the system, high operator skills and low set-up duration in machines are the major factors.

2. **In a scenario characterized by frequent operator unavailability:**
    - To maximize the number of completed parts, highly skilled operators and high buffer capacity are the most important characteristics. In addition, low loading capacity in vehicles is essential.
    - To minimize total cost, low buffer capacity is the most influential factor.
    - To minimize the average time in the system, highly skilled operators, low set-up duration in machines and low buffer capacity are the most important factors. High vehicle speed is also a central factor.

3. **In a scenario characterized by an irregular pattern of material arrivals:**
    - To maximize the number of completed parts, highly skilled operators, high buffer capacity and low set-up duration in machines are the most significant factors. A high number of vehicles constitute a less influential but also important factor.
    - To minimize total cost, low buffer capacity and low-set up duration in machines are the only significant factors.
    - To minimize the average time in the system, highly skilled operators and low set-up duration in machines are the only significant factors.

4. **In a scenario characterized by increased arrivals of material:**
    - To maximize the number of completed parts, the most important factors are highly skilled operators, high buffer capacity and low duration of machine set-ups. A low number of AGVs is also an advantage.
    - To minimize total cost, only two factors are significant, namely low buffer capacity and low duration of machine set-ups.
    - To minimize the average time in the system, the most important factors are highly skilled operators, low duration of machine set-ups and low buffer capacity.

5. **In a scenario characterized by an increased product variety:**
    - To maximize the number of completed parts, there are 4 significant factors, namely high operator skills, high buffer capacity, low duration of machine set-ups and high number of AGVs.
    - To minimize total cost, the only two significant factors are low buffer capacity and low duration of machine set-ups.
    - To minimize the average time in the system, the factors high operator skills and low duration of machine set-ups play a central role.

6. **In a scenario characterized by high variation in product mix:**
    - To maximize the number of completed parts there are only two significant factors, namely high duration of machine set-ups and low operator skills. A high vehicle speed is also an advantage for achieving a higher throughput.
    - To minimize total cost, there are three major factors, namely low buffer capacity, low operator skills and low duration of machine set-ups.
    - To minimize the average time in the system, three factors are significant, namely high operator skills, low duration of machine set-ups and high vehicle speed.

7.9 CONCLUSION

In this chapter, the results of the experimental settings related to the different considered disturbance scenarios have been presented. A statistical approach has been considered to analyse the results of the experiments. First, the original data set has been analysed by means of an exploratory data analysis. Formal statistical examination involving analysis of variance has been performed subsequently in order to validate the assumptions under which experiments were conducted. Significant factors, suitable factor levels, and interactions contributing to optimal responses in each of the considered scenarios have been also identified. The following chapter will consider this information in order to provide an optimal solution to the investigated scenarios.

CHAPTER 8

OPTIMIZATION OF RESPONSE VARIABLES

8.1 INTRODUCTION

Many designed experiments involve determining conditions where the best parameters, for achieving the optimal response, are determined. In this chapter an optimal global solution, consisting of the best system's parameters in terms of performance, is provided for each of the models defined in chapter 7. Additionally, existing trade-offs between the different responses are identified by establishing a response prioritization criterion. The best response prioritization criterion is also identified by means of a composite desirability value. In a similar way to the previous chapter, in this chapter each of the scenarios is covered in an independent section.

8.2 OPTIMIZATION METHOD GENERALITIES

Generally, in experimental designs involving more than one response, it is difficult to achieve optimal settings of the design variables for all the responses at the same time. Providing that there are three different responses involved in the experimental design, Minitab's response optimization tool has been used to optimize the models defined in the previous chapter. Minitab's Response Optimizer is a command that searches for a combination of input variable levels that jointly optimize a set of responses by satisfying the requirements for each response in the set. According to the specifications of Minitab (1997), the optimization of a response is accomplished by the following steps:

1. Obtaining an individual desirability for each response.
2. Combining the individual desirabilities to obtain the combined or composite desirability.
3. Maximizing the composite desirability and identifying the optimal input variable setting.

Note that the optimization method is the same for each of the considered scenarios and therefore, in order to avoid repetition, further details on this method are provided only in the section related to the scenario of machine breakdowns.

8.3 FREQUENT MACHINE BREAKDOWNS SCENARIO

8.3.1 Model optimisation

In accordance with the last section, the first step to calculate an optimal solution via Minitab's Response Optimizer is to obtain an individual desirability for each response; this is achieved by specifying a response target together with a lower and/or upper bounds. The specified limits depend on the goal, i.e. if the goal was to minimize the response, then a target value and the upper bound would need to be specified; if the goal was to target the response, both lower and upper bounds would need to be provided; if the goal was to maximize the response, a target value and a lower bound would need to be determined. In addition, each of the response variables has been given a comparative importance value in order to indicate the weight of each response in comparison to the others.

According to what has been stated in the preceding paragraph and taking into consideration the experimental results for the machine breakdowns scenario presented in table 7.1 at the beginning of chapter 7, the optimization parameters have been defined for each of the response variables. Those parameters are shown in table 8.1.

Table 8.1 - Optimization parameters; machine breakdowns

	Response variable		
	Parts	**Cost**	**Time**
Goal	Maximize	Minimize	Minimize
Target	668	$38,000	1,380
Min	665	n/a	n/a
Max	n/a	$67,900	1,950

As it can be noticed from table 8.1, the target values for each of the response variables come from the minimum and maximum result values in table 7.1, depending on whether the goal is either model maximization or model minimization.

After Response Optimizer calculates an individual desirability for each response, the three desirability values are combined to provide a measure for the composite desirability of the multi-response system. This measure of composite desirability is the weighted geometric mean of the individual desirabilities for the responses. As a last step and in order to determine the numerical optimal solution, Response Optimizer employs a reduced gradient algorithm with multiple starting points that maximizes the composite desirability (1997).

Since there are three response variables involved in the original design, three optimal solutions, one for each prioritized response, are provided. An additional fourth optimal solution is also provided for the three responses sharing an equal priority. The optimal solutions are shown in table 8.2 below.

Table 8.2 - Global solutions; machine breakdowns

Design factors	Prioritized response			
	Parts	Cost	Time	Equal
Skill level of operators	-1	-1	1	1
Capacity of buffers	-1	-1	-1	-1
Number of AGVs	-1	-1	1	1
Speed of AGVs	-1	1	1	1
Loading capacity of AGVs	1	1	-1	-1
Duration of set ups	-1	-1	-1	-1

In table 8.2, the lowest level of the design factor is indicated by -1, whereas the highest level of the factor is indicated by 1. The predicted responses for each of the optimal solutions above are shown in table 8.3.

Table 8.3 - Predicted responses and desirability values; machine breakdowns

RESPONSE	FREQUENT MACHINE BREAKDOWNS							
	Number of parts		Cost		Time in the system		Equal priority	
	Predicted	Desirability	Predicted	Desirability	Predicted	Desirability	Predicted	Desirability
Parts	668	0.852	667	0.747	667	0.669	667	0.669
Cost	$ 38,194	0.993	$ 38,019	0.998	$ 41,210	0.860	$ 41,210	0.860
Time	1,589	0.592	1,538	0.686	1,387	0.988	1,387	0.988
Composite desirability		0.837		0.945		0.945		0.829

In table 8.3 columns refer to each prioritized response. Desirability values indicate how close the predicted responses (in rows) are to the parameters specified in table 8.1. Composite desirability values, in the same table, combine the individual desirability of each response into an overall value reflecting the relative importance of the responses. Therefore, and considering that desirability is measured on a 0 to 1 scale, time prioritization and cost prioritization are the best optimization criterion, both with a composite desirability value of 0.945. Figure 8.1 below, graphically shows the individual desirability values of each response.

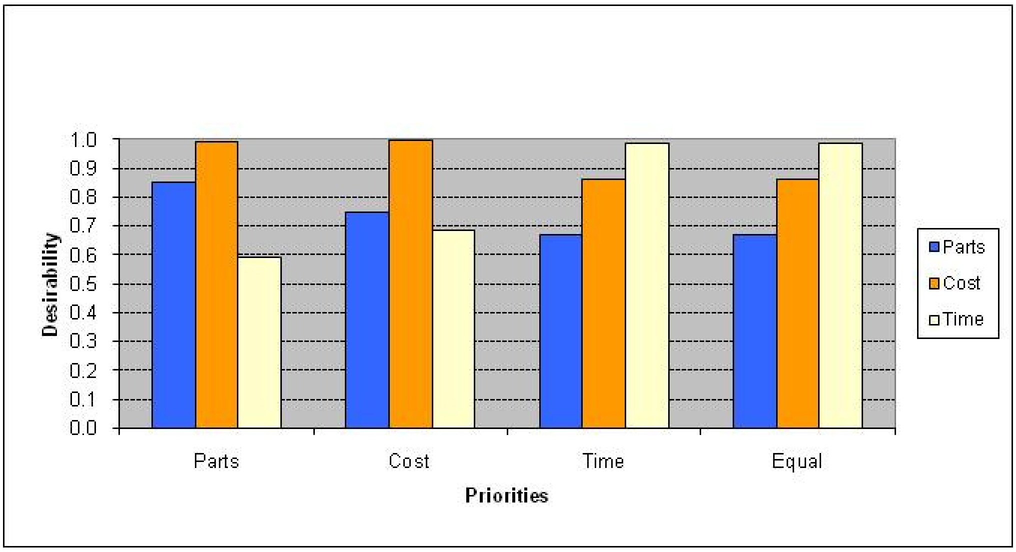

Figure 8.1 - Desirability of predicted responses vs. prioritized responses; machine breakdowns

From figure 8.1 it can be noticed that, if the number of parts was prioritized, a desirability value of 0.592 for the response time indicates that this would be most affected response. On the other hand, the response cost, with a desirability value of 0.993, would not be significantly affected. Alternatively, if cost was prioritized, there would be an important effect on the number of parts and a more serious effect on time. Furthermore, if time was prioritized, the more significant impact would occur in the number of parts and cost would experience a little decrease in its desirability value. Lastly, an equal prioritization of responses would mean acceptable desirabilities for the responses time and cost; however, the response number of parts would be significantly affected.

Figure 8.2 below, depicts the composite desirabilities of the prioritized responses.

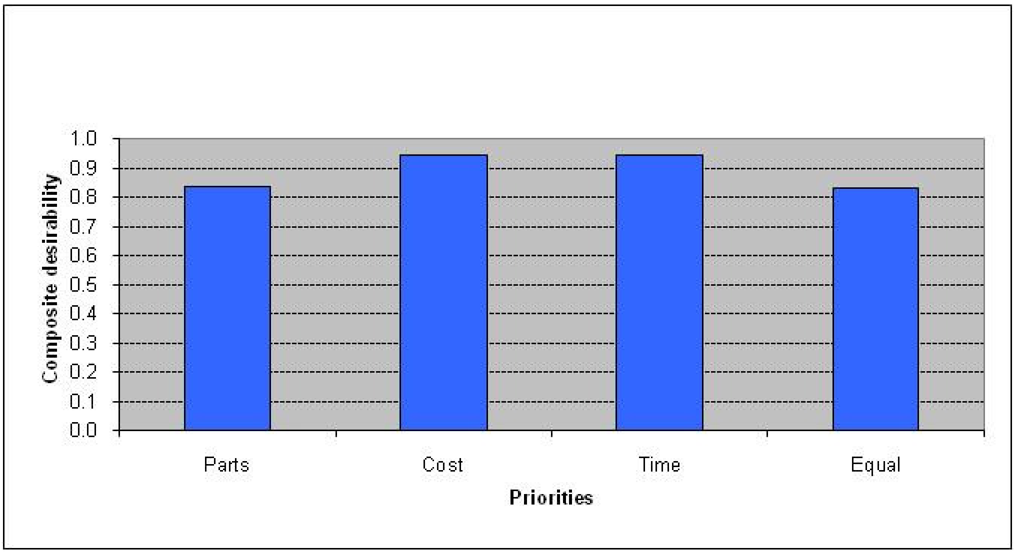

Figure 8.2 - Composite desirability vs. prioritized responses; machine breakdowns

As shown by figure 8.2, an equal prioritization of responses does not necessarily mean the highest composite desirability in this scenario. Under a machine breakdown scenario the highest composite desirability is achieved by prioritizing either cost or time.

8.4 FREQUENT OPERATOR UNAVAILABILITY SCENARIO

8.4.1 System optimisation

Table 8.4 shows the optimization parameters obtained from table 7.5 in chapter 7.

Table 8.4 - Optimization parameters; operator unavailability

	Response variable		
	Parts	**Cost**	**Time**
Goal	Maximize	Minimize	Minimize
Target	668	$35,800	1,270
Min	662	n/a	n/a
Max	n/a	$61,300	1,730

Table 8.5 shows the global solutions for each prioritized response.

Table 8.5 - Global solutions; operator unavailability

Design factors	Prioritized response			
	Parts	**Cost**	**Time**	**Equal**
Skill level of operators	1	-1	1	1
Capacity of buffers	-1	-1	-1	-1
Number of AGVs	1	-1	1	1
Speed of AGVs	1	-1	1	1
Loading capacity of AGVs	-1	1	-1	-1
Duration of set ups	-1	-1	-1	-1

Table 8.6 shows the predicted responses for each of the given global solutions above.

Table 8.6 - Predicted responses and desirability values; operator unavailability

RESPONSE	**FREQUENT OPERATOR UNAVAILABILITY**							
	Number of parts		**Cost**		**Time in the system**		**Equal priority**	
	Predicted	**Desirability**	**Predicted**	**Desirability**	**Predicted**	**Desirability**	**Predicted**	**Desirability**
Parts	668	0.962	665	0.492	668	0.962	668	0.962
Cost	$ 39,264	0.815	$ 35,810	0.983	$ 39,264	0.815	$ 39,264	0.815
Time	1,274	0.965	1,479	0.503	1,274	0.965	1,274	0.965
Composite desirability		0.949		0.877		0.951		0.911

Individual desirability values are plotted in figure 8.3 in order to identify the trade-offs between prioritized responses. Thus, if the number of parts was prioritized, the variable cost would be slightly affected, whereas the effect on time would be much less noticeable. The prioritization of cost would seriously affect the other two responses by decreasing their desirability values to around 0.5. The prioritization of time and an equal prioritization of responses would both lead to similar results to those obtained under the prioritization of the response number of parts.

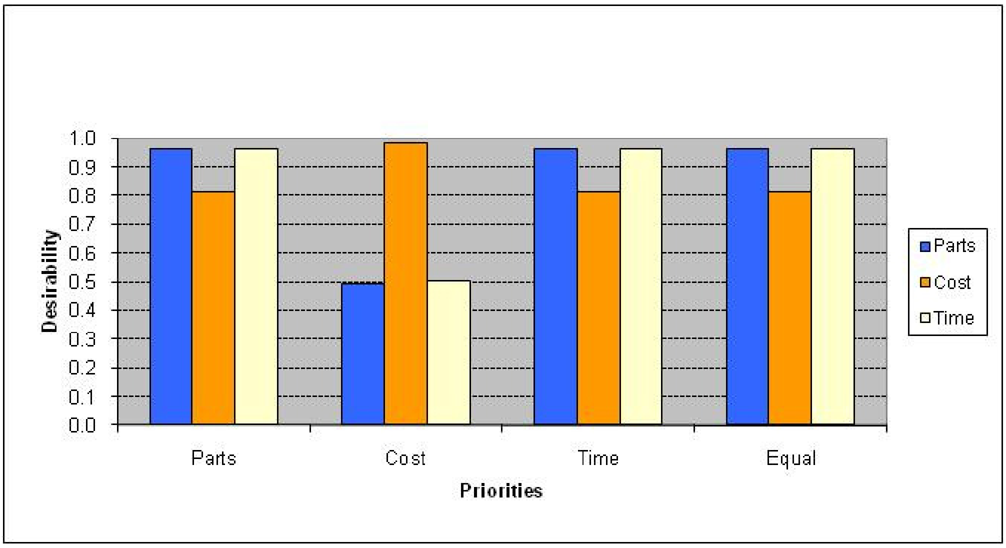

Figure 8.3 - Desirability of predicted responses vs. prioritized responses; operator unavailability

Composite desirability values are plotted in figure 8.4 in order to easily identify the best and worst response prioritization criteria.

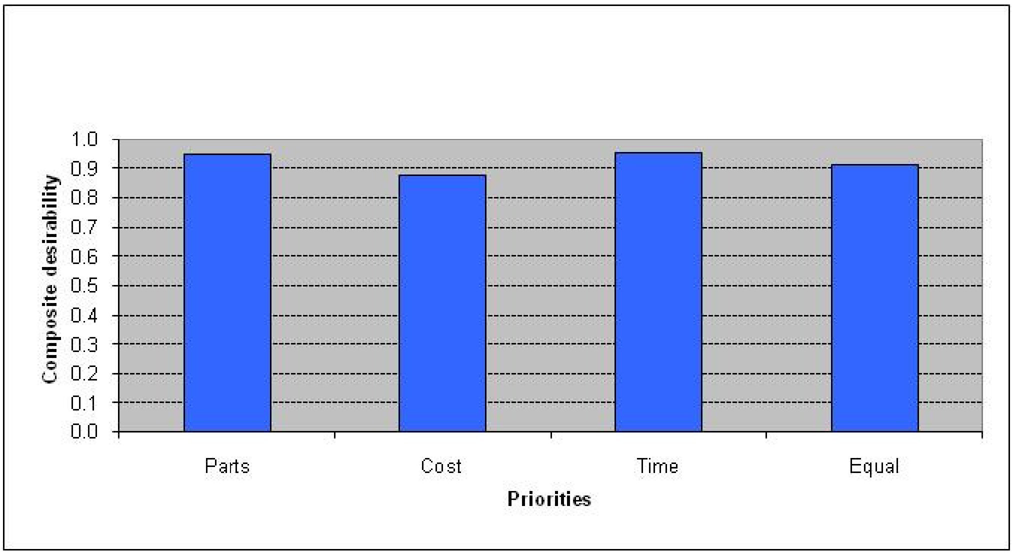

Figure 8.4 - Composite desirability vs. prioritized responses; operator unavailability

Figure 8.4 indicates that the highest composite desirability value is achieved when time is prioritized. Besides, figure 8.4 also confirms that, under an operator unavailability scenario, cost prioritization exhibits the lowest composite desirability.

8.5 IRREGULAR PATTERN OF RAW-MATERIAL-ARRIVALS SCENARIO

8.5.1 System optimisation

Table 8.7 shows the optimization parameters obtained from table 7.9 in chapter 7.

Table 8.7 - Optimization parameters; irregular arrivals of material

	Response variable		
	Parts	Cost	Time
Goal	Maximize	Minimize	Minimize
Target	789	$39,400	1,120
Min	770	n/a	n/a
Max	n/a	$71,300	1,700

Table 8.8 shows the global solutions for each prioritized response.

Table 8.8 - Global solutions; irregular arrivals of material

Design factors	Prioritized response			
	Parts	Cost	Time	Equal
Skill level of operators	1	-1	1	1
Capacity of buffers	-1	-1	-1	-1
Number of AGVs	-1	1	1	-1
Speed of AGVs	1	-1	1	1
Loading capacity of AGVs	1	-1	-1	1
Duration of set ups	-1	-1	-1	-1

Table 8.9 shows the predicted responses for each of the global solutions in the table 8.11 above.

Table 8.9 - Predicted responses and desirability values; irregular arrivals of material

RESPONSE	IRREGULAR ARRIVALS OF RAW MATERIAL							
	Number of parts		Cost		Time in the system		Equal priority	
	Predicted	Desirability	Predicted	Desirability	Predicted	Desirability	Predicted	Desirability
Parts	789	0.982	787	0.881	788	0.948	789	0.982
Cost	$ 43,652	0.841	$ 39,902	0.996	$ 43,551	0.843	$ 43,652	0.841
Time	1,132	0.979	1,279	0.684	1,130	0.986	1,132	0.979
Composite desirability		0.969		0.955		0.970		0.931

After plotting individual desirability values in figure 8.5 it can be noticed that, when the number of completed parts is prioritized, the response cost is the one with the lowest desirability with a value of 0.841; the effect on time is hardly evident. When cost is prioritized, time is the most affected response with a desirability of 0.684; the effect on parts is not significant. When time is prioritized, the results exhibit a similar behaviour as when the number of parts is prioritized with a slight decrement in the desirability value for parts.

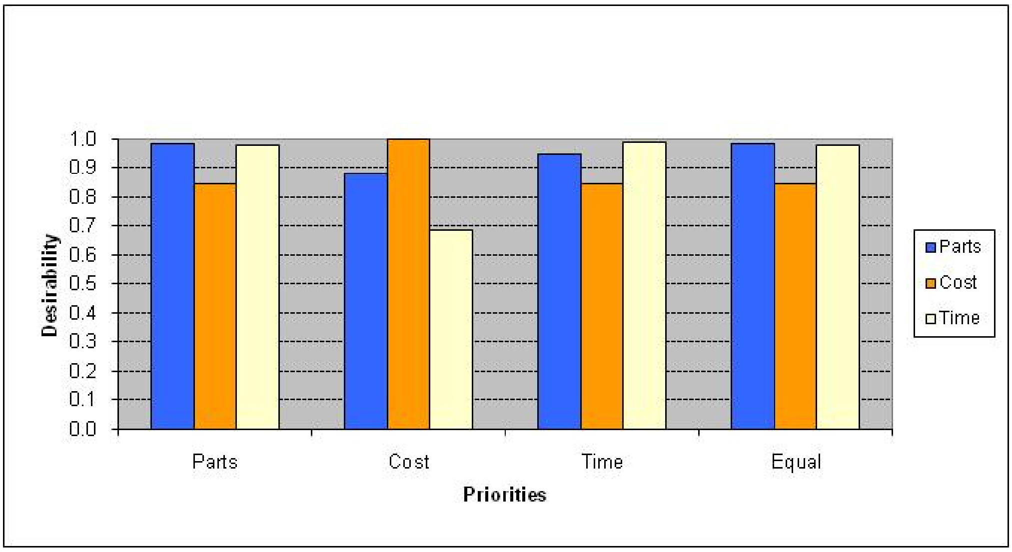

Figure 8.5 - Desirability of predicted responses vs. prioritized responses; irregular arrivals of material

When the three responses are equally prioritized, the desirability values exhibit a similar behaviour to when parts are prioritized; however, neither parts nor equal prioritization achieve the highest composite desirability.

Figure 8.6 below graphically compares the composite desirability values of the prioritized responses.

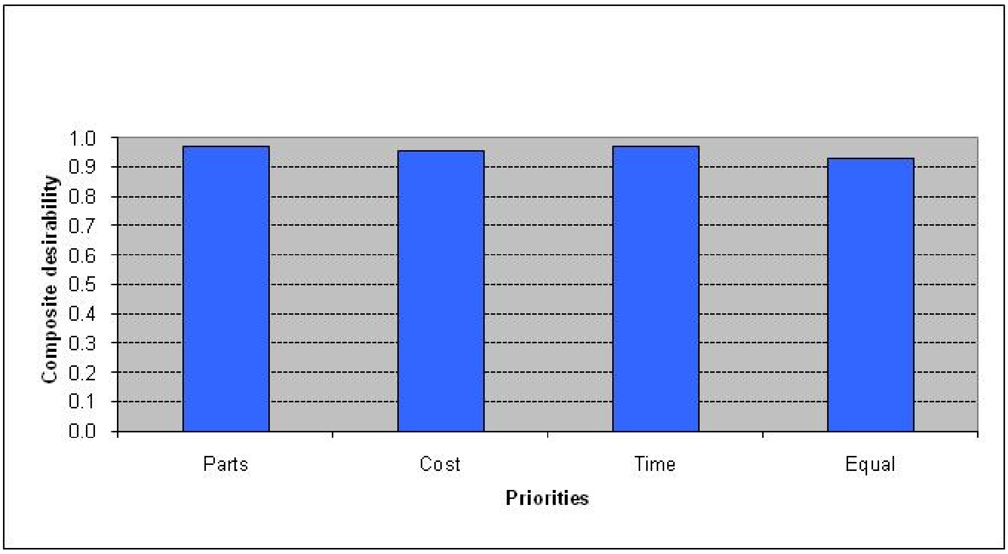

Figure 8.6 - Composite desirability vs. prioritized responses; irregular arrivals of material

Figure 8.6 shows that, in a scenario characterized by an irregular arrival of material, the four prioritization criteria achieve high composite desirabilities, being time prioritization the one achieving the highest value.

8.6 INCREASED ARRIVALS OF RAW-MATERIAL SCENARIO

8.6.1 System optimisation

Table 8.10 shows the optimization parameters obtained from table 7.13 in chapter 7.

Table 8.10 - Optimization parameters; increased arrivals of material

	Response variable		
	Parts	**Cost**	**Time**
Goal	Maximize	Minimize	Minimize
Target	1001	$47,700	938
Min	992	n/a	n/a
Max	n/a	$84,000	1,500

Table 8.11 shows the global solutions for each prioritized response.

Table 8.11 - Global solutions; increased arrivals of material

Design factors	Prioritized response			
	Parts	**Cost**	**Time**	**Equal**
Skill level of operators	1	-1	1	1
Capacity of buffers	-1	-1	-1	-1
Number of AGVs	1	1	1	1
Speed of AGVs	1	1	1	1
Loading capacity of AGVs	1	-1	-1	1
Duration of set ups	1	-1	-1	-1

Table 8.12 shows the predicted responses for each of the global solutions in the table 8.14 above.

Table 8.12 - Predicted responses and desirability values; increased arrivals of material

RESPONSE	**INCREASED ARRIVALS OF RAW MATERIAL**							
	Number of parts		**Cost**		**Time in the system**		**Equal priority**	
	Predicted	**Desirability**	**Predicted**	**Desirability**	**Predicted**	**Desirability**	**Predicted**	**Desirability**
Parts	1001	1.000	999	0.722	1000	0.887	1000	0.898
Cost	$ 56,234	0.699	$ 48,084	0.990	$ 52,000	0.850	$ 52,481	0.849
Time	1,072	0.736	1,064	0.730	938	0.989	933	0.983
Composite desirability		0.946		0.940		0.968		0.908

Figure 8.7 depicts the individual desirability values of the prioritized responses. It can be noticed that, parts prioritization leads to both cost and time experiencing an important and similar decrement in their relative desirability values. A similar decrement in the other two responses is also observed when cost is prioritized. Additionally, it can be noticed that time and equal response prioritizations are the criteria where the three variables are less compromised.

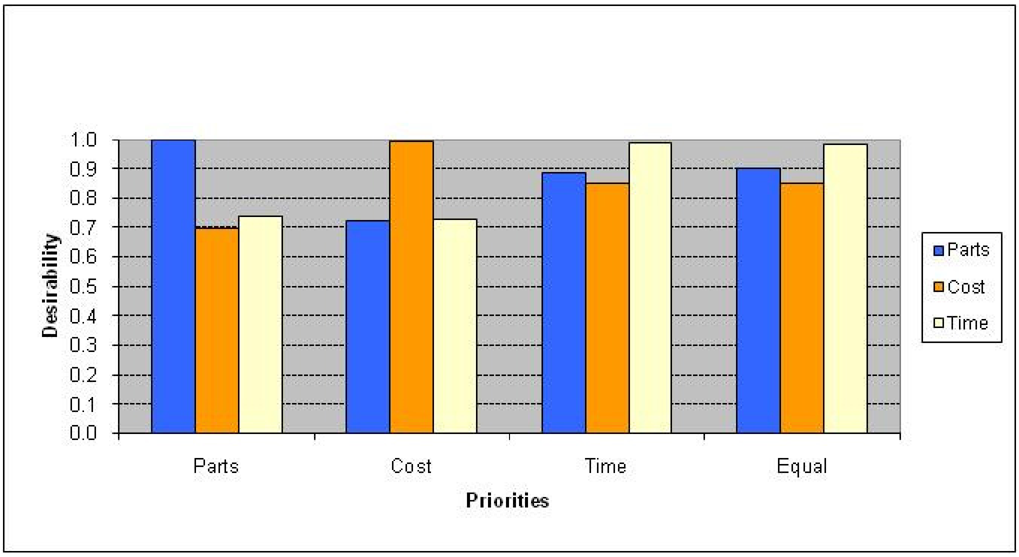

Figure 8.7 - Desirability of predicted responses vs. prioritized responses; increased arrivals of material

In terms of composite desirability, it can be noticed from figure 8.8 that under this scenario the four prioritization criteria also lead to acceptable composite desirability values.

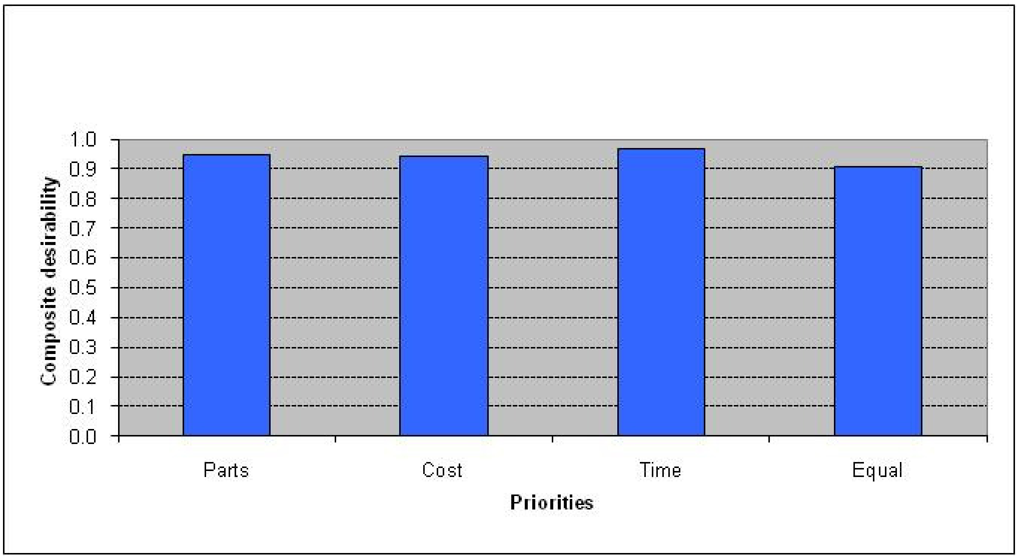

Figure 8.8 - Composite desirability vs. prioritized responses; increased arrivals of material

According to figure 8.8, time prioritization achieves the highest composite desirability, on the contrary, an equal prioritization of responses leads to the lowest composite desirability.

8.7 INCREASED PRODUCT VARIETY SCENARIO

8.7.1 System optimisation

Table 8.13 shows the optimization parameters obtained from table 7.17 in chapter 7.

Table 8.13 - Optimization parameters; increased product variety

	Response variable		
	Parts	**Cost**	**Time**
Goal	Maximize	Minimize	Minimize
Target	668	$42,380	2,290
Min	663	n/a	n/a
Max	n/a	$67,700	2,990

Table 8.14 shows the global solutions for each prioritized response.

Table 8.14 - Global solutions; increased product variety

Design factors	Prioritized response			
	Parts	**Cost**	**Time**	**Equal**
Skill level of operators	1	1	1	1
Capacity of buffers	-1	-1	-1	-1
Number of AGVs	1	1	1	1
Speed of AGVs	-1	1	1	1
Loading capacity of AGVs	-1	1	-1	1
Duration of set ups	1	-1	-1	-1

Table 8.15 shows the predicted responses for each of the global solutions in the table 8.17 above.

Table 8.15 - Predicted responses and desirability values; increased arrivals of material

RESPONSE	INCREASED PRODUCT VARIETY							
	Number of parts		Cost		Time in the system		Equal priority	
	Predicted	Desirability	Predicted	Desirability	Predicted	Desirability	Predicted	Desirability
Parts	668	1.000	668	0.904	667	0.880	668	0.904
Cost	$ 49,317	0.985	$ 45,814	0.993	$ 45,814	0.993	$ 45,814	0.993
Time	2,449	0.755	2,296	0.996	2,291	0.998	2,296	0.996
Composite desirability		0.976		0.985		0.987		0.963

According to individual desirability values plotted in figure 8.9, the prioritization of parts only produces a significant effect on time, the effect on cost is almost irrelevant. Cost prioritization leads to acceptable desirabilities in the other two responses. Similar results are observed in both time and equal response prioritization where the complementary responses also achieve good desirabilities.

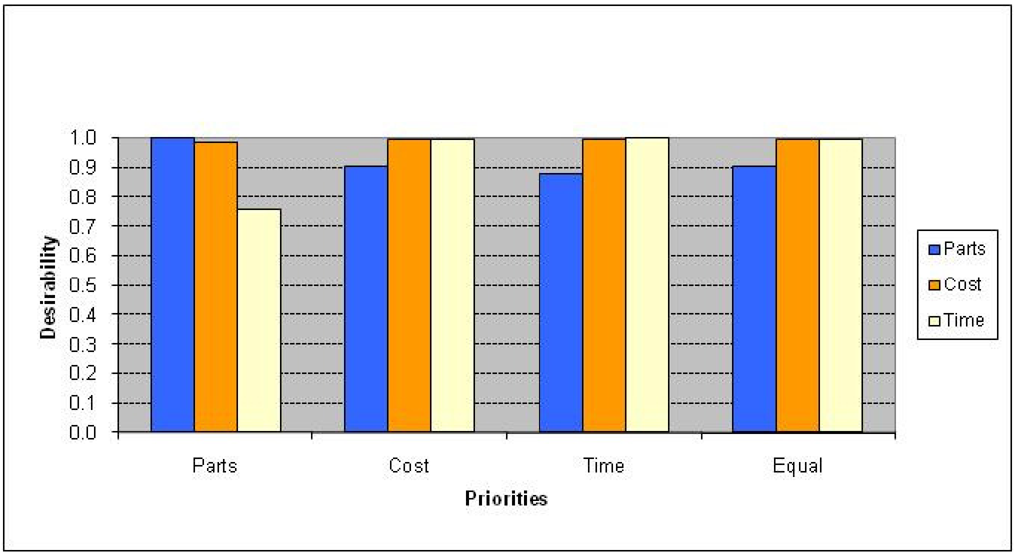

Figure 8.9 - Desirability of predicted responses vs. prioritized responses; increased product variety

Figure 8.10 depicts the composite desirability values of the prioritized responses.

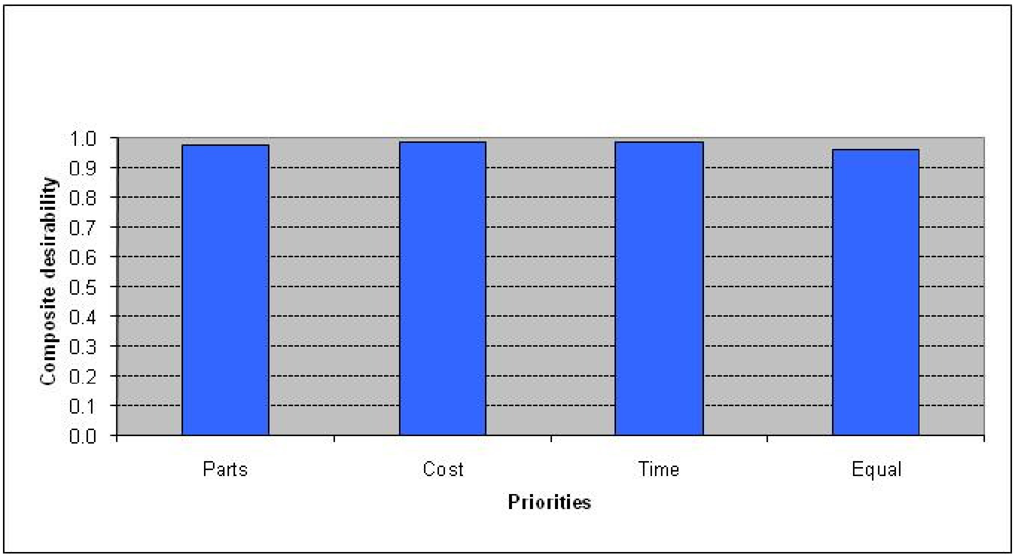

Figure 8.10 - Composite desirability vs. prioritized responses; increased product variety

It can be noticed from figure 8.10 that, in a scenario of increased product variety, the four prioritization criteria have high composite desirabilities, being time prioritization the one achieving the highest value and equal prioritization the one with the lowest value.

8.8 HIGH VARIATION IN PRODUCT MIX SCENARIO

8.8.1 System optimisation

Table 8.16 shows the optimization parameters obtained from table 7.21 in chapter 7.

Table 8.16 - Optimization parameters; high variation in product mix

	Response variable		
	Parts	**Cost**	**Time**
Goal	Maximize	Minimize	Minimize
Target	669	$34,700	1,250
Min	667	n/a	n/a
Max	n/a	$47,200	1,530

Table 8.17 shows the global solutions for each prioritized response.

Table 8.17 - Global solutions, high variation in product mix

Design factors	Prioritized response			
	Parts	**Cost**	**Time**	**Equal**
Skill level of operators	-1	-1	1	1
Capacity of buffers	-1	-1	-1	-1
Number of AGVs	-1	-1	1	-1
Speed of AGVs	1	1	1	1
Loading capacity of AGVs	-1	-1	-1	1
Duration of set ups	1	-1	-1	-1

Table 8.18 shows the predicted responses for each of the global solutions in the table 8.20 above.

Table 8.18 - Predicted responses and desirability values, high variation in product mix

RESPONSE	HIGH VARIATION IN PRODUCT MIX							
	Number of parts		**Cost**		**Time in the system**		**Equal priority**	
	Predicted	**Desirability**	**Predicted**	**Desirability**	**Predicted**	**Desirability**	**Predicted**	**Desirability**
Parts	669	1.000	668	0.355	668	0.495	668	0.521
Cost	$ 36,559	0.825	$ 34,834	0.985	$ 37,068	0.777	$ 37,154	0.770
Time	1,435	0.288	1,358	0.583	1,259	1.000	1,262	0.986
Composite desirability		0.887		0.866		0.924		0.734

Figure 8.11 depicts individual desirability values. This figure indicates that the prioritization of the number of parts would lead to an extremely low desirability value for time, whereas cost would be only slightly affected. The prioritization of cost would cause a significant reduction in the desirability values of the other responses, being number of parts the most affected response. The prioritization of time would significantly affect the number of parts and it would also have an important effect on cost.

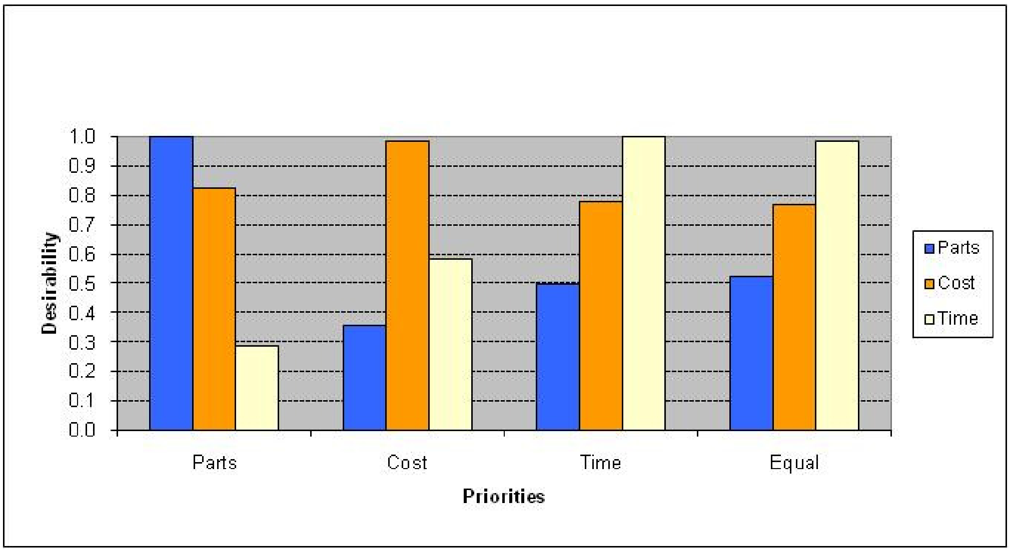

Figure 8.11 - Desirability of predicted responses vs. prioritized responses; high variation in product mix

An equal prioritization of responses leads to similar results to those observed in the prioritization of time.

Figure 8.12 depicts the composite desirability values of the four prioritized responses.

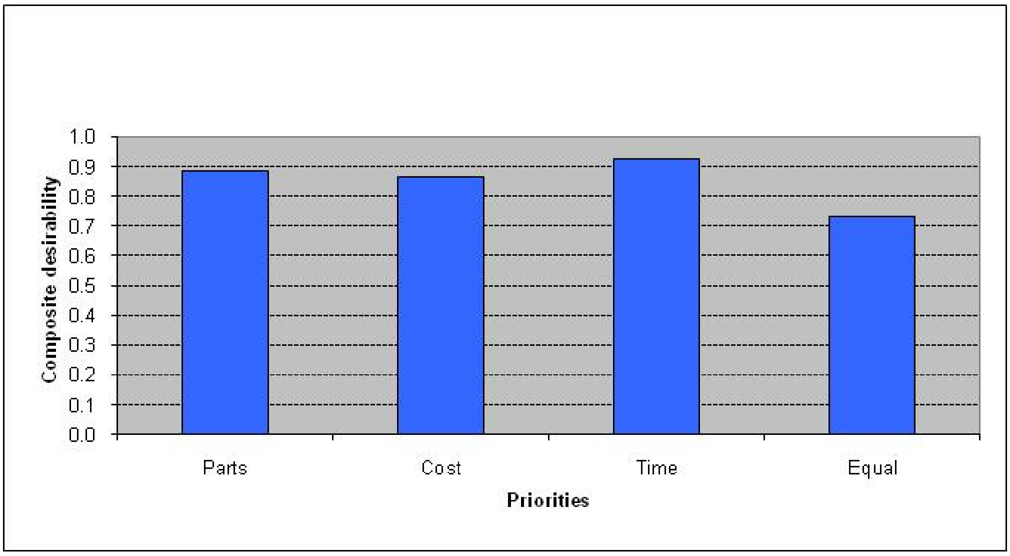

Figure 8.12 - Composite desirability vs. prioritized responses; high variation in product mix

According to figure 8.12, under a scenario of high variation in product mix, the prioritization of time leads to the highest composite desirability; on the contrary, an equal prioritization of responses achieves the lowest value.

8.9 CONCLUSION

In this chapter, global solutions for each of the experimental scenarios have been provided. The solutions involve all the experimental factors and have been determined under four different response prioritization criteria, namely parts, cost, time, and equal prioritization. Global solutions have made possible the calculation of predicted responses together with their related individual and composite desirability values. On the one hand, individual desirability values have made possible the identification of trade-offs among the responses within the different prioritization criteria. On the other hand, composite desirability values have facilitated the exposure of the best and worst response prioritization criteria in each disturbance scenario.

CHAPTER 9

SUMMARY OF FINDINGS, CONTRIBUTION TO KNOWLEDGE, CONCLUSION, AND FURTHER RESEARCH

9.1 INTRODUCTION

This chapter summarises the findings from the previous two chapters and provides an answer to the research questions stated at the beginning of the present study. In addition, general conclusions are drawn and further research opportunities are discussed. The first section of the chapter is a summary of findings, which includes the main conclusions for each of the considered experimental scenarios and, therefore, provides an answer to the research questions. The contribution this study has made to knowledge is described subsequently. Next, the chapter presents a summary of the research process, mentioning the different topics in the chapters constituting this thesis. The last part of this chapter includes a general conclusion on the current situation of manufacturing flexibility together with a perspective on its short term future. The last section of the chapter describes the limitations of this study together with further research opportunities.

9.2 SUMMARY OF FINDINGS

9.2.1 Effects of disturbance scenarios on performance

In order to evaluate the impact of each disturbance scenario on system's performance, the results of the original (baseline) model have been taken as a reference. The performance of each scenario, in terms of the considered response variables, has been compared with the performance of the original model. See appendix 69 for the results of the original model.

The relationship between the average number of completed parts (output) and the average number of parts entered into the system (input) from each experimental scenario has been considered to determine the impact of the disruptions on the number of completed parts. This relationship is depicted in figure 9.1 below.

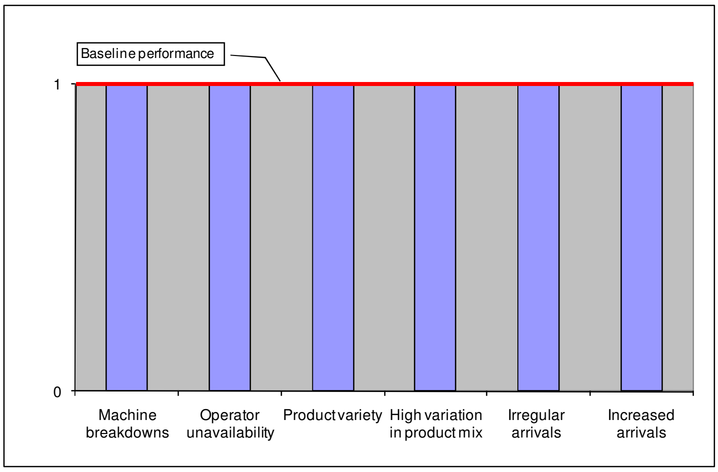

Figure 9.1 – Effect of disturbances on the response number of completed parts (output/input)

As it can be noticed from figure 9.1, none of the considered disturbances seem to have made a considerable impact on the performance in terms of the number of completed parts. However, this result could be deceiving if only such response had been considered in this study, given that it would simply be concluded that performance has not been affected whatsoever. Although there has not been a considerable impact in terms of the number of completed parts, the other two responses need to be analysed before accepting that performance has not been considerably affected. This is where the importance of relying on complementary performance measures becomes evident. Figure 9.2 shows the effect of the same disturbances on the complementary response total manufacturing cost; as it can be noticed the results do not look as positive as in the previously analysed response.

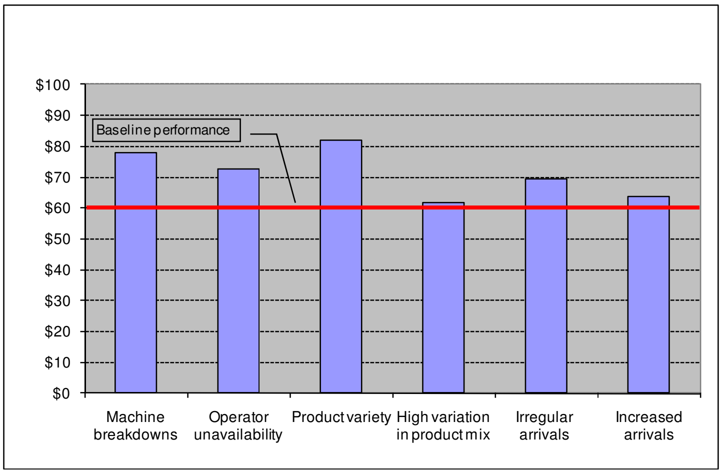

Figure 9.2 – Effect of disturbances on the response total cost ($/part)

Figure 9.2 shows that the scenarios of product variety and machine breakdowns have reflected the highest cost per part; this, respectively, is due to the high levels of WIP inventory originated as a result of a larger number of changeovers and as a result of unavailability of resources. The scenarios of operator unavailability and irregular arrivals have also shown an important impact on cost due to accumulation of WIP inventory. The scenario with the least effect on cost has been the one involving a high variation in the product mix; this is due to the fact that, since some of the products within the portfolio experience a very low demand, most of the total available resource time is allocated to highly demanded products, leading to a quicker processing of parts and in turn lower WIP inventories.

In terms of the response average time in the system, figure 9.3 shows the impact each disturbance scenario has caused on such response variable.

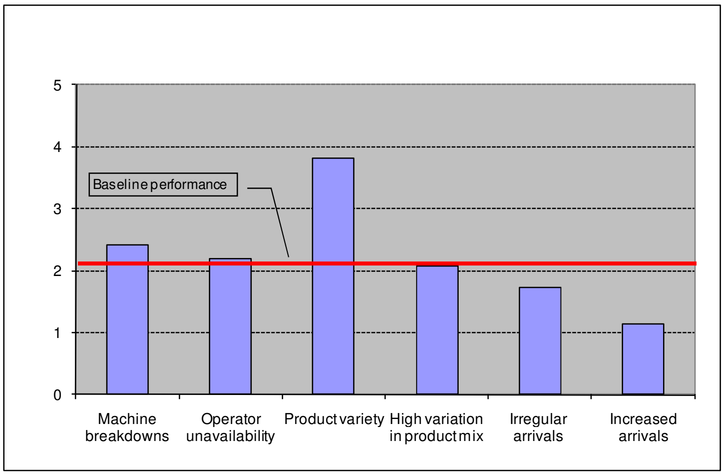

Figure 9.3 – Effect of disturbances on the response time in the system (min/part)

Figure 9.3 indicates that the scenario with the highest effect has been the one involving an extended product variety. This is because more products imply more processing routes within the system, more needed changeovers, and ultimately, the accumulation of higher levels of WIP inventory. Even though the impact on time has not been as significant as in the case of product variety, both frequent machine breakdowns and operator unavailability also have shown an important effect on time as a consequence of WIP inventories accumulating during the unavailability of resources. Note that the scenarios of irregular arrivals and increased arrivals have exhibited the lowest time per part as a result of more parts entered and completed by the system.

Taking advantage of the capabilities of the simulation software employed, it has been possible to determine the profit generated by the system in each scenario. Although profit was not originally considered in the original experimental design, it has been considered convenient to introduce it, exclusively at this point, in order to summarize the three original responses in a single response and therefore evaluate the general impact of disturbances on system performance. Figure 9.4 shows the impact of disturbances on profit.

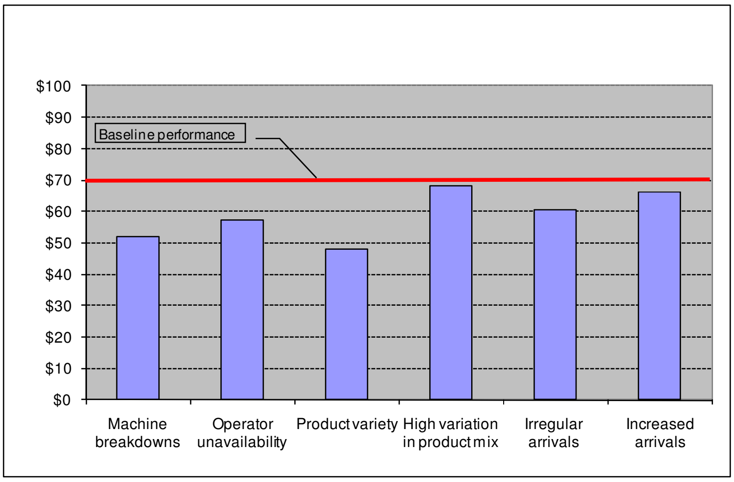

Figure 9.4 – Effect of disturbances on profit ($/part)

In general terms, figure 9.4 indicates that the scenarios with a larger effect on manufacturing performance have been, in the first place, extended product variety, mainly because it is one of the scenarios involving highest manufacturing costs resulting from more frequent production changeovers and WIP accumulation. In the second and third place respectively, frequent machine breakdowns and frequent operator unavailability scenarios, have revealed that performance is also greatly affected by two important aspects of resource unavailability, i.e. the frequency of resource unavailability and the duration of resource unavailability.

9.2.2 Flexibility contributors under different disturbance scenarios

In order to summarize the findings from the previous two chapters and to provide a quick reference, the key components contributing to system's flexibility by helping to maintain a higher system performance under different disturbance scenarios have been included in table 9.1 below.

Table 9.1 –System flexibility contributors

Disturbance scenario	Response	Work centre components			Material handling components		
		Operator skills	Buffer capacity	Set-up duration	No. of vehicles	Speed of vehicles	Loading capacity of vehicles
Machine breakdowns	Parts	8% ▼	30% ▲	-	-	-	-
	Cost	-	91% ▼	7% ▼	-	-	-
	Time	47% ▲	-	46% ▼	-	-	-
Operator unavailability	Parts	40% ▲	28% ▲	-	-	-	-
	Cost	-	95% ▼	2% ▼	-	-	-
	Time	71% ▲	-	17% ▼	-	-	-
Irregular supply	Parts	12% ▲	33% ▲	9% ▼	7% ▲	-	-
	Cost	-	86% ▼	10% ▼	-	-	-
	Time	35% ▲	-	54% ▼	-	-	-
Increased supply	Parts	48% ▲	15% ▲	4% ▼	-	-	-
	Cost	-	88% ▼	9% ▼	-	-	-
	Time	46% ▲	-	40% ▼	-	-	-
Increased product variety	Parts	26% ▲	23% ▲	6% ▼	6% ▲	-	-
	Cost	-	90% ▼	7% ▼	-	-	-
	Time	51% ▲	-	36% ▼	-	-	-
High variation in product mix	Parts	7% ▼	-	17% ▲	-	-	-
	Cost	-	92% ▼	-	-	-	-
	Time	64% ▲	-	21% ▼	-	7% ▲	-

The six considered disturbance scenarios are shown in the first column on the far left side of table 9.1. In the following column, the three response variables for each disturbance scenario are included. The next six columns correspond to each of the experimental factors in the design. In each of the six factor columns, the percentages included within the cells represent the percent contributions to the related response from each of the factors; the red arrow pointing upwards indicates the high level of the factor, whereas the black arrow pointing downwards indicates the low level. Hyphens in cells indicate negligible percent contributions. To illustrate the interpretation of table 9.1, in a scenario characterized by frequent machine breakdowns the most important factors to achieve the maximum number of parts were operators with low skills and buffers with high capacity; both with a combined percent contribution of 38%. Similarly, in order to achieve minimum cost, the most important factors were buffers with low capacity and machines with low set-up duration, whose combined percent contribution was 98%. Regarding the response time, table 9.1, shows that there were two important factors to achieve minimum time under a machine breakdowns scenario, those were operators with high skills and machines with low set-up duration, together having a percent contribution of 93%. In order to avoid repetition the description for the rest of the scenarios in the table above has been intentionally omitted. For the significant factors in the rest of the scenarios, please refer back to table 9.1.

9.2.3 Key manufacturing flexibility contributors

After having identified different system components constituting a significant advantage during particular disturbance scenarios, it can be noticed, from table 9.1, that certain factors were consistently important for most of the considered scenarios. In general terms, those factors contribute to performance stability in the presence of a number of disturbances and therefore, they constitute key contributors to system flexibility. Those factors, in order of importance, are the following:

1. The skill level of human operators, principally at a high level.
2. The buffer capacity of the work centres, which is characterized by a balance between low and high levels depending on the disturbance scenario.
3. The duration of machine setups, mostly at a low level.

In addition to the significance these three aspects have for the modelled MS in achieving flexibility, these system aspects are also likely to be of special consideration for other MS sharing similar features, i.e. cellular manufacturing configurations where the presence of a number of human operators is needed to control the machines within the cell and an automated material handling subsystem moves parts throughout the system. For such MS, counting on work centres with highly skilled operators, adaptable buffer capacity and low set-up duration, may constitute a major advantage in maintaining a high performance during disrupting circumstances, and therefore, in achieving system flexibility.

9.2.4 Optimal system flexibility configurations in different disturbance scenarios

Consistent with the structure of table 9.1, table 9.2 shows the optimal system configurations under specific disturbance scenarios and in terms of the prioritized response variables maximum number of parts, minimum cost, minimum time in the system, and equal prioritization of responses.

Table 9.2 – Optimal operative system flexibility configurations

Disturbance scenario	Priority response	Work centre components			Material handling components		
		Operator skills	Buffer capacity	Set-up duration	No. of vehicles	Speed of vehicles	Loading capacity of vehicles
Machine breakdowns	Parts	▼	▼	▼	▼	▼	▲
	Cost	▼	▼	▼	▼	▲	▲
	Time	▲	▼	▼	▲	▲	▼
	Equal	▲	▼	▼	▲	▲	▼
Operator unavailability	Parts	▲	▼	▼	▲	▲	▼
	Cost	▼	▼	▼	▼	▼	▲
	Time	▲	▼	▼	▲	▲	▼
	Equal	▲	▼	▼	▲	▲	▼
Irregular supply	Parts	▲	▼	▼	▼	▲	▲
	Cost	▼	▼	▼	▲	▼	▼
	Time	▲	▼	▼	▲	▲	▼
	Equal	▲	▼	▼	▼	▲	▲
Increased supply	Parts	▲	▼	▲	▲	▲	▲
	Cost	▼	▼	▼	▲	▲	▼
	Time	▲	▼	▼	▲	▲	▼
	Equal	▲	▼	▼	▲	▲	▲
Increased product variety	Parts	▲	▼	▲	▲	▼	▼
	Cost	▲	▼	▼	▲	▲	▲
	Time	▲	▼	▼	▲	▲	▼
	Equal	▲	▼	▼	▲	▲	▲
High variation in product mix	Parts	▼	▼	▲	▼	▲	▼
	Cost	▼	▼	▼	▼	▲	▼
	Time	▲	▼	▼	▲	▲	▼
	Equal	▲	▼	▼	▼	▲	▲

As opposed to table 9.1, table 9.2 considers all the experimental factors regardless of their level of significance to the response. The purpose of table 9.2 is to define an optimal system configuration in terms of each prioritized response and under specific disturbance scenarios. For example, table 9.2 indicates that, in a scenario with an irregular supply of material, the prioritization of the minimum cost demanded a manufacturing system featuring work centres where the operators were low skilled, the buffer capacities were low, and the machines had low set-up duration; additionally, the material handling system needed a high number of vehicles at low speed and with low loading capacity. On the contrary, the prioritization of maximum number of parts in the same scenario required work centres where the operators had high skills, the buffers had low capacities, and the machines had low set-up duration; the material handling system was characterised by a low number of vehicles at high speed and with high loading capacity. Please refer back to table 9.2 for the rest of optimal system configurations under different scenarios and prioritization criteria.

9.2.5 Trade-offs in system flexibility configurations

In order to categorize the impact of prioritizing particular responses, the composite desirability values of each response have been considered (see chapter 8). For categorization purposes, desirability values lower and equal to 0.75 have been assumed to have a high effect on the response whereas desirability values higher than 0.75 have been assumed to have a low effect on the response. Table 9.3 includes the trade-offs existing among the optimal system configurations described in the previous section.

Table 9.3 –System flexibility trade-offs

Disturbance scenario	Priority response	*IMPACT ON THE RESPONSE*		
		Number of parts	Total cost	Lead time
Machine breakdowns	**Parts**	0.85 -	0.99 ▼	0.59 ▲
	Cost	0.74 ▲	0.99 -	0.68 ▲
	Time	0.67 ▲	0.86 ▼	0.98 -
	Equal	0.67 ▲	0.86 ▼	0.98 ▼
Operator unavailability	**Parts**	0.96 -	0.81 ▼	0.96 ▼
	Cost	0.49 ▲	0.98 -	0.50 ▲
	Time	0.96 ▼	0.81 ▼	0.96 -
	Equal	0.96 ▼	0.81 ▼	0.96 ▼
Irregular supply	**Parts**	0.98 -	0.84 ▼	0.98 ▼
	Cost	0.88 ▼	0.99 -	0.68 ▲
	Time	0.95 ▼	0.84 ▼	0.98 -
	Equal	0.98 ▼	0.84 ▼	0.98 ▼
Increased supply	**Parts**	1 -	0.70 ▲	0.73 ▲
	Cost	0.72 ▲	0.99 -	0.73 ▲
	Time	0.88 ▼	0.85 ▼	0.99 -
	Equal	0.90 ▼	0.85 ▼	0.98 ▼
Increased product variety	**Parts**	1 -	0.98 ▼	0.75 ▲
	Cost	0.90 ▼	0.99 -	0.99 ▼
	Time	0.88 ▼	0.99 ▼	0.99 -
	Equal	0.90 ▼	0.99 ▼	0.99 ▼
High variation in product mix	**Parts**	1 -	0.82 ▼	0.29 ▲
	Cost	0.35 ▲	0.98 -	0.58 ▲
	Time	0.49 ▲	0.77 ▼	1 -
	Equal	0.52 ▲	0.77 ▼	0.98 ▼

Following the arrangement of the previous two tables, in table 9.3 the experimental factors have been replaced by the three considered response variables on the top of the table in order to indicate the effect of prioritizing one particular response over the other two responses. In this particular table, the red arrow pointing upwards represents a high impact on a response, whereas the black arrow pointing downwards represents a low impact. The value above the arrow indicates the composite desirability. Therefore, according to the information presented in table 9.3, in a high variation in product mix scenario, prioritizing the response time over the other two responses caused a high impact on the number of parts and a low impact on total cost. On the other hand, establishing an equal priority for all the responses, in the same disturbance scenario, leaded to a high impact on the number of parts and a low impact on both total cost and lead time. Please refer back to table 9.3 for consulting more existing trade-offs in the response variables.

9.3 CONTRIBUTION TO KNOWLEDGE

The proposed research has expanded the perspective on the concept of flexibility by providing an inclusive context where the role of different elements in the achievement of overall system flexibility has been analysed. The first important contribution made by the present study is the perspective from which the concept of manufacturing flexibility is analysed. As opposed to most of the existing research on manufacturing flexibility which tends to focus on the flexibility dimensions of range and mobility, in this study manufacturing flexibility was investigated in terms of the commonly neglected dimension of uniformity. Looking at the concept of manufacturing flexibility from the perspective of uniformity has provided a context to facilitate a better understanding of flexibility and alternative ways to achieve it.

A second central contribution of this study is the approach adopted to produce the findings. Even though there is a significant amount of research on manufacturing flexibility, a review of the existing literature confirmed that most of the research adopts an exclusive and focused perspective, i.e. only one or a few system aspects are particularly investigated considering only one or two specific noise factors. The methods adopted by most of the existing research are also exclusive, i.e. some literature considers only simulation approaches and some other literature specially favours analytical ones. As a MS is a collection of interconnected components trying to achieve a common objective, it is necessary to understand both the behaviour of specific components and the interactions occurring among the different components within the system. The methodology of this study uses not only discrete event simulation to understand overall system's behaviour, but also analytical methods, such as mathematical programming, to analyse the contribution of specific components to system's flexibility. In addition to the methodology itself, another original characteristic of this study is the adoption of a more inclusive perspective on flexibility. This is achieved by simultaneously investigating a number of different MS aspects under the influence of several noise factors and in terms of different response measures. The approach taken allowed for the exploration of, not only the contribution of specific factors, but also of the combined effects of a number of key aspects taking into consideration the interactions occurring among system's components.

A third and last key contribution is represented by the specific findings. These are shown in the three summary tables presented in this last chapter. Table 9.1, titled system flexibility contributors, identifies those system aspects which are essential to achieve system flexibility in different disturbance settings. The findings reveal that, in semi-automated cellular MS, aspects such as the skill level of operators, the inter-storage capacity and the duration of set-ups, may significantly contribute to overall system flexibility. Table 9.2, titled optimal operative system flexibility configurations, describes those cellular-system configurations which would achieve a higher flexibility in terms of different response priorities and under different disturbance scenarios. Table 9.3, titled system flexibility trade-offs, specifies the response trade-offs involved in different scenarios. By representing different alternatives to maintain a higher performance under disturbance situations, the findings encompassed in the three tables provide valuable information for either the design or operation of semi-automated cellular MS.

In summary, the present study has contributed to knowledge on the topic of manufacturing flexibility by expanding the understanding of the concept, by demonstrating the benefits of the considered methodology and, lastly, by identifying a number of alternatives for semi-automated cellular MS to achieve flexibility.

9.4 SUMMARY OF THE RESEARCH PROCESS

The following aspects have been covered along the development process of the present research:

Chapter 1 established the context in which the research has been developed. The objective, the research questions, the methodology, the scope, and the assumptions of this study were all stated in this chapter.

Chapter 2 provided a better perspective on the conceptual basis of this study by reviewing some of the most important approaches in the literature. Some research gaps were identified as a result of the literature review.

Chapter 3 looked at the conceptual basis of the study by expanding on aspects such as manufacturing systems, disturbances, and actions against disturbances.

Chapter 4 defined and evaluated different analytical approaches for manufacturing systems. Discrete event simulation was chosen as a result of its advantages over the other approaches.

Chapter 5 described each of the stages involved in the development process of the simulation model considered in this research. The assumptions under which the model operates were also stated in this chapter.

Chapter 6 explained the different aspects of the research methodology. In this chapter the research problem was defined, the response variables and experimental factors were identified, and the experimental design was established.

Chapter 7 presented the results of all the experimental settings. The results and experimental assumptions were validated with statistical analysis.

Chapter 8 provided an optimal solution for the different experimental settings of the research. In addition, trade-offs in the response variables were identified.

9.5 GENERAL CONCLUSION

Even though there is a strong association between the concept of flexible manufacturing systems and the use of highly automated equipment (e.g. automated material handling devices and computer controlled systems), the present research has demonstrated that flexibility in manufacturing does not necessarily denote technological sophistication. To take a better advantage of flexibility in manufacturing systems, it is necessary to broaden our view. Therefore, not only should attention be paid to the range and mobility dimensions, but also to the flexibility dimension of uniformity.

Although a series of alternatives for semi-automated cellular manufacturing systems to achieve manufacturing flexibility have been identified in this study; it is important to mention that other aspects of this study are not necessarily restricted to cellular systems. The consideration of the uniformity dimension in the evaluation of manufacturing flexibility, in addition to the methodology employed in this study, can be applied to a variety of manufacturing system configurations.

Regarding the misleading association between flexibility and full automation, manufacturing flexibility should not be exclusively viewed in terms of completely automated capabilities. In particular, there are still outstanding issues related to the proper integration of physical system capabilities and control strategies. Further to this, as manual and semi-automated operations are still widely required in the manufacturing industry and will remain so for some time, for manufacturing systems to be flexible, it is necessary to focus on and develop current capabilities.

9.6 LIMITATIONS AND FURTHER RESEARCH OPPORTUNITIES

Since the experiments have been performed using a model of a theoretical manufacturing system, the validity of the results presented in the presentment study is limited and determined by the assumptions made in chapter 5. Given that the objective of the present research is contributing to achieve a better understanding on the concept of manufacturing flexibility and the alternative ways to attain it, the results and conclusions from this research are intended exclusively for instructive purposes and, by no means it is the intention to generalize the applicability of the conclusions to different types of real manufacturing systems.

The topic of manufacturing systems and their capability to cope with environmental disturbances represents an extensive area of research opportunities. The results presented in this study constitute only a modest insight into the topic. In order to expand the knowledge on this field, this study can be developed further by considering several other issues, which, because of time limitations, have not been taken into account. Additional research opportunities that have been identified along the development process of this research are described next.

Firstly, it is necessary to explore further the three dimensions of flexibility. By simultaneously exploring the range, mobility and uniformity dimensions within an inclusive context, additional alternative ways to achieve flexibility may be identified. An inclusive approach, in terms of the three dimensions, would constitute an important contribution to the understanding of manufacturing flexibility.

Moreover, other aspects of manufacturing disturbances can be further investigated. This study considers only the aspects of type and fixed size of disturbances; however, there are other aspects such as the variable intensity of disturbances, the interval of occurrence, and the incidence of disturbances that need to be thoroughly explored.

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