DEVELOPMENT OF A BUSINESS MODEL FOR DIAGNOSING UNCERTAINTY IN MRP ENVIRONMENTS

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This thesis is dedicated to papa.
May he look on me from above with pride.

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Abstract

Over the last thirty years, Materials Requirements Planning (MRP) based systems have become commonplace within batch manufacturing environments, but are still widely held to be under performing. This research hypothesises that there may be inherent problems associated with the application due to uncertainties that exist within dynamic operating environments.

Research has highlighted both the absence of any business model that uses a structured and systematic approach to deal with uncertainty holistically and the lack of any widely used, consistent performance measures to allow comparison of research results. The industrial need for such a holistic approach became apparent from survey work, which showed MRP under-performed in the presence of uncertainty even when numerous Buffering and Dampening (BAD) approaches were applied.

A business model of uncertainty that structures the causes and effects of uncertainty as a hierarchy of four levels has been proposed, to be verified and validated through industrial survey and simulation respectively.

The relationship between causes and effects in the business model has been verified from survey results using Analysis of Variance (ANOVA), which identified twenty-three significant uncertainties within Mixed-Mode (MM) operating environments. Using a multi-product, multi-level dependent demand MRP simulation model within an MM operating environment driven by planned order release, an experimental programme has been carried out that showed finished products delivered late to be insensitive as a performance measure. Parts Delivered Late (PDL) was found to be more sensitive and has been adopted as the preferred measure. ANOVA on the simulation results validated the cause-and-effect relationships, showing that the higher the level of uncertainty, the worse was delivery performance.

Individual uncertainties produced effects that were not discretely recognised in the literature. 'Knock-on' effects are created by uncertainties delaying the issue of batches and affected particular Bill of Materials chains. 'Compound' effects are caused by uncertainties affecting resource availability and also induced consequent knock-on effects.

Simulation results also showed that late deliveries from suppliers, machine breakdowns, unexpected or urgent changes to schedules affecting machines and customer design changes are the most significant uncertainties within the parameter levels modelled. Several significant two-way and three-way interactions were found.

The business model of uncertainty represents a practical and pragmatic attempt to act as a diagnostic tool to identify significant underlying causes affecting PDL for MM companies using MRP, enabling more effective application of suitable BAD approaches.

Using the business model to drive a continuous improvement programme that monitored both levels of uncertainty and PDL would allow internal and external benchmarking for the efficacy of BAD approaches and for the reduction of uncertainties.

Nomenclature

$\bar{X}$	Sample Mean
ANOVA	Analysis of Variance
ASS1	Assembler class one
ASS2	Assembler class two
ASS3	Assembler class three
ASS4	Assembler class four
ATO/MTO	Assemble-to-order/Make-to-order
BAD	Buffering and Dampening
BD	Breakdown
BOM	Bill of Materials
BRKPRS	Break press
CDC	Customer Design Changes
CLR	Coiler
DBRR	Deburr
df	Degrees of freedom
DRL	Drill
DTI	Department of Trade and Industry
EDD	Earliest Due Date
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
F	F probability distribution random variable
FCLR	Finish coiler
FDIST	F probability distribution
FIFO	First-In-First-Out
FIXA	Fixture A
FIXB	Fixture B
FIXC	Fixture C
FIXD	Fixture D
FPDL	Finished Product Delivered Late
GUIL	Guillotine
h	Distribution half width

$h*$	Desired distribution half width
INS	Inspector
INSC	Insecure Stores
LA	Unexpected/Urgent Changes To Schedule (Labour Assignment)
LDFS	Late Delivery From Supplier
LFL	Lot-for-Lot
LIFO	Last-In-First-Out
MA	Unexpected/Urgent Changes To Schedule (Machine Assignment)
MIX	Mix
MM	Mixed-Mode
MPS	Master Production Schedule
MRP	Material Requirements Planning
MS	Mean Square
MTBF	Mean Time Between Failures
MTO	Make-to-order
MTS	Make-to-stock
MTTR	Mean Time To Repair
n	Number of replications
$n*$	Total replications required
OLAB	MRP Planned Overload (Infinite Scheduling of Labour)
OMC	MRP Planned Overload (Infinite Scheduling of Machine)
ONS	Office of National Statistics
p	F probability distribution to indicate whether the variable analysed or interaction identified is significant
PDE	Parts Delivered Early
PDL	Parts Delivered Late
POR	Planned Order Release
POT	Parts Delivered On-Time
PPB	Part Period Balancing
PSE	Planned Set-up/Change-over Time Exceeded
$S(x)$	An unbiased estimator of the standard deviation
SCLR	Sub-assembly coiler
SETTG	Settings
SM	Silver Meal
SS	Sum of Square

STEP	Standard for Transfer and Exchange Product
SWTLNC	Schedule/Work-to-list Not Controlled
$t_{1-\alpha/2,\ n-1}$	Standard deviate in t-distribution for α confidence level
TBO	Time Between Order
TPCH	Turret punch press
WELD	Weld
WFINS	Waiting For Inspection Labour
WFL	Waiting For Labour
WFT	Waiting For Tooling
WIP	Work-in-progress
α	Confidence level

Chapter 1: Introduction

1.1 Introduction

Modern manufacturing industry is facing increasing pressure to improve its responsiveness to market dynamics. Central to this are the issues addressed by Production Planning and Control systems and philosophies. Customer expectations for shorter delivery lead-times, greater agility, improved quality and reduced costs have made the effective application of an appropriate system a significant determinant of survival for many manufacturing companies.

Within batch manufacturing, a wide variety of systems each with its own philosophy may be adopted. These include Material Requirements Planning (MRP), Just-In-Time, Optimised Production Technology and Advanced Production Scheduling, either used discretely or in combination.

This research focussed on how systems with MRP at their core performed in practice. Such systems included amongst others, Manufacturing Resource Planning, Enterprise Resource Planning (ERP) and Customer Relationship Management.

Whatever system is chosen, it must be capable of performing within an uncertain world. The starting point for this research was the belief that causes and effects of uncertainty were not generally well understood or managed within batch manufacturing industries using MRP based systems. Consequently, it was believed that customer expectations, particularly with respect to due date performance, were not being met.

As an introduction to the problem, the remainder of this chapter discusses firstly the theories of both MRP and uncertainty. Measures of performance for MRP based systems are then introduced, from which an initial hypothesis for the research was derived. Finally, the research goal and objectives are presented and the overall structure of the research explained.

1.2 MRP theory

MRP is designed and developed to operate within batch manufacturing environments and is defined as a set of techniques that uses Bill of Materials (BOM) data, inventory data and a Master Production Schedule (MPS) to calculate net requirements for materials. Using time-phased logic, it determines what and when to manufacture or purchase from the highest to the lowest levels of the BOM via back scheduling from due date (Cox and Blackstone, 1998). Figure 1.1 shows the process flow of MRP.

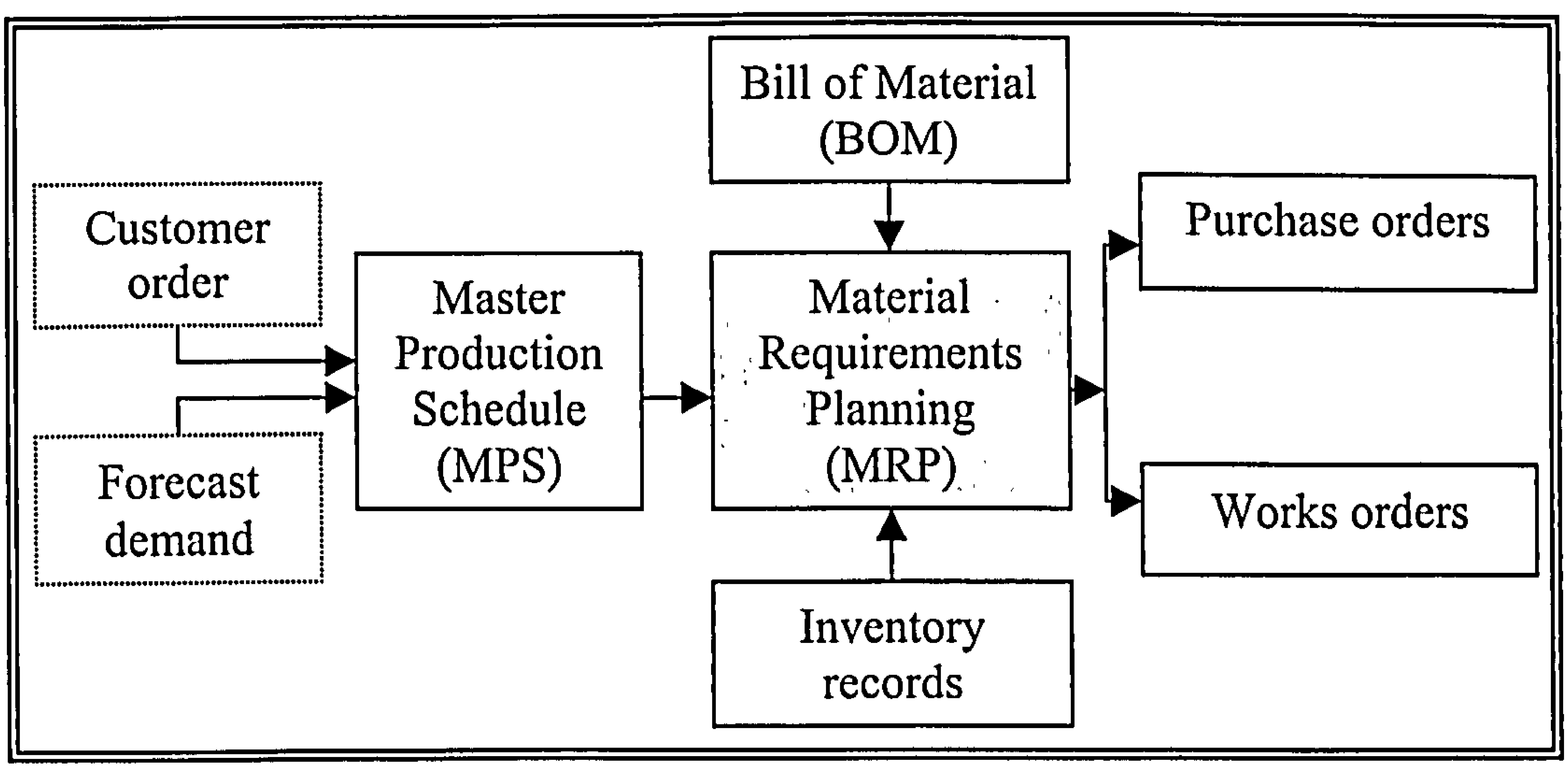

Figure 1.1: Process flow of MRP (after Slack *et al*, 1995)

MRP plans that the right material is available to produce the right product in the right quantity for delivery at the right time. Netting algorithms are applied through the time-phased logic to provide a set of planned orders, which are output as a series of recommendations to purchase or manufacture.

To show how the MRP calculations work, an example of a simple BOM and its respective net requirements plan follows.

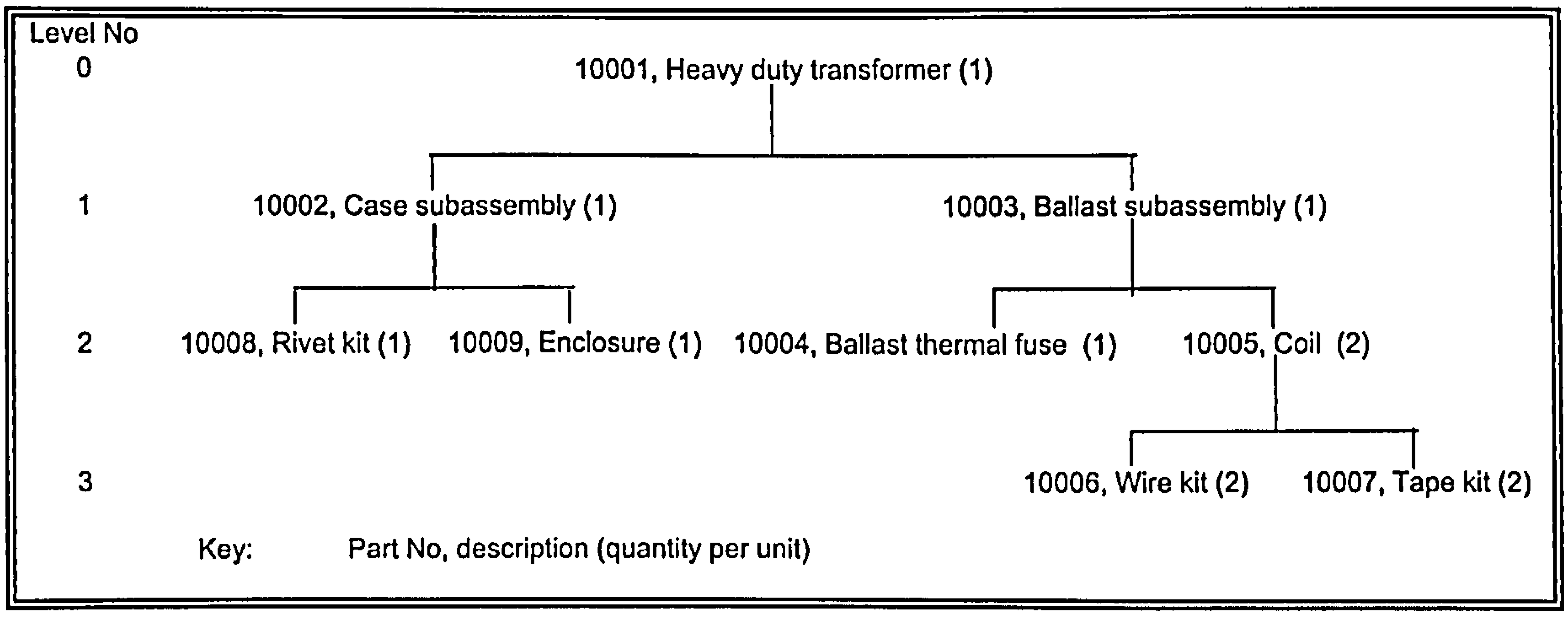

Figure 1.2: A simplified BOM of a heavy-duty transformer

Figure 1.2 shows the parent-child relationship between all parts leading to final assembly and associated quantities. This data is often shown together with manufacture or purchase decisions and lead-times as in Table 1.1.

Level	Part No	Description	Quantity Per unit	Make (M)/ Buy (B)	Lead-time (Days)
0	10001	Heavy duty transformer	1	M	1
.1	10002	Case subassembly	1	M	1
..2	10008	Rivet kit	1	B	1
..2	10009	Enclosure	1	B	3
.1	10003	Ballast subassembly	1	M	1
..2	10004	Ballast thermal fuse	1	B	1
..2	10005	Coil	2	M	1
...3	10006	Wire kit	2	B	2
...3	10007	Tape kit	2	B	1

Table 1.1: Indented explosion of a heavy duty transformer

Table 1.2 gives details of the netting process for an order of 100 off of the heavy-duty transformer, due for delivery in Day 6. The netting process is repeated for all products in the MPS and consolidated to produce listings of all requirements by time period.

10001-Heavy-duty transformer	Day					
	1	2	3	4	5	6
Gross requirements						100
Scheduled receipts						
On-hand inventory (20)	20	20	20	20	20	20
Net requirements						80
Planned order release					80	
10002-Case subassembly	Day					
	1	2	3	4	5	6
Gross requirements					80	
Scheduled receipts						
On-hand inventory (40)	40	40	40	40	40	
Net requirements					40	
Planned order release				40		
10003-Ballast subassembly	Day					
	1	2	3	4	5	6
Gross requirements					80	
Scheduled receipts						
On-hand inventory (20)	20	20	20	20	20	
Net requirements					60	
Planned order release				60		
10008-Rivet kit	Day					
	1	2	3	4	5	6
Gross requirements				40		
Scheduled receipts				10		
On-hand inventory (10)	10	10	10	10		
Net requirements				20		
Planned order release			20			
10009-Enclosure	Day					
	1	2	3	4	5	6
Gross requirements				40		
Scheduled receipts						
On-hand inventory (5)	5	5	5	5		
Net requirements				35		
Planned order release	35					
10004-Ballast thermal fuse	Day					
	1	2	3	4	5	6
Gross requirements				60		
Scheduled receipts						
On-hand inventory (0)	0	0	0	0		
Net requirements				60		
Planned order release			60			
10005-Coil	Day					
	1	2	3	4	5	6
Gross requirements				120		
Scheduled receipts						
On-hand inventory (0)	0	0	0	0		
Net requirements				120		
Planned order release			120			
10006-Wire kit	Day					
	1	2	3	4	5	6
Gross requirements			240			
Scheduled receipts			100			
On-hand inventory (0)	0	0	0			
Net requirements			140			
Planned order release	140					
10007-Tape kit	Day					
	1	2	3	4	5	6
Gross requirements			240			
Scheduled receipts						
On-hand inventory (80)	80	80	80			
Net requirements			160			
Planned order release		160				

Table 1.2: Net requirements plan for the heavy-duty transformer

1.3 Uncertainty theory

Without the existence of uncertainty MRP outputs would be a definitive, workable plan that would guarantee on time delivery, but in real life:

'Anything that can go wrong will go wrong' (Murphy's Law).

To put this quote into an MRP context, it suggests that a plan that was generated yesterday might not be executable today due to events that are both unpredictable and unexpected. An example of this uncertainty is late delivery of a purchased part from a supplier. The effect of this would be a delay in the manufacture of the parent assembly that is difficult to quantify because the loading on the shop floor when the part ultimately arrives may be very different to that planned when it was due to arrive. This may result in other planned work being displaced to make way for the delayed assembly or delay may be increased if a suitable production space cannot be found.

Cox and Blackstone (1998) defined uncertainty as unknown future events that cannot be predicted quantitatively within useful limits. Thus the occurrence of uncertainty is unpredictable, its effect is difficult to quantify. Since MRP is designed to operate in stable and predictable batch manufacturing environments (Dilworth, 1996), the presence of uncertainty may prevent optimum performance.

1.4 Performance of MRP based systems and initial hypothesis

Over the last thirty years, many millions of pounds and considerable man-years of effort have been invested in designing, developing and implementing MRP based systems. Boston-based Advanced Manufacturing Research predicts the Enterprise Requirements Planning market (using MRP as the core) will reach $66.6 billion by 2003 at an estimated compound annual growth rate of 32% (Angerosa, 1999). However, a contemporary study by Forrester Research identified that 40% of companies believe MRP based systems will not provide any optimisation capabilities while 46% expect them to play a partial role at best (Gormley, 1998).

In spite of such a rapidly growing market, MRP based systems were still identified as under performing. It was conjectured that the underlying causes of MRP under-performance have been neither completely recognised nor yet resolved. From this the initial hypothesis was derived, namely that MRP under-performance was due largely to the effects of uncertainty.

1.5 Research goal and objectives

Based on the initial hypothesis, the goal of this research was the development of a business model for diagnosing uncertainty in MRP environments to act as a tool to improve MRP performance. Objectives to achieve the goal were:

[1] To carry out a comprehensive literature review covering MRP capability and performance and uncertainty in MRP environments.

[2] To investigate how MRP performs in industry in the presence of uncertainty.

[3] To develop a business model of uncertainty in MRP environments.

[4] To verify the business model of uncertainty.

[5] To validate the business model of uncertainty.

1.6 Structure of the thesis

This thesis is presented in nine chapters. Chapter 1 introduces the theory of both MRP and uncertainty and looks briefly at the performance of MRP based systems. From this an initial hypothesis was derived and the research goal and objectives stated.

In Chapter 2, a comprehensive literature review is presented covering MRP benefits and limitations, performance of MRP based systems, identification and classification of uncertainties, the buffering and dampening approaches used to cope with uncertainty and performance measures used with MRP based systems. Questionnaire survey was selected to conduct both preliminary examinations into MRP performance and detailed investigations into uncertainty in industry and simulation was chosen to model the effects of different frequencies and magnitudes of uncertainty on MRP performance.

The design of a questionnaire survey, together with sampling procedures is described in Chapter 3. Results, analysis and discussion are reported and a categorisation system for MRP companies was derived.

Chapter 4 illustrates the derivation of a business model of causes and effects of uncertainty through the use of expert opinion.

A second questionnaire survey, together with sampling procedures is described in Chapter 5. The results of the survey were used to verify the business model, with Analysis of Variance (ANOVA) providing statistical confidence for the results.

Chapter 6 details the design logic, operating policies and development procedure to create a deterministic simulation model of a dependent demand MRP domain. The transient and steady state of the simulation model were established.

Chapter 7 identifies a range of uncertainties to be simulated and extends the simulation model to represent the uncertainties and their limits. This exercise serves to validate the business model of uncertainty. Experimental design methods and potential performance measures were introduced.

Experimental design and analysis of results for the simulation studies are presented in Chapter 8. Uncertainties were simulated firstly discretely, secondly as a complete set and thirdly as combinations of those found to be significant from the second stage. Results of the second and third stages were analysed using ANOVA.

Finally in Chapter 9 the achievement of research objectives, together with research contribution of the programme, a summary of the conclusions and recommendations for further research are presented. The potential impact of the research on company performance was also assessed.

Chapter 2: Literature review

2.1 Introduction

This chapter reports a comprehensive literature review of benefits, limitations and performance of MRP based systems and includes study on uncertainty in MRP environments. Many approaches, using many different performance measures have been proposed to cope with uncertainty, each of which will be reviewed. A review of research methodology is included, with the most appropriate approaches selected to attain the research objectives set.

2.2 Benefits of MRP

A multitude of benefits were claimed for MRP based systems, but a definitive list has proved elusive. A search of the theoretical literature was carried out, which identified eleven claimed benefits as shown in Table 2.1.

Having established these benefits, the search was extended to include case studies to see if the reality matched the theory. Twenty-one case study companies were identified from published sources, from which twenty-two additional benefits were identified as shown in Table 2.2.

Benefit	Authors	Year
Determination of order feasibility at planning stage	Dilworth Sipper and Bulfin	1996 1998
Design change flexibility	Dilworth	1996
Paperwork reduction	Clode	1993
Better inventory planning and scheduling	White *et al.* Cox and Clark Clode Heizer and Render Schlussel Dilworth Silver *et al.* Sipper and Bulfin	1982 1984 1993 1993 1994 1996 1998 1998
Reduced inventory	White *et al.* Cox and Clark The Oliver Wight Companies Clode Heizer and Render Schlussel Dilworth Chase *et al.* Sipper and Bulfin	1982 1984 1986 1993 1993 1994 1996 1998 1998
Increased sales	Cox and Clark Schlussel Chase *et al.*	1984 1994 1998
Better cash flow planning	Cox and Clark Dilworth	1984 1996
Improved plant efficiency	White *et al.* Cox and Clark Clode Heizer and Render Dilworth Sipper and Bulfin	1982 1984 1993 1993 1996 1998
Vendor rating	Sipper and Bulfin	1998
Reduced set-up and change-over costs	White *et al.* Cox and Clark Chase *et al.*	1982 1984 1998
Recommendations for order due date changes	Dilworth	1996

Table 2.1: Eleven claimed benefits of MRP in theory

Benefit	Case study company	Authors	Year
Reduced customer delivery lead-times	Negretti Aviation	Slack *et al.*	1995
	SKF Roller Bearings (Nice)	Dilworth, J.B.	1996
	AVO International	Guest, D.	1998
	Elkay	PeopleSoft	1998
	Harpers Inc.	Chase *et al.*	1998
	Huck Manufacturing	Alliance Manufacturing	1998
	Westomatic Vending Services	SAP	1998
	Nissan	The Oliver Wight Co	1998
Improved productivity	Herman Voss Gmbh & Co	SAP	1998
Reduced costs	Proctor and Gamble	The New York Times	1991
	Elkay	PeopleSoft	1998
	Herman Voss Gmbh & Co	SAP	1998
	Sony	The Oliver Wight Co	1998
Shorten transaction times	SKF Roller Bearings (Nice)	Dilworth, J.B.	1996
	Elkay	PeopleSoft	1998
	Harpers Inc.	Chase *et al.*	1998
	Herman Voss Gmbh & Co	SAP	1998
	Sony	The Oliver Wight Co	1998
Optimised quality controls	Collins Industries	Heizer and Render	1993
	Herman Voss Gmbh & Co	SAP	1998
Faster Return On Investment	Negretti Aviation	Slack *et al.*	1995
	Herman Voss Gmbh & Co	SAP	1998
Information sharing and communication	Proctor and Gamble	The New York Times	1991
	Bucklebridge	SAP	1998
	Dennis	The Oliver Wight Co	1998
	Elkay	PeopleSoft	1998
	Harpers Inc.	Chase *et al.*	1998
	Huck Manufacturing	Alliance Manufacturing	1998
	Nestle	QAD	1998
	Sony	The Oliver Wight Co	1998
Routing changes flexibility	Westomatic Vending Services	SAP	1998
Reduced number of suppliers	Elida Gibbs (Unilever)	Slack *et al.*	1995
	AVO International	Guest, D.	1998
Increased inventory accuracy	Collins Industries	Heizer and Render	1993
	Staedler	Slack *et al.*	1995
	SKF Roller Bearings (Nice)	Dilworth, J.B.	1996
	SKF Roller Bearings (PA)	Dilworth, J.B.	1996
	AVO International	Guest, D.	1998
	Bucklebridge	SAP	1998
	Elkay	PeopleSoft	1998
	Glaxo Wellcome	PeopleSoft	1998
	Harpers Inc.	Chase, *et al.*	1998
	Huck Manufacturing	Alliance Manufacturing	1998
	Sony	The Oliver Wight Co	1998
Improved inventory turns	Negretti Aviation	Slack *et al.*	1995
	SKF Roller Bearings (Nice)	Dilworth, J.B.	1996
	SKF Roller Bearings (PA)	Dilworth, J.B.	1996
	AVO International	Guest, D.	1998
	Bucklebridge	SAP	1998
	Glaxo Wellcome	PeopleSoft	1998
	Huck Manufacturing	Alliance Manufacturing	1998
	Westomatic Vending Services	SAP	1998
	Nissan	The Oliver Wight Co	1998
	Sony	The Oliver Wight Co	1998
Improved BOM accuracy	Collins Industries	Heizer and Render	1993
	Elida Gibbs (Unilever)	Slack *et al.*	1995
	Staedler	Slack *et al.*	1995
	SKF Roller Bearings (Nice)	Dilworth, J.B.	1996
	AVO International	Guest, D.	1998
	Elkay	PeopleSoft	1998
	Harpers Inc.	Chase *et al.*	1998
	Huck Manufacturing	Alliance Manufacturing	1998

Faster end-of-month accounting	Elkay Westomatic Vending Services	PeopleSoft SAP	1998 1998
Measurement of costs by job	Bucklebridge	SAP	1998
Local MRP run	Merit Brass Co	Flowers, A.	1993
BOM as Bill of Resources	Merit Brass Co Elkay	Flowers, A. PeopleSoft	1993 1998
Shorten supplier delivery lead-times	Merit Brass Co Elida Gibbs (Unilever) Nissan	Flowers, A. Slack *et al.* The Oliver Wight Co	1993 1995 1998
Improved MPS accuracy	Merit Brass Co Elida Gibbs (Unilever) Racal Recorders Staedler Harpers Inc. Huck Manufacturing Westomatic Vending Services Nissan	Flowers, A. Slack *et al.* Slack *et al.* Slack *et al.* Chase *et al.* Alliance Manufacturing SAP The Oliver Wight Co	1993 1995 1995 1995 1998 1998 1998 1998
Reduced backlogs	SKF Roller Bearings (Nice) SKF Roller Bearings (PA)	Dilworth, J.B. Dilworth, J.B.	1996 1996
New attitudes at every level of management	SKF Roller Bearings (Nice) Nestle	Dilworth, J.B. QAD	1996 1998
Increased routing accuracy	SKF Roller Bearings (Nice) AVO International Elkay Harpers Inc. Huck Manufacturing	Dilworth, J.B. Guest, D. PeopleSoft Chase *et al.* Alliance Manufacturing	1996 1998 1998 1998 1998
Coping with complexity of manufacturing systems	Elida Gibbs (Unilever)	Slack *et al.*	1995

Table 2.2: Twenty-two claimed benefits for MRP from case studies

In order to establish the relative importance of each benefit, a frequency analysis was carried out for the occurrence of each as claimed by the case study companies, with the top ten results shown in Figure 2.1.

2.3 Limitations of MRP

As with all control systems, MRP based systems must operate within control limits that are known and understood. There follows a brief explanation of some of the main limitations.

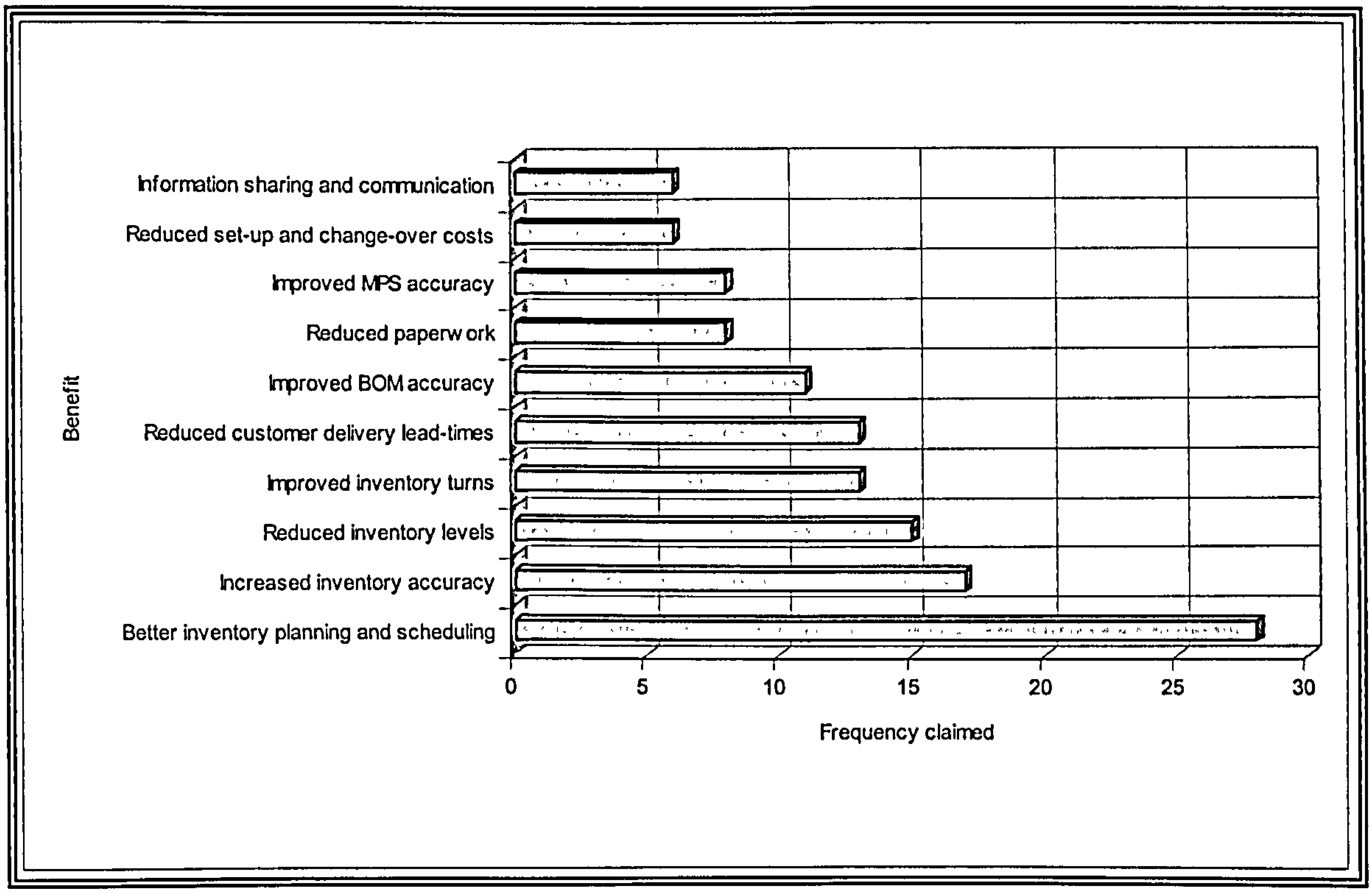

Figure 2.1: Frequency analysis for claimed MRP benefits

MRP based systems use fixed lead-times to plan purchases and manufactures. In reality, such lead-times are known to vary. Without controlling actions, component and/or product shortages/overages may occur, directly affecting total costs of the system and due date performance.

In infinite capacity systems, net requirement plans are created with no regard to the availability of resources, loadings for which are aggregated and reported separately, necessitating a re-planning loop. Advanced MRP based systems provide the facility to allow such re-planning and many also include finite scheduling. In reality, variable or unknown effects of efficiency losses and changes in utilisation are largely ignored.

MRP based systems use predefined routing(s) to sequence the flow of materials and subassemblies from work centre to work centre. In the case of unplanned events, necessary routing changes may occur that are not recorded in the system.

Variability in production quality may be incorporated by the use of a planned scrap rate. Any variation from this rate will affect either due date performance or yield or both.

All the above limitations of MRP based systems were widely recognised and researched by, amongst others, Watson (1993), Watson *et al.* (1995), Euwe *et al.* (1998) and Du and Wolfe (2000).

2.4 Performance of MRP

Research identified a mixture of successful and less successful applications of MRP based systems. The Oliver Wight Companies (1986) reported that companies implementing and operating MRP correctly find benefits even greater than expected. However, their study was based predominantly on what they define as 'A' class companies, representing only a proportion of total users. To support this, Turnipseed and Riggs (1992) reported that 77% of companies perform as well as they expected, according to their own criteria.

In contrast, White *et al.* (1982) and Duchessi *et al.* (1989) identified that 73% and 72% respectively of sample companies were dissatisfied with their MRP performance. In addition, Blood (1992), Ang *et al.* (1994), Capron (1994), Halsall *et al.*, (1994a), Turner and Saunders (1994), Turbide (1996), Gormley (1998), Yusuf and Little (1998) and Tinham (1999) all reported MRP users dissatisfied with their systems performance. All concluded that MRP under-performance was mainly due to ineffective implementation and lack of education. Ang *et al.* (1994) and Yusuf and Little (1998) also identified that a high degree of integration of MRP modules correlates highly with MRP success.

2.5 Classification of uncertainty

Chu and Hayya (1988), Yeung *et al.* (1998) and Guide and Srivastava (2000) have carried out reviews of parameters affecting MRP performance and approaches to cope with uncertainty, but none adopted a consistent classification structure. To correct this omission and to provide a structure for this literature review, a classification system has been devised.

The classification uses the principles of systems theory, which states that a system consists of an input, a process and an output. This approach can be adapted to classify uncertainty according to where it occurs within the manufacturing process. Table 2.3 shows the resulting definitions.

Uncertainty	Definition
Input	Uncertainties created from external supply and demand e.g. late delivery from supplier and customer changing delivery lead-time.
Process	Uncertainties created from internal supply and demand e.g. machine breakdown and labour absenteeism
Output	Uncertainties resulting from a combination of *input* and *process* uncertainties e.g. material shortages and scrap/rework

Table 2.3: Classification of uncertainty

A variety of approaches can be used to cope with the unwanted effects of uncertainty e.g. safety stock, safety lead-time, overtime and subcontract. The approach used depends on the type of uncertainty, the severity of its effect and company preferences. The classification system has been extended to include two classes of approach used to cope with uncertainty, namely buffering and dampening (BAD).

Buffering is defined as a quantity of resource waiting for processing (Cox and Blackstone, 1998), e.g. raw material, semi-finished stores or a work backlog that is purposely maintained behind a work centre. It can include other resources such as machines, labour and money. No previous classification has been given to those approaches that do not fit the Cox and Blackstone definition so the term dampening has been coined. They are mainly concerned with planning methodologies such as rescheduling and safety lead-time.

2.6 Uncertainty review

Each of *input, process* and *output* uncertainties was reviewed in turn. Both discrete and combination studies on uncertainty were considered, with associated BAD approaches used to cope with uncertainty and the experimental methods used by researchers explored.

2.6.1 *Input* uncertainty

A summary of the research on *input* uncertainty is shown in Table 2.4.

Input Uncertainty					
Type of uncertainty	Buffering approaches	Dampening approaches	Experimental methods used	Authors	Year
External supply	Safety stock	None	Simulation modelling	Grasso and Taylor	1984
External demand	Safety stock	None	Mathematical modelling	Miller	1979
		EOQ as lot-sizing rule	Mathematical modelling	Bodt *et al.*	1982
		None	Simulation modelling	Bodt and Wassenhove	1983
		Order Requirement Scheduling	Scheduling heuristic	Lowerre	1985
		None	Simulation modelling	Wemmerlov	1986
		Improving forecast accuracy	Simulation modelling	Sridharan and LaForge	1989
		Safety lead-time	Scheduling heuristic	Buzacott and Shanthikumar	1994
		'Dual-buffer' production scheduling policy	Scheduling heuristic	Vargas and Metters	1996
		Forecast tracking signal	Mathematical modelling	Krupp	1997
		SM and PPB as lot-sizing rules	Simulation modelling	Ho and Ireland	1998
	None	Freezing MPS	Mathematical modelling	Sridharan and LaForge	1994
		Safety production plans	Scheduling heuristic and Laplace transform methodology	Grubbstrom and Molinder	1996
		Improving forecast accuracy	Mathematical modelling	Fildes and Kingsman	1997
		Knowledge-based systems	Knowledge based and simulation modelling	Kochhar *et al.*	1998
External demand/ External supply	Safety stock	Safety lead-time	Simulation modelling	Whybark and Williams	1976
	Quantity trigger	Lot-sizing rule, time trigger and firm planned orders	Simulation modelling	Minifie and Davis	1990
	None	Open-order rescheduling	Scheduling heuristic	Ho *et al.*	1986
		Feedback model for production planning dataflow	Knowledge-based feedback modelling	Halsall *et al.*	1994b

Table 2.4: Summary of research on *input* uncertainty

2.6.1.1 External supply

Suppliers not delivering as planned were the main cause of external supply uncertainty. Although increasing research effort on the issue of Supply Chain Management was identified, it has not been incorporated in this review. There was little evidence of direct studies of external supply uncertainty within MRP environments.

Grasso and Taylor (1984) suggested that allowing purchased parts to arrive late more frequently than early would be advantageous since it resulted in lowest total costs. The results of their simulation modelling showed that when buffering against timing in supply, it was more prudent to use safety stock instead of safety lead-time. This contrasts with the results obtained by Whybark and Williams (1976), who suggested that safety lead-time should be used for timing uncertainty while safety stock was more appropriate for quantity uncertainty.

2.6.1.2 External demand

External demand uncertainty refers mainly to inaccurate forecasts and customer order changes and has been the predominant area within MRP research. Wacker (1985), Murthy and Ma (1991) and Yeung *et al.* (1998) supported this view. Study of Table 2.4 shows safety stock was the most used buffer against external demand uncertainty, with a wide range of dampening approaches.

Miller (1979) used mathematical modelling for hedging the MPS using safety stock. The MPS hedge was used to pull 'pipeline safety stocks' through a production inventory system to protect against stock-outs or undesirable backlogs. This was justified on the basis that value was added to a product over time.

Bodt *et al.* (1982) investigated the effect of time and demand variations on a number of lot sizing and safety stock policies. The results from mathematical modelling concluded that demand uncertainty had an influence on the cost effectiveness of lot sizing heuristics. It was identified that Economic Order Quantity (EOQ) performed better when forecast errors were very large making it more cost effective to dampen external demand uncertainty. When there was sufficient safety stock to cover the increased demand calculated from an EOQ lot-sizing rule, shortages would not occur assuming that the resources required were available.

One year later, Bodt and Wassenhove (1983) extended the research and identified that forecast errors had an effect on the cost effectiveness of lot-sizing techniques even when the forecast errors were small. Simulation showed that products with a relatively low ordering cost or small Time Between Order (TBO) gained more cost benefit from buffering (safety stock) than products with large TBO. They concluded that buffering was only appropriate with low demand variability and small TBO.

Lowerre (1985) suggested that Order Requirement Scheduling would be able to improve MRP performance by scheduling protective or safety stocks proportional to forecast errors of time and quantity. This scheduling heuristic allowed forecast errors to be dampened to meet production plans while eliminating 'noisy', 'jittery' schedules.

Wemmerlov (1986) simulated multi-dimensional effects of demand uncertainty and identified stock-outs, larger inventories and more orders occurred simultaneously when demand uncertainty was introduced. Service levels deteriorated and inventory levels increased when forecast errors became larger which required an injection of safety stocks to buffer the effect, increasing inventory levels and order frequency.

Sridharan and LaForge (1989) concluded that improved forecast accuracy and a reduction of set-up costs might be useful approaches to dampen schedule instability. Their simulation results suggested that safety stock should be used with caution if it was introduced for the purpose of stabilising schedules, possibly causing increased nervousness, and was especially ineffective when demand was highly uncertain. Increases in schedule stability consistently occurred when the expected TBO was reduced and the forecast errors were low.

Buzacott and Shanthikumar (1994), using a scheduling heuristic, concluded that safety lead-time was preferable to safety stock with accurate forecasts of future requirements over the lead-time. Otherwise, safety stock was more robust in coping with changes in customer requirements in the lead-time or with fluctuations in forecasts of lead-time demand.

Vargas and Metters (1996) identified that a 'dual-buffer' production scheduling heuristic outperformed a single buffer policy in stochastic demand environments. The 'dual-buffer' heuristic dampened demand uncertainty by establishing two levels of safety stock with differing functions: a safety stock level for triggering production and a different safety stock level for stock replenishment.

Krupp (1997) proposed a statistical model that expressed deviation in units of time rather than quantity to provide safety stock calculations that were responsive to trend and/or seasonality in future forecasts. Krupp used a forecast tracking signal to dampen forecast inaccuracy by adjusting safety stock calculations in cases where forecasts were consistently overoptimistic. A service factor multiplier was also designed to optimise the balance between safety stock carrying costs and recouped profit.

Through simulation modelling, Ho and Ireland (1998) found that forecast errors might not cause a high degree of scheduling instability. Scheduling instability or system nervousness could be dampened using an appropriate lot-sizing rule. Their study concluded that applying EOQ and Lot for Lot (LFL) created significantly more nervous systems than applying Silver Meal (SM) and Part Period Balancing (PPB).

A number of works were identified that applied only dampening approaches. The results of a mathematical model developed by Sridharan and LaForge (1994) showed that freezing the MPS reduced customer service in an uncertain demand environment, but the loss in service was predictable and not catastrophic.

Grubbstrom and Molinder (1996) identified that as uncertainty in product demand increased over time, uncertainty in current production schedules at lower BOM levels would be amplified. They devised safety production plans using Laplace Transform

Methodology, which incorporated future cumulative uncertainties of external demand and were taken into account before the parts explosion began. They found that as uncertainty in demand increased over time, compensation took place in the form of increasing safety stock.

Fildes and Kingsman (1997) identified that the behaviour of lot-sizing rules was quite different in conditions of demand uncertainty. The choice of lot-sizing rule between 'good' rules such as EOQ and Least Total Cost was relatively less important in reducing unit cost than improving forecast accuracy. The effect of demand uncertainty on unit cost for a given service level increased non-linearly as the variance of the demand increased. With high forecast errors and short TBO, their mathematical model suggested that by improving forecast accuracy, errors would be dampened and unit costs reduced. This finding is consistent with the results obtained by Sridharan and LaForge (1989).

Kochhar *et al.* (1998) proposed the use of a knowledge-based system to prevent an inaccurate and unrealistic MPS. By combining what-if simulation into a knowledge-based system it was hoped to identify potential problems in a tentative MPS, provide feasible solutions to the problems, simulate the implementation of these solutions and analyse the outcome of the simulation.

2.6.1.3 External demand and external supply

Whybark and Williams (1976) simulated supply and demand uncertainties with quantity and timing elements. They concluded that under conditions of uncertainty in timing, safety lead-time was the preferred dampening approach, while safety stock was preferred for buffering quantity uncertainty. These conclusions did not change with the source of uncertainty. It was also identified that supply timing uncertainty and demand quantity uncertainty gave the largest differences in service levels.

Minifie and Davis (1990) simulated a variety of different lot-sizes, quantity triggers, time triggers, firm planned orders and policy fences on a number of performance measures. The results from Multivariate Analysis of Variance showed that there was a significant effect derived from the buffering approach of quantity triggers and the dampening approaches of lot-sizes, time triggers and firm planned orders.

Ho *et al.* (1986) suggested a scheduling heuristic of releasing a less-than-planned-lead-time planned order to substitute for open-order quantity rescheduling. For manufacturing companies who preferred open-order rescheduling, they should first explore the possibility of using a less-than-planned-lead-time order.

Halsall *et al.* (1994b) created a knowledge-based feedback model for production planning dataflow. The feedback model displayed the current work completed and planned, a report of customer orders which were predicted not to meet required due dates and permitted the manager to input changes to the plan and recalculate the effect.

2.6.2 *Process* uncertainty

A summary of the research on *process* uncertainty is shown in Table 2.5.

Process Uncertainty					
Type of uncertainty	Buffering approaches	Dampening approaches	Experimental methods used	Authors	Year
Process yield losses	Mean yield rate and fixed buffer stocks with yield to finish, desired service level yield rate and variable yield rate by batch	None	Mathematical modelling	New and Mapes	1984
	None	Orlicky and marginal rules	Simulation modelling	Kurtulus	1996
Lot-sizing and planning horizon	None	Freezing MPS and forecast beyond the planning horizon	Simulation modelling	Blackburn *et al.*	1986
Quality variations	None	Over planning	Planning heuristic	Murthy and Ma	1991
Job operation times	None	Finite loading	Simulation modelling	Matsuura *et al.*	1995
Batch size variations	None	Optimum batch size selection	Simulation modelling	Enns	1999
Engineering changes	None	STEP-based integration	Simulation modelling	Yang and Pei	1999
Material release times	None	Real time optimisation	Simulation modelling	Homem-de-Mello *et al.*	1999
Capacity loading	None	None	Simulation modelling	Byrne and Mapfaira	1998

Table 2.5: A summary of research on *process* uncertainty

2.6.2.1 Process yield losses

New and Mapes (1984) studied the effect of process yield losses. Their mathematical model showed that the application of mean yield rate and fixed buffer stock was appropriate for continuous schedule make-to-stock (MTS) environments. In continuous schedule make-to-order (MTO) environments, mean yield rate, fixed buffers and a yield to finish monitoring system were suitable. For single batch production MTO environments it was more appropriate to use mean yield rate, fixed buffers and a desired service level yield rate. Multiple batch production MTO environments should use mean yield rate, fixed buffers and a variable yield rate by batch.

Kurtulus (1996) simulated the Orlicky, Marginal, Expected value and Compound Yield Rules to dampen yield loss. The results showed that the Orlicky and Marginal Rules performed better in over-planning at the MPS level then the Compound Yield Rule, which over-plans only at the component level.

2.6.2.2 Lot-sizing and planning horizon

Blackburn *et al.* (1986) studied the effect of freezing schedules within the planning horizon using LFL lot sizing. Safety stocks, forecasts beyond the planning horizon and change cost procedures were also applied. The simulation results indicated that when sources of nervousness were due to changes in decisions caused by a rolling planning horizon, safety stock and LFL approaches were not cost effective. The study concluded that by freezing the MPS and forecasting beyond the planning horizon, lot sizing and planning horizon nervousness could be dampened.

2.6.2.3 Quality variations

Murthy and Ma (1991) identified two measures of defectiveness: individual items being defective or not and the number or fraction of non-defective items in a batch. They developed an over-planning dampening approach to resolve quality uncertainty that led to smaller over-planning since it tried to balance excess costs with shortage costs.

2.6.2.4 Job operation times

Matsuura *et al.* (1995) used simulation to model finite and infinite loading. They concluded that by considering workload status superior results were achieved when faced with uncertainty in job operation times. However, the superiority deteriorated when uncertainty was high.

2.6.2.5 Batch size variations

A simulation study by Enns (1999) on the effect of batch size selection showed that batch size affected inventory and delivery performance. For both measures, the larger the finished product batch size, the tardier the delivery performance and the higher the inventory level.

2.6.2.6 Engineering changes

Yang and Pei (1999) simulated the impact of engineering changes within a Standard for Transfer and Exchange Product (STEP) model database integration environment. For each engineering change activity the Engineering BOM data was extracted from a Computer Aided Design database and translated to Manufacturing BOM data stored in an MRP database. The modified MRP record was generated and compared with the original data. Based on this information, a designer could determine a suitable design alternative such that the impact on inventory was reduced to a minimum.

2.6.2.7 Material release times

Homem-de-Mello *et al.* (1999) simulated an MRP environment with process lead-time variation mimicking the uncertainty of material release times. The outcome suggested that to minimise tardiness and flow time costs, a real-time optimisation dampening approach should be used.

2.6.2.8 Capacity loading

Byrne and Mapfaira (1998) simulated system performance with uncertainty in capacity loading. They classified the effects of uncertainty into three levels of variation: no variability, low variability and high variability. The results of the simulation showed that performance of a batch production system was significantly affected when the system was overloaded. It was found that systems with low variability outperformed all others as a consequence of positive knock-on effects from normal lead-time variations.

2.6.3 *Output* uncertainty

A summary of research on *output* uncertainty is shown in Table 2.6.

Output Uncertainty					
Type of uncertainty	Buffering approach	Dampening approaches	Experimental method used	Authors	Year
Scrap	Safety stock	Expected-value and marginal rules	Simulation modelling	Kurtulus and Pentico	1988

Table 2.6: A summary of research on *output* uncertainty

2.6.3.1 Scrap

Kurtulus and Pentico (1988) studied the dampening effect of Expected value and Marginal rules on scrap losses. Simulation results showed the Expected value rule produced minimum component inventory and the Marginal rule produced minimum shortages of MPS requirements.

2.6.4 *Input* and *process* uncertainties in combination

A summary of research on *input* and *process* uncertainties in combination is shown in Table 2.7.

Input and *process* uncertainties								
Input uncertainty	Buffering approaches	Dampening approaches	Process uncertainty	Buffering approaches	Dampening approaches	Experimental methods used	Authors	Year
External supply	Protective capacity	None	Quality variations	Protective capacity	None	Simulation modelling	Atwater and Chakravorty	1994
			Breakdowns					
	None	Overplanning	Quality variations	None	Overplanning	Mathematical modelling	Murthy and Ma	1996
		Scheduling lead-time	Process lead-time		Scheduling lead-time	Simulation modelling	Kanet and Sridharan	1998
			Interop move time					
			Queue wait time					
External demand	Safety stock	Net change schedule	Capacity loading	Safety capacity	Regenerative schedule	Simulation modelling	Schmitt	1984
		None	Variability in set-up and run times		None	Simulation modelling	Vargas and Dear	1991
			Variability in resources supply	Safety stock				
		Safety lead-time	Process lead-time variations		Safety lead-time	Simulation modelling and Simulated annealing	Molinder	1997
	None	Pegging Stabilise lot-sizing Firm planned order	Allocation not issued in expected quantity	None	Pegging Stabilise lot-sizing Firm planned order	Planning heuristic	Steele	1975
			Order released in unplanned quantity					
			Order released early					
		SM and EOQ as lot-sizing rules	Process lead-time		SM as lot-sizing rule	Scheduling heuristic	Ho	1993
		Static dampening Auto rescheduling Cost-based dampening	System uncertainty		Static dampening Auto rescheduling Cost-based dampening	Simulation modelling	Ho and Carter	1996
		PPB, SM and EOQ lot sizing rules	Process lead-time		PPB, SM and EOQ lot sizing rules	Simulation modelling	Ho and Ho	1999
		None	Set-up and process times Breakdowns		None	Questionnaire survey	Halsall *et al.*	1994b
External supply and demand	Safety stock	None	Internal supply	Safety stock	None	Mathematical modelling	Wacker	1985
	None		Process lead-time	None		Simulation modelling	Brennan and Gupta	1993
	Safety stock Safety capacity	Safety lead-time Reschedule	System uncertainty	Safety stock Safety capacity	Safety lead-time Reschedule	Simulation modelling	Ho *et al.*	1995

Table 2.7: A summary of research on *input* and *process* uncertainties in combination

2.6.4.1 External supply and *process* uncertainties

Atwater and Chakravorty (1994) identified the viability of using protective capacity at non-constraints above the systems constraints capacity. The external supply uncertainty considered was late receipt of material; the *process* uncertainties were quality variations and breakdowns. Simulation results showed that production lines with protective capacity required fewer inventories in the system to achieve relatively stable cycle times.

Murthy and Ma (1996) studied uncertain product quality due to external supply and production processes. A mathematical model was developed to measure the optimal overplanning factor for scrap resulting from the uncertainty. This optimal overplanning factor would be used to dampen the uncertainty in the planning process.

Kanet and Sridharan (1998) applied actual scheduling lead-times as their only dampening approach. Their simulation modelling examined the external supply uncertainty of late delivery of raw materials while *process* uncertainties included process lead-time, interoperation move time and queue waiting time. Queue waiting time was the most dominant, but it did not necessarily have the greatest effect on company performance. This raised the question of whether to keep resources busy at all times, i.e. minimising queues, or to keep work in progress (WIP) relatively high, i.e. make only what was needed. Their results suggested that scheduling lead-time information could be used to tightly plan raw material deliveries, significantly reducing raw material inventory.

2.6.4.2 External demand and *process* uncertainties

Schmitt (1984) studied external demand and capacity loading uncertainties. The effectiveness of safety stock on three different rescheduling policies of regenerative update, safety capacity under regenerative update and net change update were simulated. The study concluded that safety stock and net change scheduling were more effective for buffering and dampening forecast errors. Safety capacity and regenerative scheduling were suitable for capacity loading uncertainties.

Vargas and Dear (1991) studied the effects of safety stock located at all production stages, safety lead-time for all end and component items, safety capacity and forecast inflation. Simulation results showed that when there was variability in demand or resource supply, safety stock performed best but at the cost of increased inventory. Safety capacity performed second best, with lower inventory levels but additional fixed investments. When there was variability in set-up and run times, safety capacity performed best. They identified that set-up and run time variability caused the most systems disruption, whereas end item demand variability was the uncertainty hardest to eliminate.

Molinder (1997) examined external demand and process lead-time uncertainties and variations in stock-out cost/inventory holding cost ratio using simulation modelling and simulated annealing. The results showed that when using safety stock in high demand and low lead-time uncertainty environments, minimum total costs were achieved. When both demand and lead-time uncertainties were high, the lowest cost was obtained by using safety lead-time. Molinder concluded that for a low stock out/inventory holding cost ratio, the safety stock principle dominated in all cases. For higher values of this ratio, safety lead-time was preferred, particularly with high demand uncertainty.

Steele (1975) studied nervous systems caused by MPS changes and unplanned external demand. *Process* uncertainties included allocations not issued in expected quantity, orders released in unplanned quantity and orders released prematurely. The results from the planning heuristic suggested that using pegging, stabilising lot sizes and firming planned orders could dampen MRP nervousness.

Ho (1993) studied external demand and process lead-time uncertainties discretely. The results from the scheduling heuristic showed the SM lot-sizing rule performed best under demand and process lead-time uncertainties. With low process lead-time uncertainty, lot sizing could be evaluated by traditional set-up and carrying cost measures but as the uncertainty increased, the rescheduling cost became a more important component. Ho concluded that dampening system nervousness did not necessarily lead to better system performance as measured by total costs. Ho also concluded that EOQ performed better in low demand uncertainty rather than high demand lumpiness environments. This specific conclusion contradicts Bodt *et al.* (1982).

In a simulation study carried out by Ho and Carter (1996), automatic rescheduling, static and cost-based dampening were modelled to cope with external demand and system uncertainties. The results indicated that performance of a dampening procedure depended upon the operating environment and also that reductions in uncertainties, as measured by rescheduling frequency, did not necessarily lead to better system performance, rather it was the appropriate use of dampening procedures that resulted in system improvement.

Ho and Ho (1999) extended the work carried out by Ho (1993) to add that the PPB lot-sizing rule performed equally as well as SM when demand and process lead-time uncertainties were high.

A questionnaire survey by Halsall *et al.* (1994b) identified that under-performance of systems was due to both internal and external uncertainties. In the survey, external demand, set-up time, process time and breakdowns were studied, with the conclusion that external demand uncertainty appeared significant e.g. customer requirements were not entirely known before jobs were started and delivery dates were subject to change after a job had commenced. It was also found that internal factors such as job processing times caused appreciable problems.

2.6.4.3 External demand and external supply with *process* uncertainties

Wacker (1985) developed a theoretical model that considered quantity and timing variations in external demand and internal and external supply. An empirical methodology was developed to estimate safety stock statistically. Wacker concluded that MRP should not have to be monitored constantly for demand and supply variations, but have these variations taken into account by the system itself.

Brennan and Gupta (1993) simulated the effects of external demand, supplier lead-time and process lead-time uncertainty on product structure, product structure variant, demand variant, lead-time-bias-factor, set-up to holding cost ratio, shortage cost and lot-sizing rules. ANOVA showed that all uncertainties modelled were individually and interactively significant determinants of performance. The number of items at a given level in the product structure and its shape were significant when lead-time and demand uncertainties were applied. The choice of lot-sizing rule and the ratio of set-up to holding cost had a significant impact on performance.

Ho *et al.* (1995) simulated an uncertainty-dampening framework to reduce system nervousness caused by external demand and external supply and *process* uncertainties. They classified dampening approaches into inventory-oriented, including safety stock, safety lead-time and safety capacity, and information-oriented including static and cost-based dampening and automatic rescheduling. The work suggested that safety stock and safety capacity were appropriate to buffer external demand, external supply and systems uncertainties, whereas safety lead-time and rescheduling were appropriate to dampen them.

2.6.5 *Process* and *output* uncertainties in combination

A summary of research on *process* and *output* uncertainties in combination is shown in Table 2.8.

Process and *output* uncertainties								
Process uncertainty	Buffering approach	Dampening approach	Output uncertainty	Buffering approach	Dampening approach	Experimental method used	Authors	Year
Process lead-time	None	None	Scrap	None	None	Simulation modelling	Pandey and Hasin	1998

Table 2.8: A summary of research on *process* and *output* uncertainties in combination

2.6.5.1 Process lead-time and scrap

Pandey and Hasin (1998) simulated the impact of scrap on process lead-time in a shop with an intermittent-flow, batch-oriented, discrete-parts manufacturing environment, producing MTS items. They identified the need for process lead-time adjustment when the planned scrap level differs to the actual scrap level.

2.6.6 *Input, process* and *output* uncertainties in combination

A summary of research on *input, process* and *output* uncertainties in combination is shown in Table 2.9.

Input, process and *output* uncertainties								
Input uncertainty	Dampening approaches	Process uncertainty	Dampening approaches	Output uncertainty	Dampening approaches	Experimental methods used	Authors	Year
External demand	Integration of machine system and MRP design	Work centre breakdowns Operator absence Tooling unavailability	Integration of machine system and MRP design	Material unavailability Scrap/rework WIP lost	Integration of machine system and MRP design	Questionnaire survey	Turner and Saunders	1994
External demand and external supply	None	Plant fall down Lot-size changes Lead-time changes Safety stock changes Engineering changes Record errors Unplanned transactions	None	Scrap/spoilage	None	Planning heuristic	Mather	1977

Table 2.9: A summary of research on *input, process* and *output* uncertainties in combination

2.6.6.1 External demand, *process* and *output* uncertainties

Turner and Saunders (1994) conducted a questionnaire survey including most types of uncertainty except external supply and concluded that schedule disturbance derived from material unavailability, customer order changes, work centre breakdown, operator absence, scrap/rework, tooling unavailability and WIP lost. They suggested that integration of machine system and MRP design could dampen all types of uncertainties studied.

2.6.6.2 External demand and external supply, *process* and *output* uncertainties

Mather (1977) studied MPS changes and vendor fall down as *input* uncertainties together with a variety of process uncertainties. The results from the planning heuristic suggested that rescheduling was the main cause of nervousness. The study concluded that by attacking the causes of rescheduling, nervousness could be reduced or eliminated significantly and that dampening approaches should be considered only after the elimination of MRP nervousness. It was identified that most reschedules were not caused by reactions to customer wishes, but resulted from sophisticated mathematical algorithms for calculating lot-sizes and lead-times and from poor execution of manufacturing plans.

2.7 Summary of uncertainties reviewed

Figure 2.2 shows a summary of the main *input, process* and *output* uncertainties identified within the literature review.

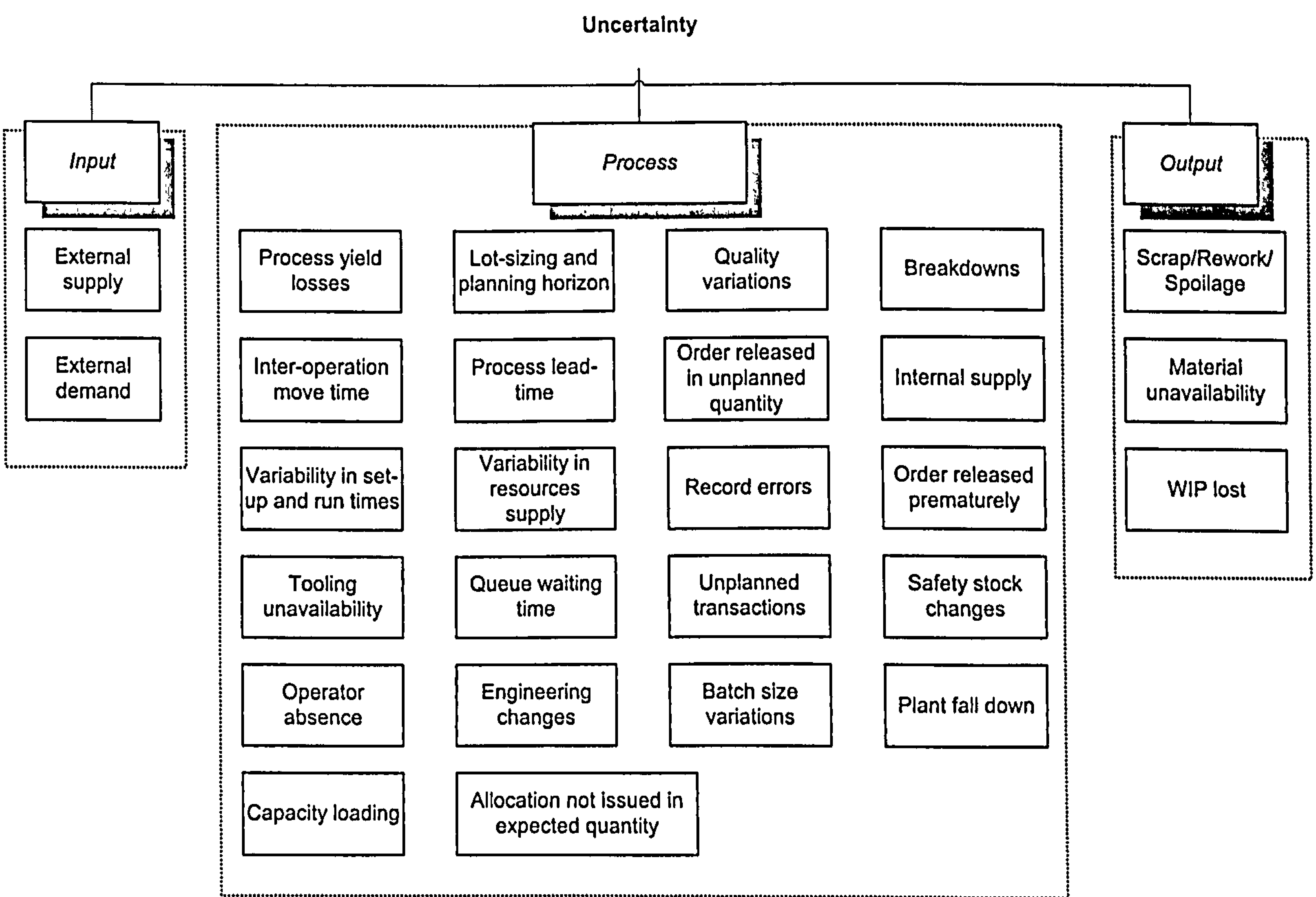

Figure 2.2: Types of uncertainty identified from the literature review

2.8 Performance measures

A range of performance measures identified from the literature review is shown in

Table 2.10. They have been classified into six main types namely cost-related, service-related, schedule-related, over-planning-related, inventory-related and multiple measures. Amongst the authors who used single measures, only two used service related measures. This was an interesting finding as it could be argued that service level was the ultimate objective for many companies.

Years	Authors	Performance measures
		Single Measures
		Cost
1982	Bodt *et al.*	Cost effectiveness
1983	Bodt and Wassenhove	Cost effectiveness
1984	Grasso and Taylor	Cost effectiveness
1985	Lowerre	Cost effectiveness
1986	Blackburn *et al.*	Cost effectiveness
1993	Ho	Carrying cost, set-up cost and rescheduling cost
1997	Fildes and Kingsman	Cost effectiveness
		Service
1976	Whybark and Williams	Service level
1994	Sridharan and LaForge	Customer service
		Schedule
1989	Sridharan and LaForge	Schedule instability
1996	Ho and Carter	Rescheduling frequency
1998	Ho and Ireland	Schedule instability
		Overplanning
1996	Murthy and Ma	Optimal overplanning factor
		Inventory
1999	Yang and Pei	Inventory level
		Multiple Measures
1984	New and Mapes	Cost effectiveness and customer satisfaction
1984	Schmitt	Capacity loading, capacity variability, inventory level and cost effectiveness
1986	Wemmerlov	Service level, inventory level and order frequency
1988	Kurtulus and Pentico	Inventory level and component shortage
1990	Minifie and Davis	Late delivery, number of set-up, ending inventory level, component shortage and number of exception report
1991	Vargas and Dear	End item inventory level, capacity utilisation, accumulative backorders and customer support
1993	Brennan and Gupta	Cost effectiveness and service level
1994	Atwater and Chakravorty	Inventory level and cycle time
1995	Matsuura *et al.*	Average loading times, Capacity requirements variations and overtime rate
1997	Molinder	Total cost and stock out level
1998	Byrne and Mapfaira	Average machine utilisation, average queue length, average queue delay, average component waiting time, average component flow time, average order lateness and average number of late orders
1999	Enns	Mean finished product tardiness and WIP inventory level
1999	Ho and Ho	Total cost of system and weighted rescheduling
1999	Homem-de-Mello *et al.*	Tardiness and flow time cost

Note: Researchers not using particular performance measures do not appear

Table 2.10: Performance measures used by the researchers in the review

2.9 Research methodology

It has been established from the literature review that a variety of research methodologies have been used to study uncertainty. These have been reviewed, along with the additional methodologies of interview and case study with the intention of establishing the most suitable methods for this research programme.

2.9.1 Mathematical modelling

Mathematical modelling uses derived algorithms to model quantifiable uncertainties to allow, for example, maximisation or minimisation of performance measures within specified parameters.

It was identified from the literature review that mathematical modelling has been regularly adopted, mainly through linear programming. It was also particularly suitable to be applied after simulation to develop generic metamodels (Law and Kelton, 2000).

The major restriction was the number of simultaneous parameters that can be modelled. Additionally, to create a robust algorithm, all interactions between parameters must be known in advance.

2.9.2 Analytical modelling

Analytical modelling uses both quantitative and/or qualitative data within a structured set of algorithms. The main difference from mathematical modelling is that scenarios may be developed to aid decision making under conditions of complexity. A number of recognised techniques use this approach including the MRP algorithms themselves, spreadsheets and decision support tools such as the Analytical Hierarchy Process.

The major application within the literature was the use of MRP software and spreadsheet modelling. A particular value was in performing 'what-if?' analysis to identify the effects of discrete variations within complex environments. Conversely, it was not easily possible to identify the significance of individual variations when applying multiple variations to the analytical models.

2.9.3 Simulation modelling

Law and Kelton (2000) defined simulation as a method for studying a wide variety of real world systems by numerical evaluation using software designed to mimic the system's operations or characteristics, often over time.

Simulation modelling was identified from the literature review as the predominant approach adopted. It can model combinations of parameters and their variations and can be used to identify interactions occurring between parameters. Most simulation software is written in special-purpose languages, such as SIMANV, SLAMII and SIMUL8. When extra functionality is required, other general-purpose languages such as Fortran, VBA and C++ can be integrated. This produces a higher level of flexibility in modelling.

The major drawback was the need to validate simulation models against measurable real-life scenarios. The outputs from simulation will represent scenarios that have not yet been encountered in real-life, so until the scenario was implemented full validation was impossible.

2.9.4 Questionnaire surveys

Questionnaire surveys use a sampling approach to ask both open-ended and closed questions, enabling customised data collection from a sample population. It requires effort to identify suitable respondents, to ask the right questions and to encourage a statistically acceptable response rate.

The literature review identified some use of postal surveys, for which the response rate is known to be very low compared to other sampling approaches such as quota sampling. A 30% response rate would be considered excellent (Belson, 1986).

Structured approaches to performing questionnaire surveys are widely available, including Oppenheim (1992) and Cooper and Schindler (1998). After collation of results, various statistical analyses can be applied such as Student t-test, regression analysis and ANOVA.

Prior to statistical examination, responses must be verified to remove errors and misrepresentations. Once this was done and provided the sample size was statistically large enough to represent the general population, the conclusions made can be generalised.

2.9.5 Interviews

Interview, for which no evidence was found from the literature review, is the oldest and yet sometimes the most ill-used research methodology (Wragg, 1987). Any interview must have clearly defined objectives that are satisfied by identifying suitable persons, asking the right questions and most important of all making valid observations and interpretation of the results. In this way, expert opinion may be sought.

Interviews have great flexibility as they can be tailored to circumstances. However, care must be taken in planning and controlling interviews as well as drawing valid conclusions. An ever-present danger of interviewer bias exists.

2.9.6 Case studies

Case studies incorporate a variety of data collection approaches within single or small groups of companies, from which analysis is carried out and conclusions are drawn. A sufficient time period has to be spent to observe, to collect relevant information and to analyse performance. This industrial exposure provides the opportunity to gain insight in case companies that cannot be achieved by conducting a questionnaire survey or interview. Results are only applicable to the companies studied and are useful to verify data collected by other means and also as 'test-beds' for theories developed.

2.10 Conclusions

The literature review clearly highlighted a number of aspects of uncertainty in MRP environments. The most important of which were:

[1] MRP under-performance has been found even after extensive research on uncertainty covering, in this review, the years 1977 to 2000.

[2] There was no evidence for the existence of a detailed structure of types of uncertainty making it impossible to identify whether underlying causes or merely effects were being addressed. The relative significance of different uncertainties was not established under any operating conditions, making the selection of BAD approaches relevant only to the specific problem being addressed and not to manufacturing system performance as a whole.

[3] Few research works were identified that studied *input*, *process* and *output* uncertainty in combination, with most studying only discrete uncertainties.

[4] Considering *input* uncertainties of external demand and external supply, the former has received more research attention than the latter.

[5] It was identified that *process* uncertainty studies dominated all others. This was due to the large range of *process* uncertainties occurring within MRP environments. However, few *output* uncertainties have been explored.

[6] Safety stock was the predominant buffering approach used to cope with a variety of uncertainties. No predominant dampening approach was identified.

[7] A wide range of performance measures has been used to assess the effects of uncertainties and the effectiveness of BAD approaches. The absence of a definitive measure made study comparison largely invalid.

[8] Little research has identified the significance of interactions between uncertainties.

[9] The type of operating environment, e.g. MTS, MTO has been largely

ignored as a factor in the study of uncertainty. The implicit assumption was that characteristics of specific operating environments were not seen to be important in examining the effect of uncertainty and BAD approaches.

[10] Although the logic of MRP was well known and understood, no simulation representing this logic in its entirety could be found. Although some claims were made, they were unsupported.

[11] Past research has mainly created simulations that allowed free flow of materials into the system and subsequent matching for assembly operations. Such simulations were controlled by process times rather than by MRP planned lead times. MRP operating in a batch environment with release into assemblies at higher BOM levels governed by a Planned Order Release (POR) has not been truly represented.

[12] From the research methodologies discussed, the uses of questionnaire survey, interview (expert opinion), analytical modelling and simulation modelling have been identified as suitable in this research area.

2.11 Programme of work

The literature review has highlighted a number of research gaps. Since MRP under-performance was encountered it may be due to those gaps. Therefore, areas in which research should be directed in this thesis include:

[1] Development of a structure for diagnosing significant uncertainties that considers the effects of uncertainty and also the underlying causes. The provision of a causes and effects business model for diagnosing uncertainty would ultimately facilitate the application of BAD approaches for coping with significant underlying causes.

[2] Development of a business model of uncertainty should take a holistic approach to causes and effects.

[3] Research in the effectiveness and efficiency of BAD approaches to examine what industry was actually doing.

[4] Derivation of a common performance measure to enable comparison between the significance of uncertainty in MRP environments and the effectiveness of BAD approaches for coping with uncertainty.

[5] A study of different operating environments to establish the levels and types of uncertainties faced.

[6] Development of a true multi-product, multi-level dependent demand MRP simulation model driven by POR.

[7] An analysis of significance of individual uncertainties and their interactions using typical industrial parameters.

Chapter 3: Preliminary examination of MRP performance in industry

3.1 Introduction

While the literature review exposed the existence of many different uncertainties, no evidence could be found to establish how industry actually performed in the presence of uncertainties. This chapter explains the preliminary investigation carried out to investigate MRP performance in the presence of uncertainties, through the design, application and interpretation of a questionnaire survey.

Although some general questions were included, the main purpose of the survey was to measure the benefits of MRP achieved and the effects of uncertainty experienced, to establish the significance of a variety of performance measures and to identify BAD approaches employed to cope with uncertainty.

3.2 Design of first questionnaire survey

This questionnaire was structured in four sections and is shown as Appendix 1. The first section examined general company background to include a profile of respondents by size, manufacturing sector and operating environment. Section two sought to establish the level of MRP benefits experienced. The third section assessed performance of MRP from both systems and operational aspects. The systems assessment included planning and execution policies, the complexity of BOM's and the proportion of bought-out, made-in and subcontracted parts while the operational assessment included the effects of uncertainty experienced, the delivery performance to customer and the significance of a number of performance measures. The last section examined BAD approaches used to cope with uncertainty.

3.2.1 Section 1 – company details

A normal method of company comparison is by size, measured by number of employees and annual turnover. To allow this comparison, company size definitions according to the Department of Trade and Industry (DTI) were used as shown in Table 3.1.

Description	Number of employees	Annual turnover
Small	< 50	< £2.8 million
Medium	50-249	< £11.2 million
Large	≥ 250	> £11.2 million

Table 3.1: DTI definitions of company size

Manufacturing sector was not included as a specific question on the survey; instead it was to be assessed through examination of products produced according to the Office of National Statistics (ONS) system as shown in Table 3.2. A short key was allocated to each sector to aid analysis.

Finally, the operating environment of the respondents was to be established from product mix according to custom made, Assemble-To-Order/Make-To-Order (ATO/MTO), or MTS policies as described by Cox and Blackstone (1998).

3.2.2 Section 2 – MRP benefits

To identify whether the claimed benefits of MRP were achieved in practice, the ranking of MRP benefits identified from the literature (Section 2.2) was requested. A five-point Likert scale was designed for this purpose as shown in Table 3.3.

Short key	ONS definitions
1FBT	Food products; beverages and tobacco
2T/TP	Textiles and textile products
3WDF	Wearing apparel; dressing and dyeing of fur
4L/LP	Leather and leather products
5W/WP	Wood and wood products
6PP/PP	Pulp, paper and paper products
7PPR	Publishing, printing and reproduction of recorded media
8CRPNF	Coke, refined petroleum products and nuclear fuel
9CPMF	Chemicals, chemical products and man-made fibres
10RPP	Rubber and plastic products
11ONMP	Other non-metallic mineral products
12BM	Basic metals
13FMP	Fabricated metal products, except machinery and equipment
14ME	Machinery and equipment not elsewhere classified
15OMC	Office machinery and computers
16EM	Electrical machinery and apparatus not elsewhere classified
17RTCE	Radio, television and communication equipment and apparatus
18MPOI	Medical, precision and optical instruments, watches and clocks
19MVT	Motor vehicles, trailers and semi-trailers
20OTE	Other transport equipment
21OM	Manufacturing not elsewhere classified

Table 3.2: ONS definitions of UK manufacturing sectors

Point	Definition
1	Need major improvement
2	Need significant improvement
3	Need on-going improvement
4	Need little improvement
5	Need no improvement

Table 3.3: Five-point Likert scale to rate MRP benefits achieved by industry

3.2.3 Section 3 – MRP performance

Cox and Blackstone (1998) identified that uncertainty is difficult to quantify. To ease collection of empirical data, bandwidths for the measurement of uncertainty have been introduced. Exponential bandwidths were used to allow coverage of a wide span of levels of effects of uncertainty in a very few bandwidths. In order to conduct consequent analysis, the bands were converted into a classification scale. Table 3.4 shows the survey bandwidths and classification scale.

Bandwidths	Scale
< 2%	1
(2-5)%	2
(6-15)%	3
(16-30)%	4
> 30%	5

Table 3.4: Survey bandwidths and classification scale

In the preliminary investigation, only eight uncertainties were examined, derived from Mather (1977) and Turner and Saunders (1994). These were late delivery from supplier, engineering design changes, rework, machine breakdown, materials shortages, labour shortages, customer order changes, and MPS changes.

Late delivery to customer was identified using the same bandwidths and scale.

To examine the relative significance of measures used to assess MRP based systems, the top-ten MRP benefits identified from the literature review were re-described in terms of performance measures as shown in Table 3.5. Respondents were asked to rank these according to a ten-point Likert scale.

MRP benefits	Performance measures
Better inventory planning and scheduling	Efficiency in production planning and control
Increased inventory accuracy	Improvement in procurement
Reduced inventory levels	Reduction in inventory values
Improved inventory turns	Improvement in parts tracking
Reduced customer delivery lead-times	Improvement in meeting customer due dates
Improved BOM accuracy	Reduction in WIP values
Reduced paperwork	Reduction on non-added value activities
Improved MPS accuracy	Improvement in forecast accuracy
Reduced set-up and change-over costs	Reduction in supply and manufacture total lead-times
Information sharing and communication	Total enterprise integration

Table 3.5: MRP benefits and corresponding performance measures

3.2.4 Section 4 – BAD approaches

To examine BAD approaches used by industry, respondents were asked to identify which they used from a list. The complete list is included in Appendix 1.

Mapping analysis was carried out to identify the approaches most used according to the level of delivery performance achieved and the level of uncertainty encountered. Table 3.6 shows the categories of MRP user designed for this purpose. Any responses not falling within these categories would be excluded from further analysis to ensure concentration on the extremes of performance only.

Category	Late delivery to customer	Level of uncertainty
Good	≤5%	≤5%
Poor	≥16%	≥16%
Laggard	≥16%	≤5%
Improver	≤5%	≥16%

Table 3.6: Categorisation of MRP users

3.2.5 Sampling procedures

Various attempts were made to find information on companies that use MRP based systems in the UK. These included: -

- MRP/ERP software vendors,
- MRP/ERP information web sites,
- MRP/ERP software implementers/partners,
- The Oliver Wight Companies,
- The Business Link Database, and
- The Institute of Electrical Engineers *Bite* Database.

Software vendors and implementers/partners were reluctant to provide details of their customer base. From some 30 companies contacted, none were prepared to provide a list of customers, with a few referring to web sites that gave details only of successful implementations. The combination of these scenarios implied that vendors and implementers/partners were reluctant to share their 'failures'.

As a long-standing organisation within the field, The Oliver Wight Companies were expected to have information on companies that used MRP based systems, but they would only provide their 'Class A' examples, representing users in the excellent category. If any survey were directed only to the 'successful' companies, it would have produced unacceptable bias. Neither of the databases examined contained any relevant data.

In the absence of any definitive data regarding MRP users, the survey was directed to general manufacturing companies in the UK, with a first filter of identifying MRP users. With a non-representative sample and an expected low response rate, a large sample was needed to ensure a sufficient number of MRP users would be found.

The questionnaire was sent to a sample of 2500 manufacturing companies in the UK, addressed to named individuals identified from University of Hertfordshire records of partner companies and the DTI Business Link Hertfordshire Database.

3.3 Results, analysis and discussion

3.3.1 Profile of respondents

The overall response rate was 17.36% without follow-up activity. Due to the non-representative sample involved this response rate was considered acceptable. Table 3.7 shows the nature of the respondents.

Nature of respondents	Number of respondents	% of respondents from original sample size (2500)	% of respondents from responses sample size (434)
MRP users	126	5.04	29.00
MRP users no information	36	1.44	8.00
MRP users at infant stage	31	1.24	7.00
Non MRP users	241	9.64	56.00
Total responses	434	17.36	-

Table 3.7: Nature of respondents

44% of respondents used MRP based systems, but only 29% were useful as some 15% either provided no further information or were at the infant stage of implementation.

Figure 3.1 summarises MRP users by company size showing the majority of MRP users tended to be medium and large companies, a view consistent with Little *et al.* (1997).

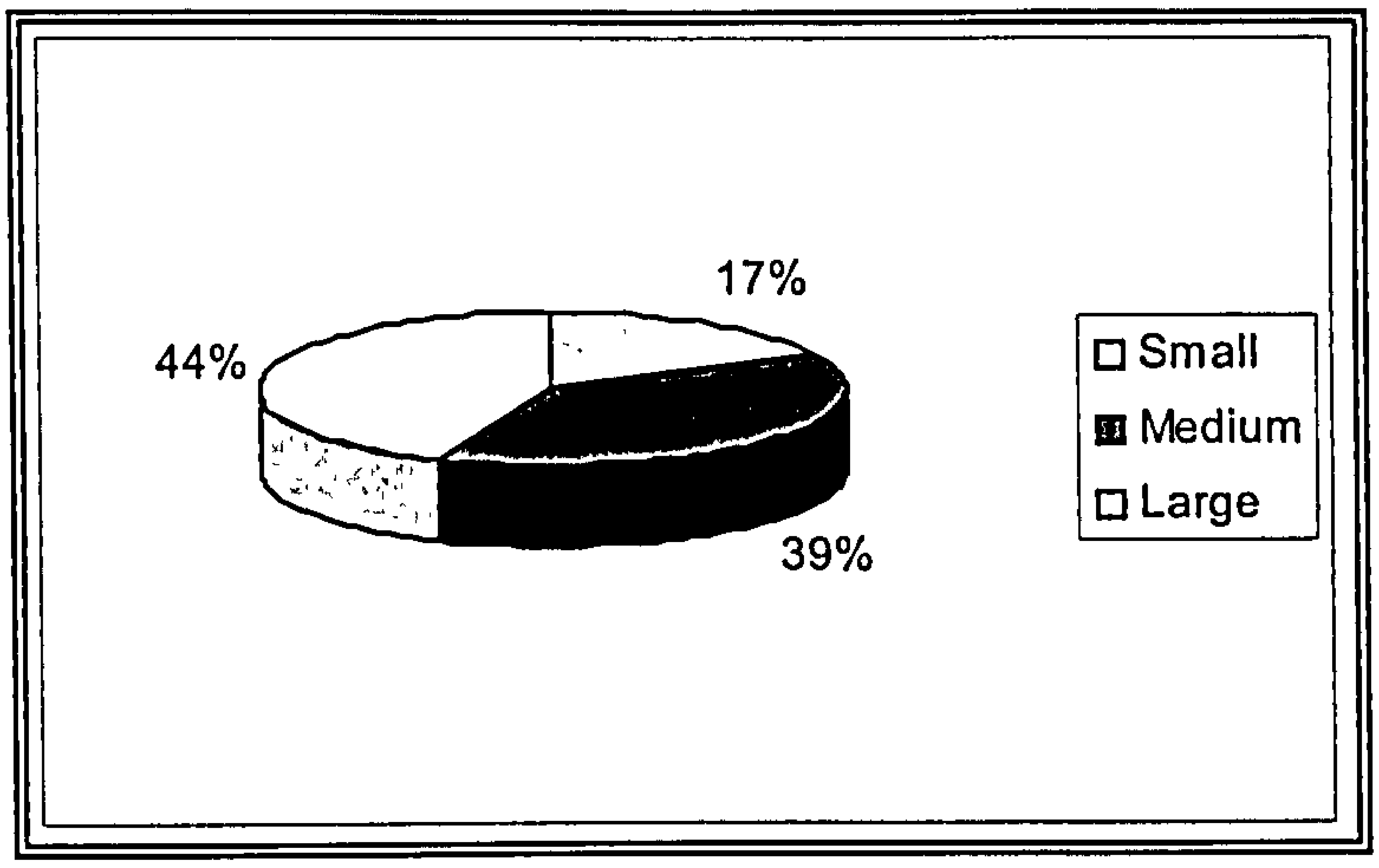

Figure 3.1: MRP users by company size

Analysis of manufacturing sector concluded that MRP based systems have been implemented across a wide variety of sectors. Figure 3.2 shows the profile of MRP users by manufacturing sector using the short key introduced in Section 3.2.1.

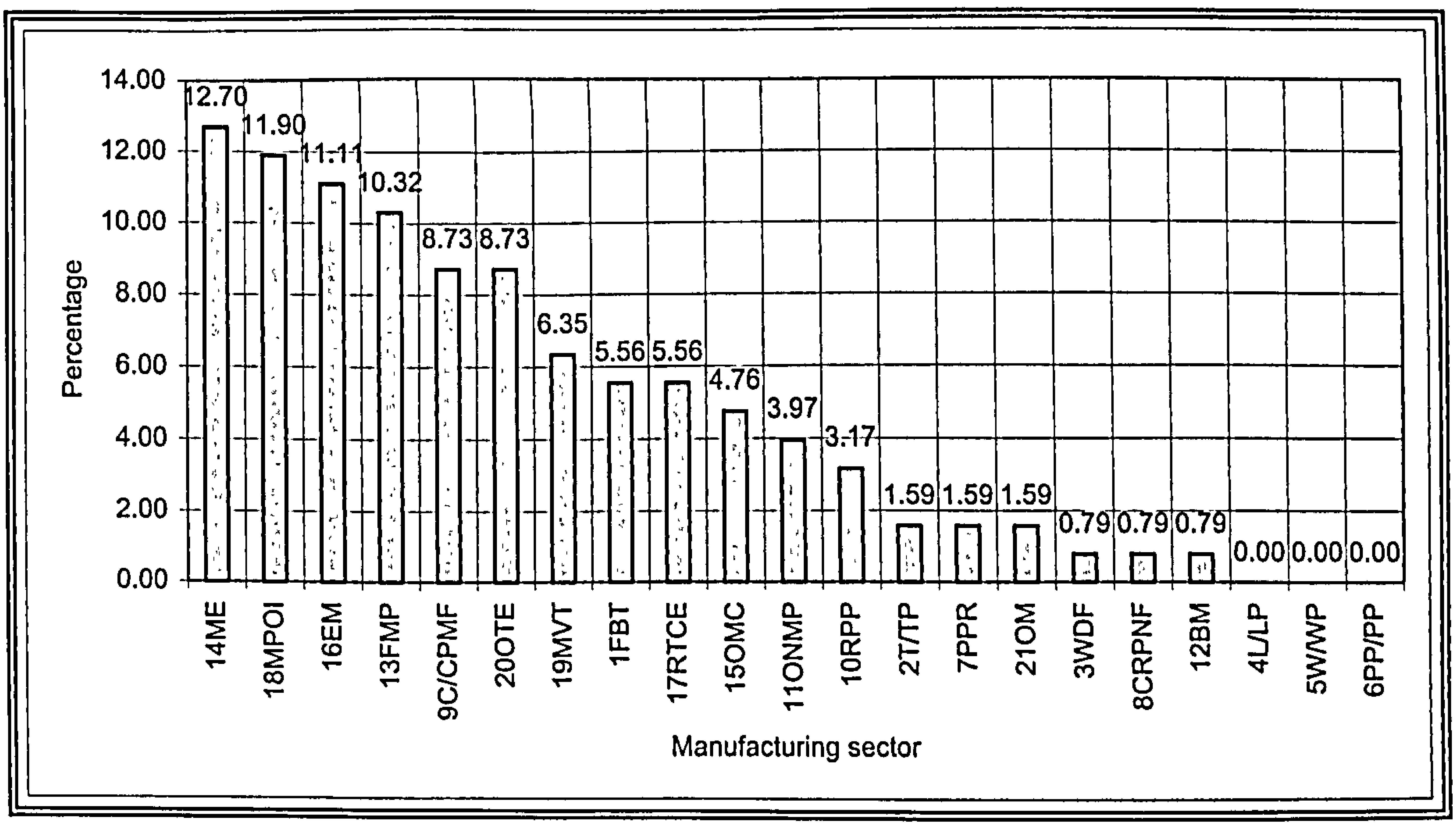

Figure 3.2: MRP users by manufacturing sector

Analysing the operating environments showed that an overwhelming proportion of respondents operated with a mix of project, ATO/MTO and MTS in approximately equal proportions. No generic definition could be found to describe such mixes and therefore the term Mixed-Mode (MM) has been coined. Table 3.8 shows the respondents operating environments.

Operating environment	No. of respondents	%
Project	14	11.11
ATO/MTO	19	15.08
MTS	14	11.11
MM	77	61.11
Process	2	1.59
Total	126	100

Table 3.8: MRP users by operating environment

Figure 3.3 shows the MRP run frequency indicating that the majority of the users ran MRP either daily or weekly.

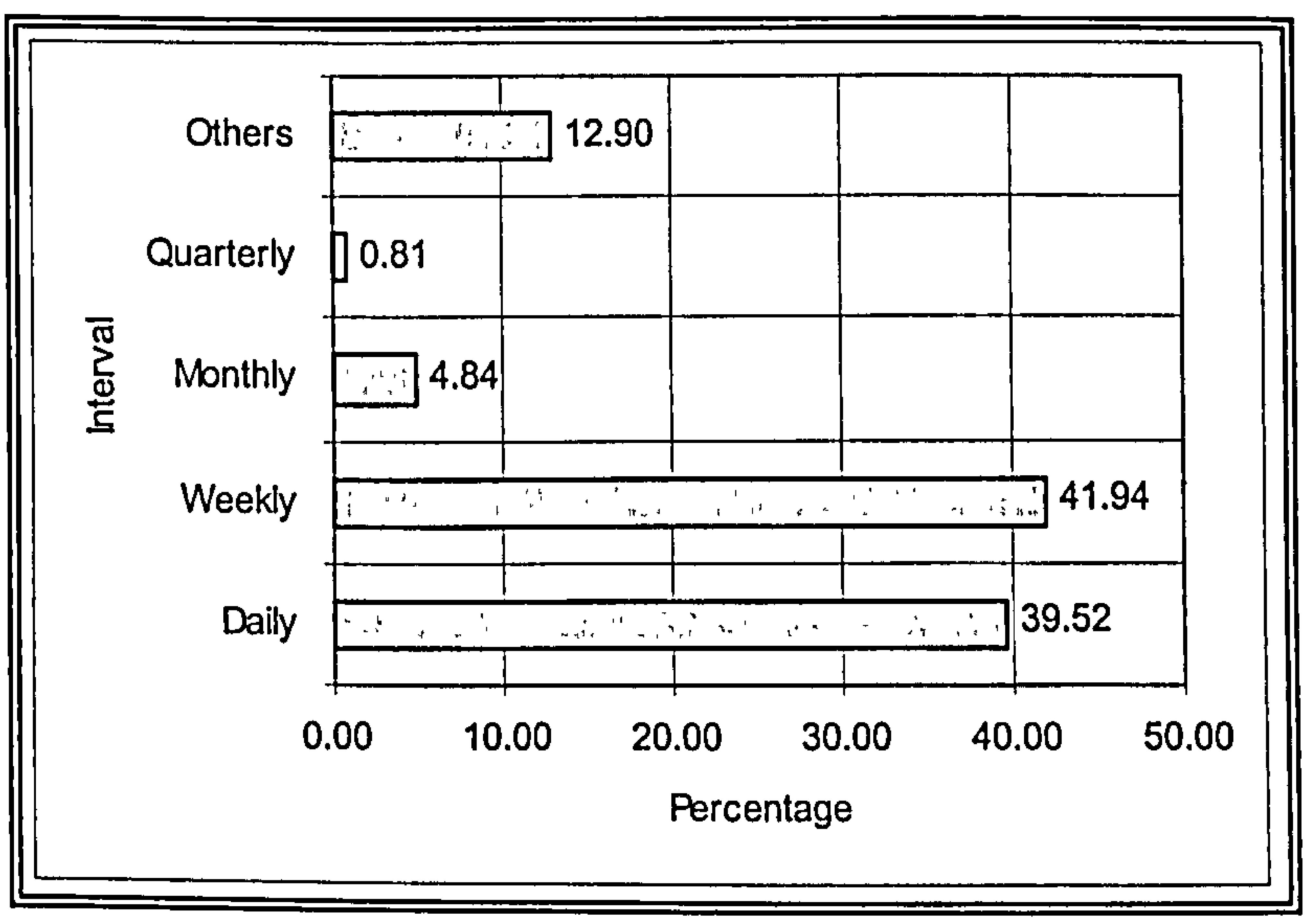

Figure 3.3: MRP run frequency

MRP rescheduling policies are shown in Figure 3.4. Respondents used mainly a mix of both regenerative and net-change. When using only one or the other, regenerative was more widely adopted.

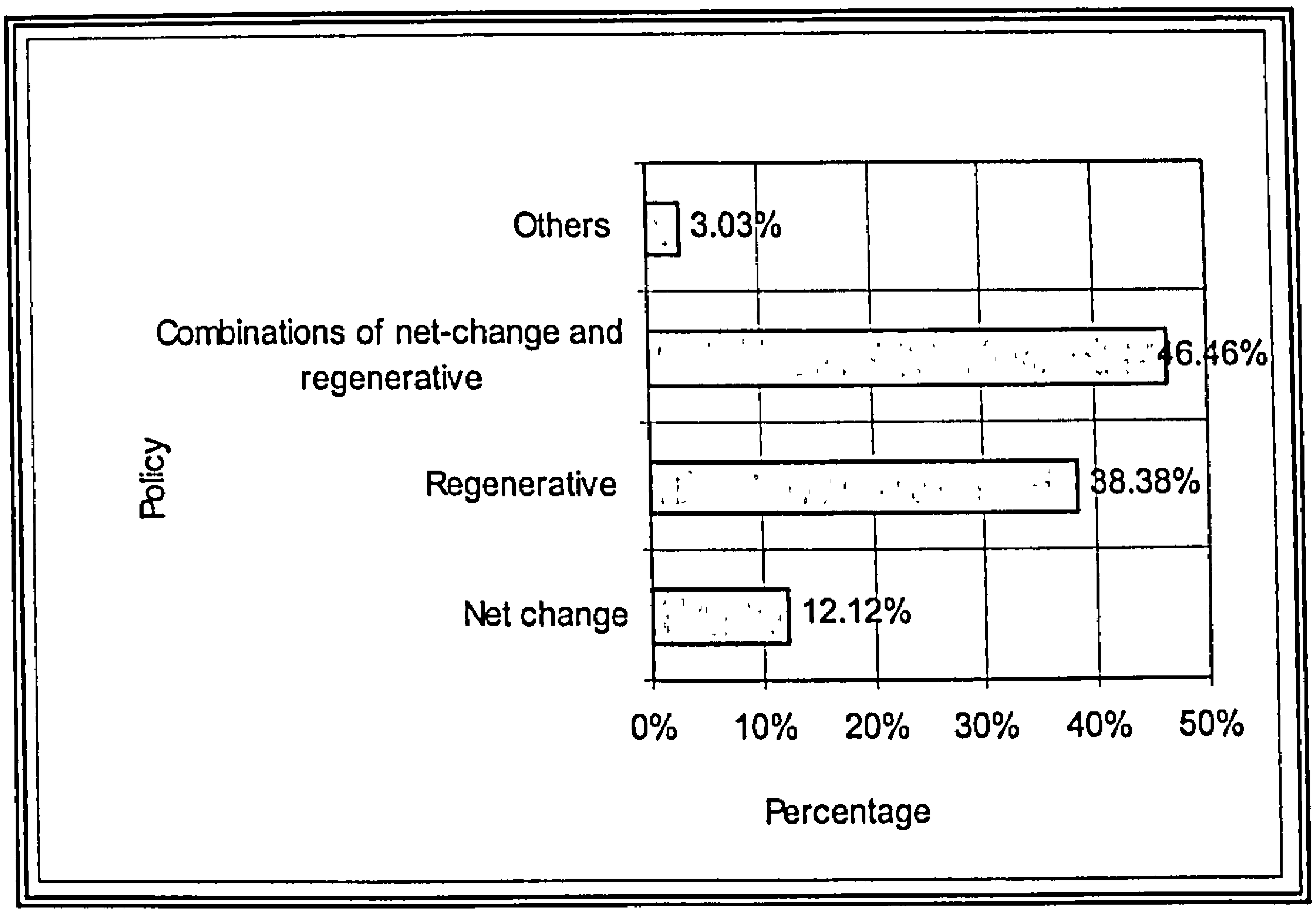

Figure 3.4: MRP rescheduling policies

The number of levels in the BOM and the proportion of bought-out, made-in and subcontracted parts are important determinants in understanding the complexity of the product and the level of resource commitment to manufacture.

Figure 3.5 shows over half the average number of BOM levels were between 1 and 3, with a smaller proportion having up to 9 levels.

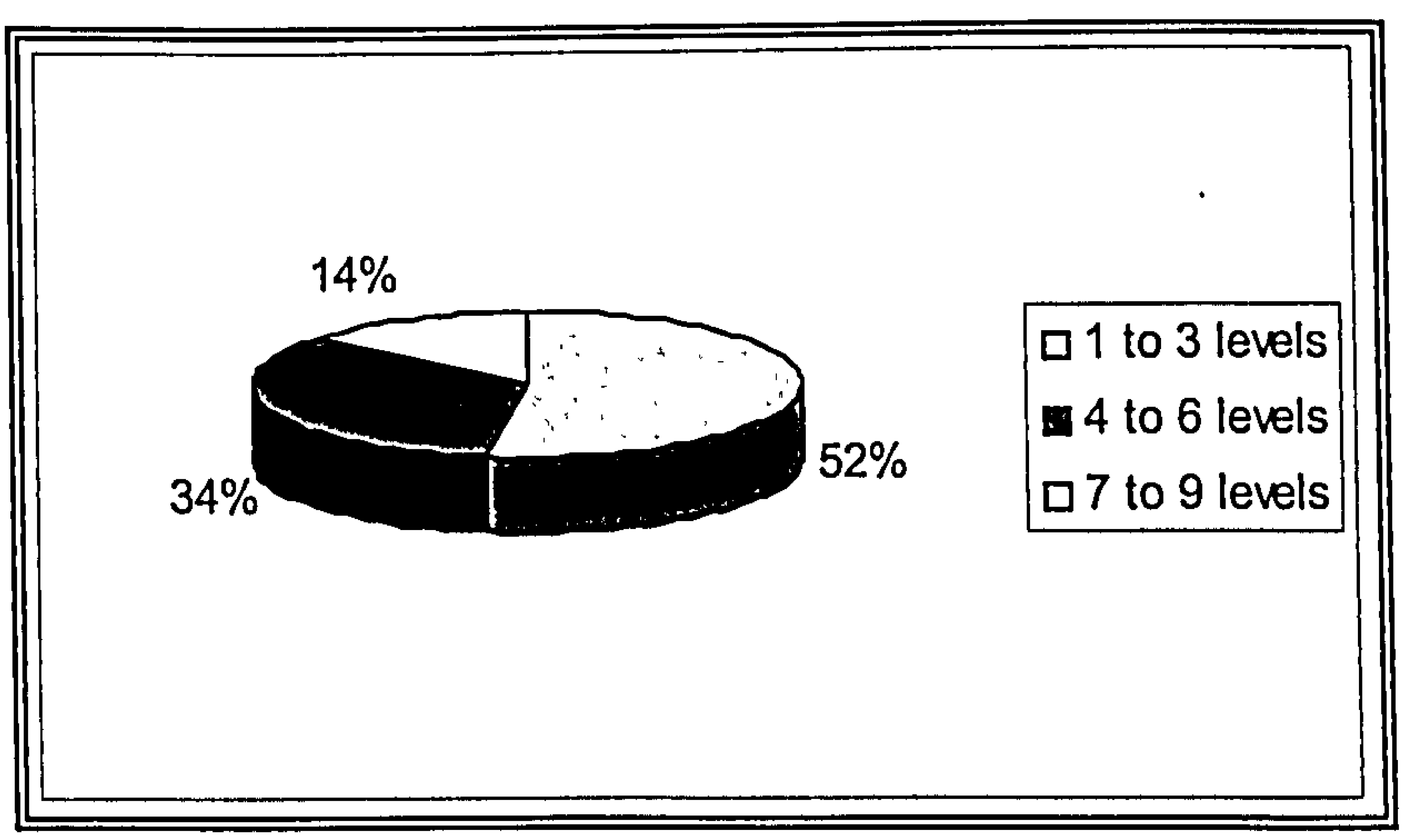

Figure 3.5: Levels in BOM

Figure 3.6 shows the average proportions of bought-out, made-in and subcontracted parts, with bought-out being predominant.

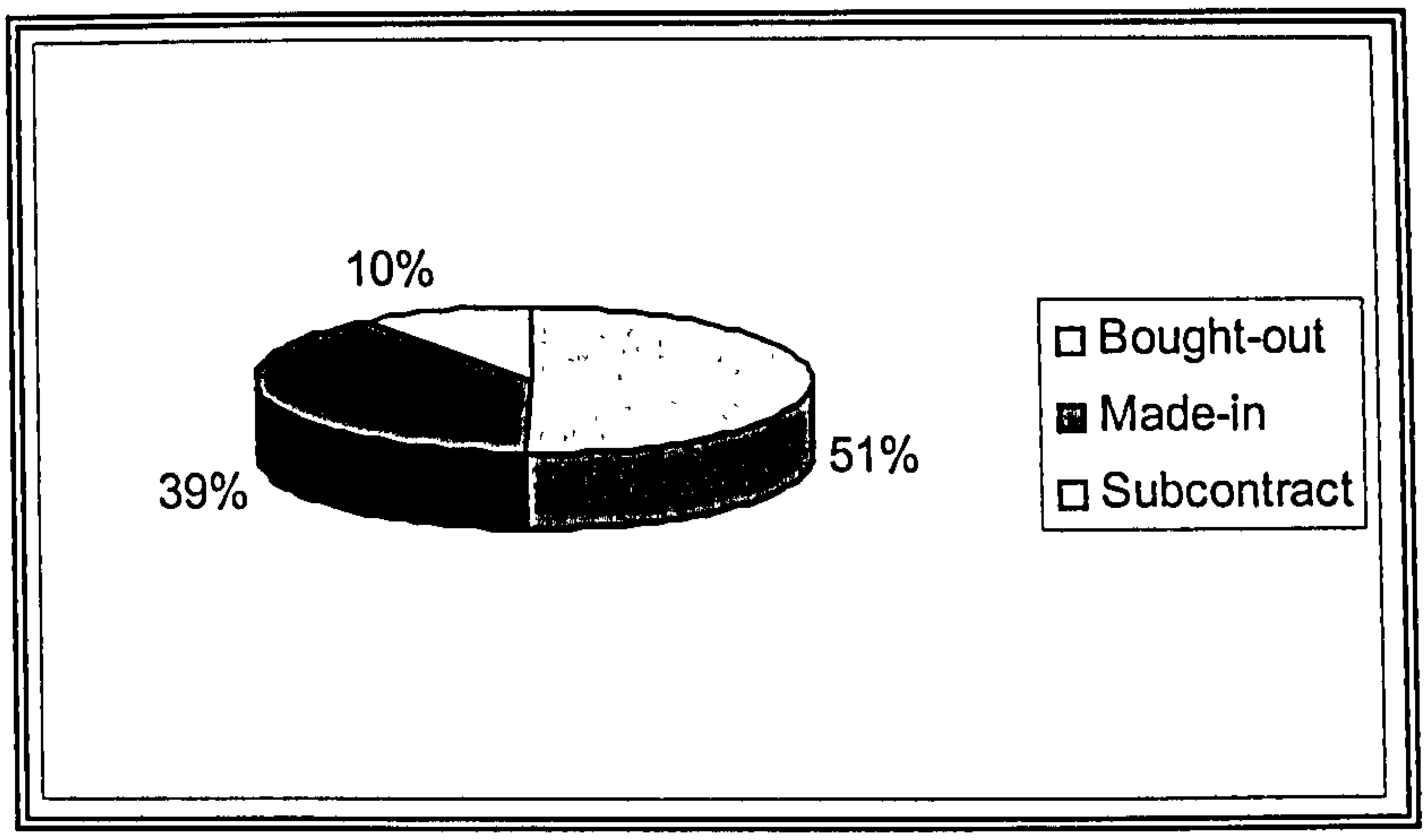

Figure 3.6: Average proportions of bought-out, made-in and subcontracted parts

Figure 3.7 shows the approaches taken to order execution. The majority used a work-to-list, with only a minority using modern approaches such as Kanban cards.

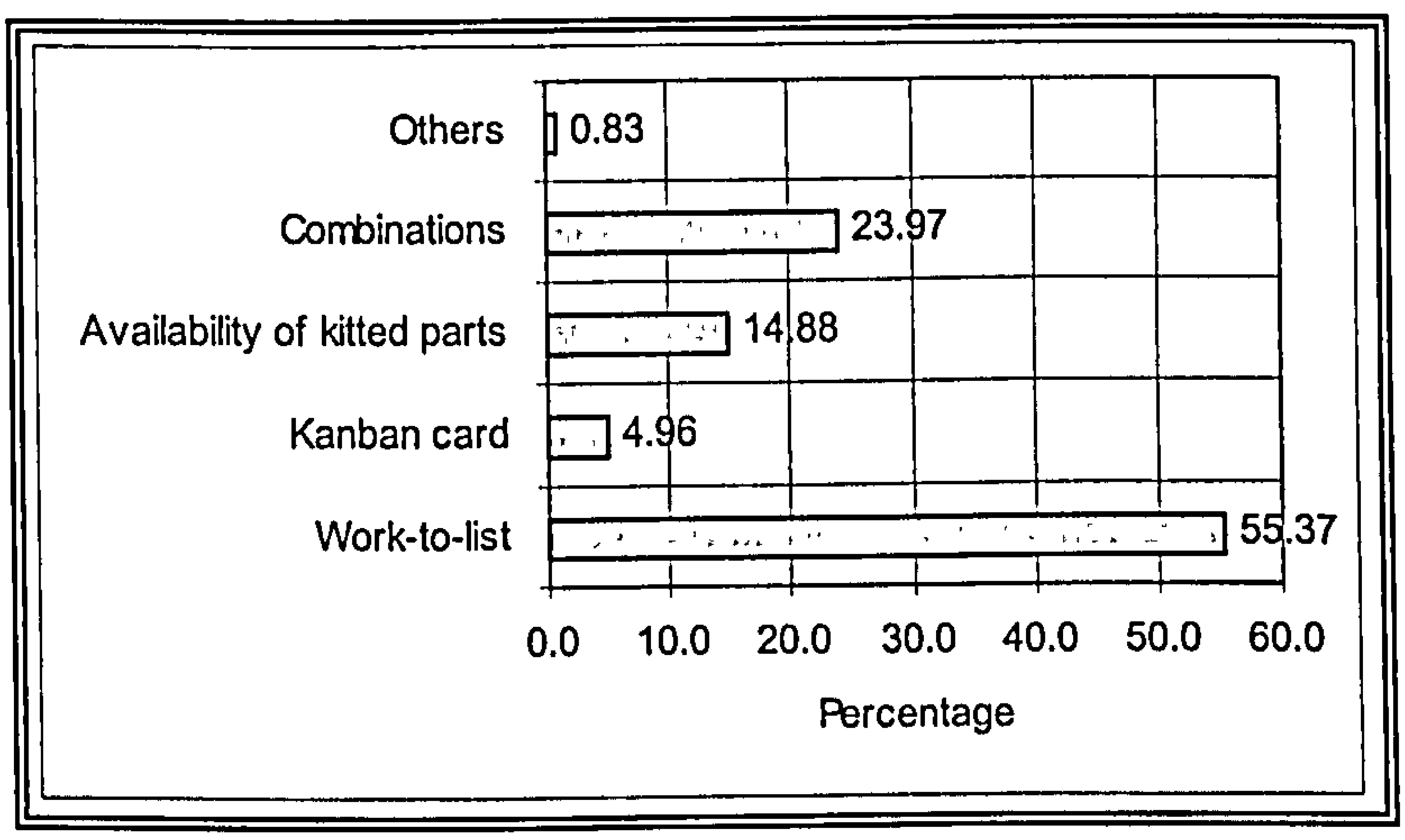

Figure 3.7: Mode of order execution

3.3.2 MRP benefits

Using the five-point Likert scale described in Section 3.2.2, respondents were asked to rate each claimed benefit. Results are presented in Table 3.9 and showed that on average MRP users considered the major benefits achieved to have been in the area of BOM improvement and inventory management. Output measures, such as improved planning and scheduling and better due date performance appeared as still requiring considerable further improvement. With a very narrow distribution of mean values reported, detailed analysis became difficult, but in general most companies clearly identified the need to improve across all areas.

MRP Benefit	Level (frequency reported)					Mean
	1	2	3	4	5	
Improved BOM accuracy	3	9	36	56	16	3.58
Increased inventory accuracy	3	13	58	43	9	3.30
Reduced inventory levels	4	20	46	38	12	3.26
Improved MPS accuracy	5	20	43	38	12	3.24
Better inventory planning & scheduling	6	18	47	47	8	3.22
Reduced customer delivery lead times	5	18	49	46	6	3.22
Reduced set-up and change-over costs	9	19	38	39	12	3.19
Reduced paperwork	6	15	55	41	6	3.19
Increased inventory turns	2	23	55	38	8	3.18
Information sharing and communication	6	26	59	26	6	2.95

Table 3.9: MRP benefits achieved in industry

3.3.3 Uncertainties

Figure 3.8 shows the average class for the levels of uncertainties experienced was between classes 1 and 3 (2% -15%).

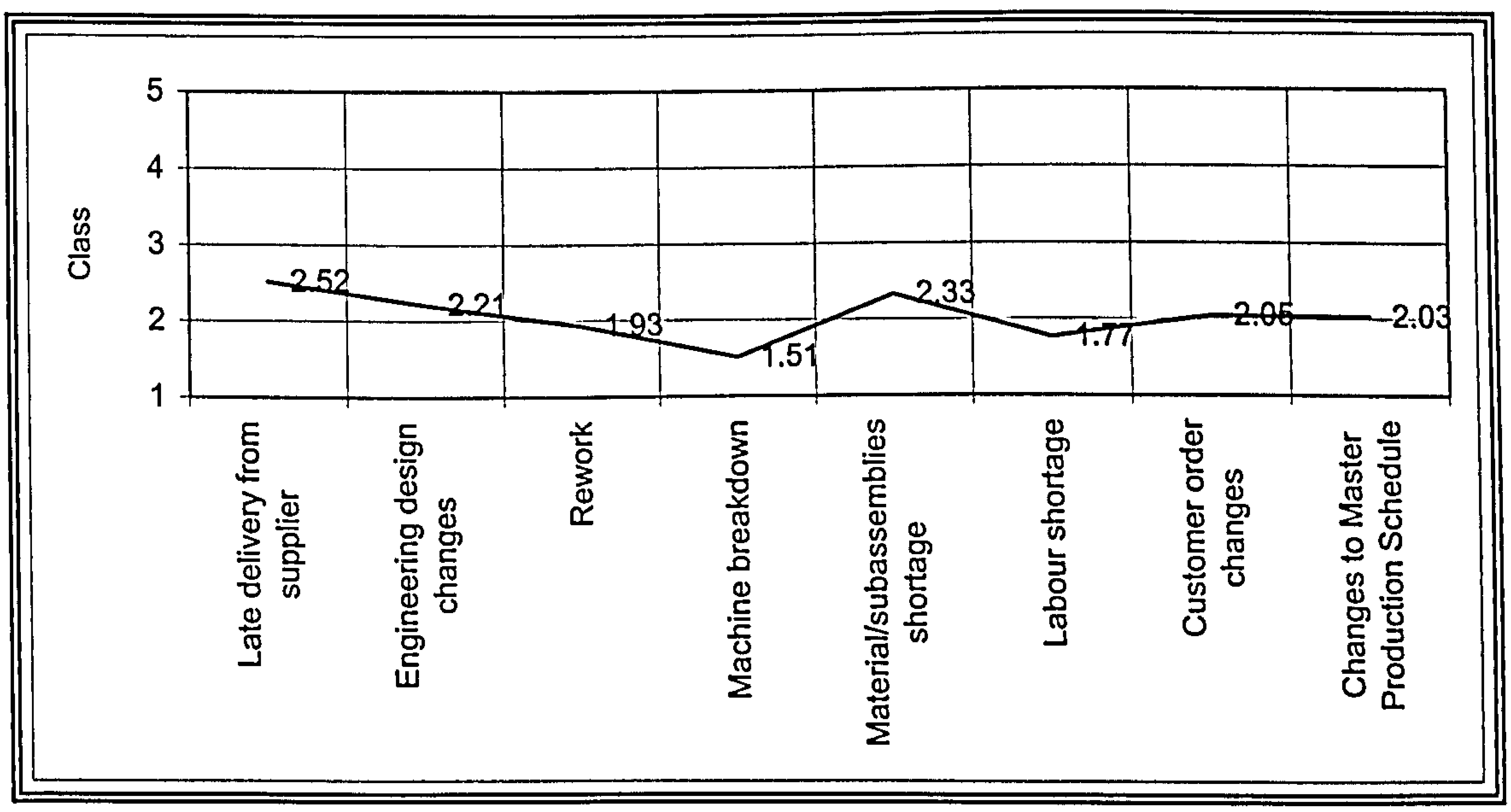

Figure 3.8: Average class of uncertainties experienced

The results showed that most uncertainties occurred at a relatively high level. Late delivery from suppliers, material/subassembly shortages and engineering design changes all occurred at between 6% and 15%. Customer order changes and changes to MPS fell at or around 6%. Only rework, machine breakdowns and labour shortages occurred at much lower levels.

Using the same classes, the average level of late delivery to customer was found to lie between 6% and 15%.

3.3.4 MRP performance measures

Figure 3.9 shows the average significance ranking of the range of performance measures examined. It was clearly identified that improvement in meeting customer's due date was the most significant performance measure. This finding was also supported by the views of Bozarth and Chapman (1996).

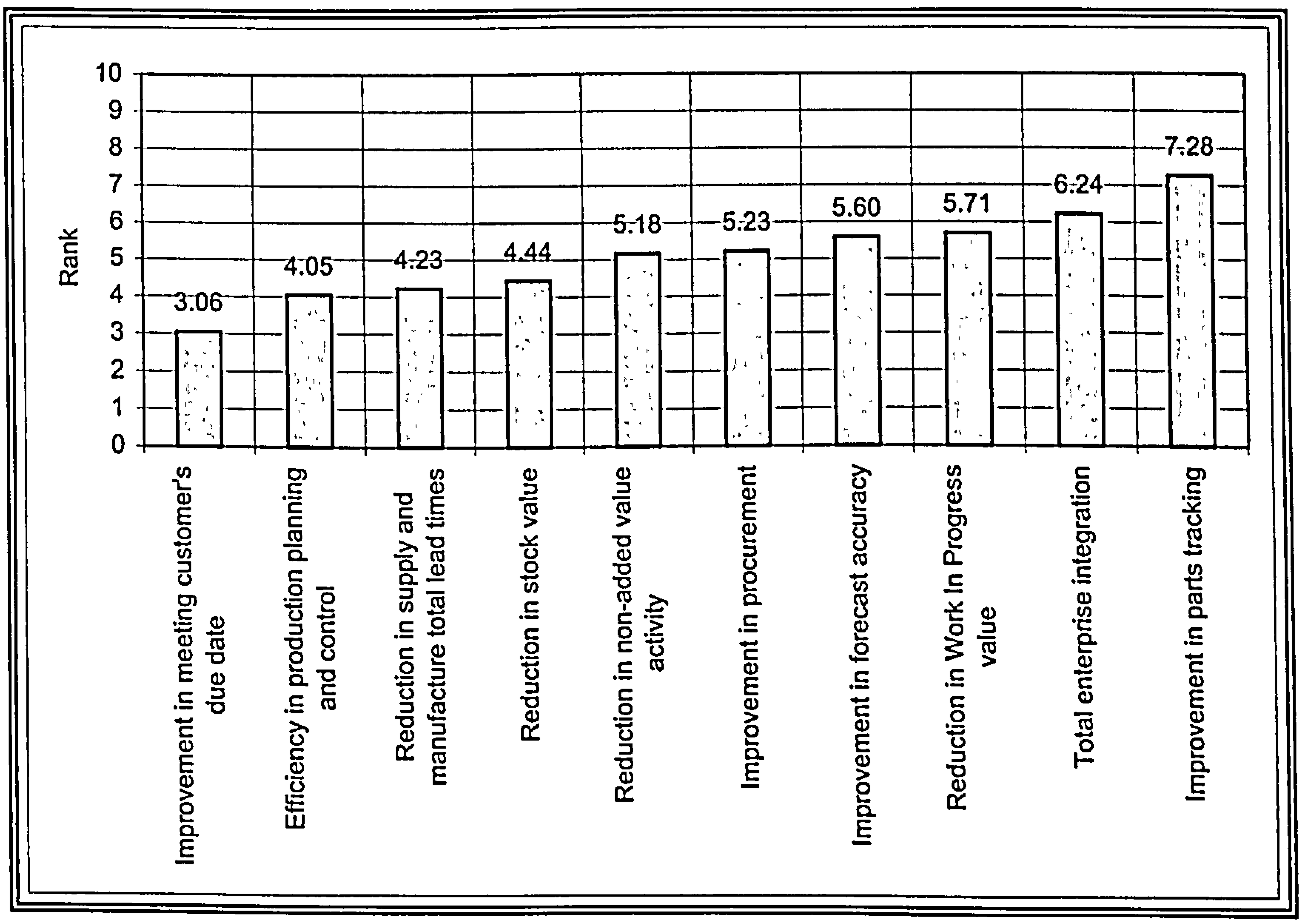

Figure 3.9: Average ranking of significance of performance measures

3.3.5 BAD approaches

The results showed that MRP users adopted a variety of BAD approaches to cope with uncertainties. To identify those most used, a cut-off point of 70% usage was set. Based on that cut-off point, the main BAD approaches for each company category are shown in Tables 3.10 to 3.13.

	Material/Subassembly shortages	Labour shortages	Machine breakdown	Rework	Changes to MPS	Customer Order changes	Supplier late delivery	Design changes
Overtime				✓	✓	✓		✓
Multi-skilling Labour	✓	✓	✓	✓	✓	✓	✓	✓

Table 3.10: BAD approaches used by Good companies

	Material/Subassembly shortages	Labour shortages	Machine breakdown	Rework	Changes to MPS	Customer Order changes	Supplier late delivery	Design changes
Overtime	✓	✓	✓	✓	✓	✓	✓	✓
Sub-contract				✓				✓
Reschedule		✓	✓		✓			
Finished Safety Stock		✓	✓			✓		
Part Safety Stocks		✓	✓					
Increase Lead time		✓	✓		✓			
Spare capacity			✓					
Spare Labour		✓						
Hedging		✓						
Over planning		✓			✓			
Supply Chain Mgmt			✓					
Preventive Maintenance			✓					
Multi-skilling Labour		✓	✓	✓	✓	✓	✓	✓
Forecast Improvements		✓	✓					
Product standardisation		✓						
Process standardisation		✓	✓			✓		
Procedure standardisation			✓					
Volume flexibility		✓	✓			✓		

Table 3.11: BAD approaches used by Poor companies

	Material/Subassembly shortages	Labour shortages	Machine breakdown	Rework	Changes to MPS	Customer Order changes	Supplier late delivery	Design changes
Overtime	✓			✓	✓	✓		✓
Sub-contract	✓			✓			✓	
JIT							✓	
Finished safety Stock			✓	✓	✓			
Part safety Stocks	✓		✓	✓	✓	✓		
Preventive Maintenance			✓					
Multi-skilling Labour	✓		✓	✓	✓	✓	✓	✓
Product standardisation			✓					
Performance review								✓
Shorten lead times			✓					
Fast set-ups			✓					

Table 3.12: BAD approaches used by Laggard companies

	Material/Subassembly shortages	Labour shortages	Machine breakdown	Rework	Changes to MPS	Customer Order changes	Supplier late delivery	Design changes
Overtime		✓	✓	✓	✓	✓	✓	✓
Sub-contract		✓	✓	✓		✓	✓	
Reschedule				✓				
Supply Chain Mgmt				✓				
Preventive Maintenance	✓							
Multi-skilling Labour		✓	✓	✓	✓	✓	✓	✓
Planner Training	✓							

Table 3.13: BAD approaches used by Improver companies

Good companies mainly adopted overtime and multi-skilling labour, while Poor and Laggard companies appeared to use a mixture of approaches. Improvers used a mixture of approaches but not as many as Poor companies. Overtime and multi-skilling labour appeared to be the most widely used approaches to cope with a variety of uncertainties in all categories.

The survey did not seek to identify specific uncertainties for each category of company, but the results gave some guidance to perceptions of each as to the uncertainties that they faced. Good companies recognised the existence of all identified uncertainties, using multi-skilling as a universal solution. For Poor companies, labour shortages and machine breakdown were the most common uncertainties, tackled by a number of BAD approaches. For Laggard companies, machine breakdown predominated and for Improvers, rework was their core.

Although the uncertainties experienced and the BAD approaches adopted by each category were identified, no direct correlation could be drawn to show which were the *optimum* BAD approaches for specific uncertainties. This finding raised the fundamental question of whether the BAD approaches were being used appropriately.

3.4 Conclusions

Empirical evidence from this survey supported the view that no structured and systematic approaches were used to cope with uncertainty and the use of BAD approaches was *sub-optimised.* In many cases there appeared to be a random use of BAD approaches, with late deliveries to customers still encountered.

Amongst BAD approaches used, the main two were overtime and multi-skilling labour. However, the literature review identified safety stock as the generally acceptable *optimum* approach. This difference further suggested that both in theory and practice, BAD approaches were adopted *sub-optimally.*

The survey showed that a mix of MRP performances was achieved, but most companies felt improvements were possible and additional benefits achievable, implying the need for on-going improvement.

Meeting customer due date was identified as the most significant MRP performance measure hence it would be used in subsequent studies in this research.

Chapter 4: Derivation of business model of uncertainty

4.1 Introduction

The theoretical and practical evidence showed that uncertainty has been tackled discretely. The need was to provide a structure within which uncertainties could be placed. This chapter seeks to achieve this objective through the derivation of a business model to structure uncertainties using cause-and-effect analysis. Once derived, this model will form the basis of a program to develop proof of its efficacy. The business model derivation will be discussed and the definition of each uncertainty given, with justification for the existence of each cause-and-effect relationship.

4.2 Derivation of the business model

In the case of dependent demand MRP based systems, there is a clear hierarchy of parts, subassemblies and finished products, which govern the production planning process. The major driver is achieving due date for the finished product, hence, it is normally at this finished product level that performance of the system is recognised and measured. Although uncertainty could occur at any or all levels of the planning hierarchy, the evidence for the effect of the uncertainty may be masked until the finished product becomes overdue. By that stage it may not be possible to equate back to the actual cause, timing and location of the uncertainty. In real-world situations, many of the uncertainties could be masked by the use of BAD approaches, making it even more difficult to disaggregate causes and effects. As stated by Gelders and Wassenhove (1982), it is meaningless if uncertainties are not disaggregated back to the detailed level.

The starting point for development of the business model was the work of Mather (1977) and Turner and Saunders (1994). Figure 4.1 shows the original attempt to put the uncertainties they identified into a cause-and-effect diagram.

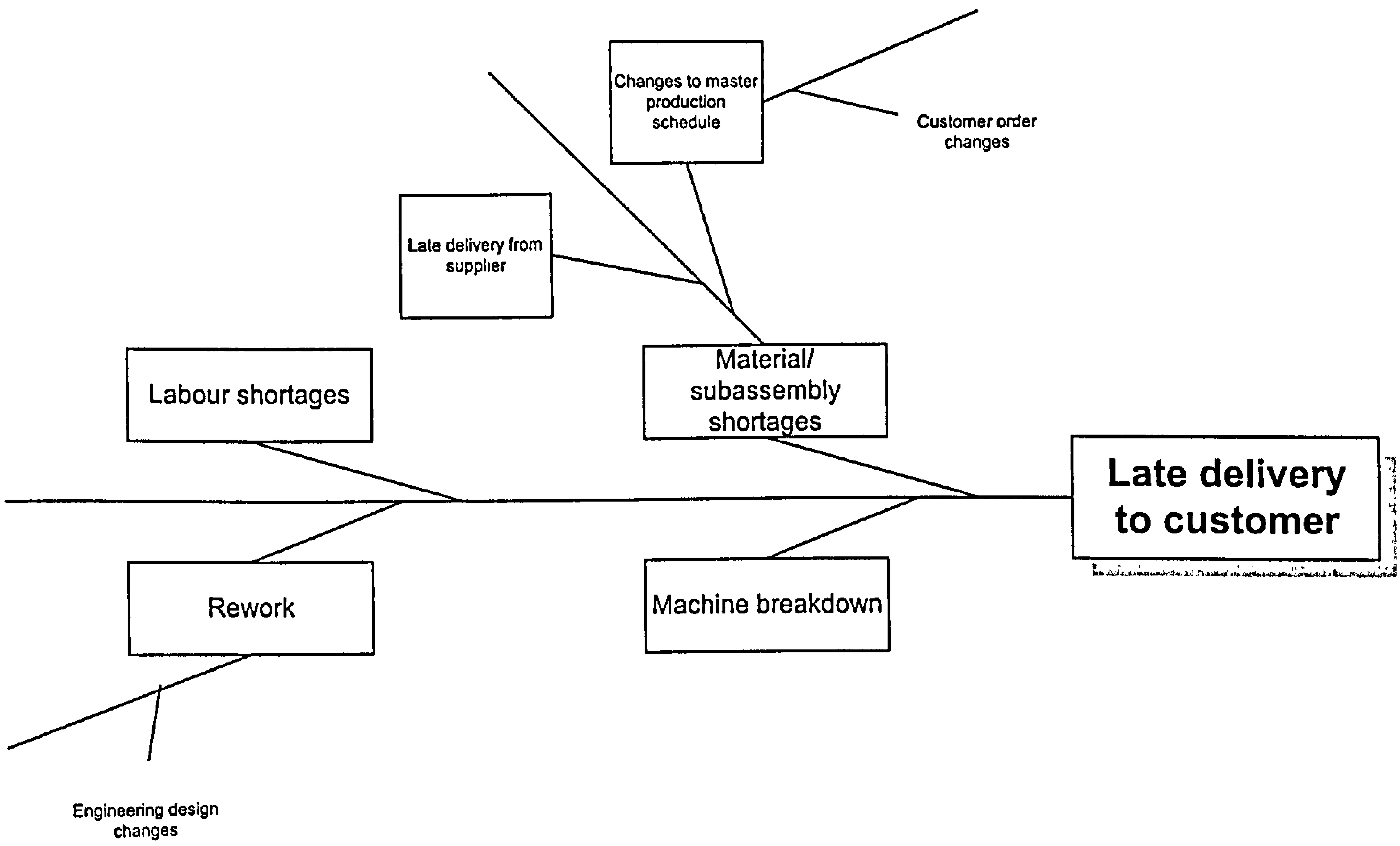

Figure 4.1 Causes and effects of uncertainty (after Mather (1977) and Turner and Saunders (1994))

Following this initial attempt, expert opinion was used to examine each identified strand in some detail, first to ensure all potential uncertainties were identified within each strand and then to establish potential causes and effects, i.e. a suitable structure for the uncertainties.

4.2.1 Material/subassembly shortages

It was considered that a number of the original eight uncertainties were, in fact, causes and effects of each other. This was particularly true in this strand where customer order changes were identified as causing changes to the MPS, which would eventually be seen as a material or subassembly shortage. Equally, late delivery from suppliers, although measurable, had the ultimate effect of causing a material/subassembly shortage. Figure 4.2 shows the full result of the analysis of this strand. Table 4.1 provides a definition for each of the uncertainties identified.

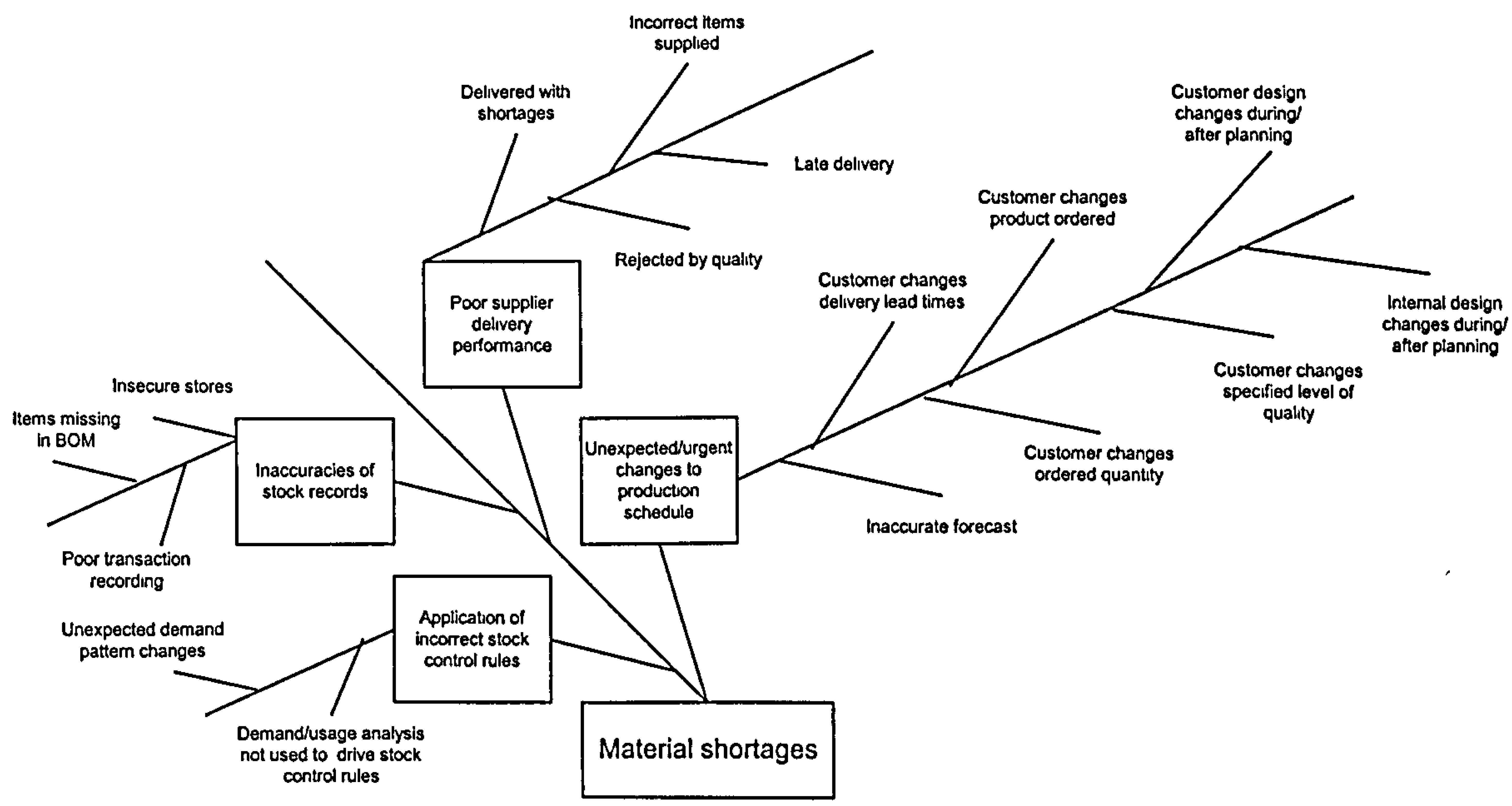

Figure 4.2: Material shortages strand

4.2.2 Labour shortages

The original business model assumed that labour shortages were a primary cause of late delivery. However, expert opinion concluded that such shortages were only a recognisable symptom of many underlying causes. The cause-and-effect diagram constructed to show these is shown in Figure 4.3. Table 4.2 provides a definition for each of the uncertainties identified.

Description	Definition
Causes of material shortages	
Poor supplier delivery performance	Supplier not achieving promise date, supplying faulty item, short delivery or incorrect item.
Inaccurate stock records	Item not available when required when inventory records state availability. Includes items not found.
Application of incorrect stock control rules	Incorrect or inappropriate application of a stock control rule causing stock-outs to occur.
Unexpected/urgent changes to production schedule	Unplanned changes to production plan with materials required not available.
Causes of poor supplier delivery performance	
Rejected by quality	Quality rejection of incoming material
Delivered with shortages	Supplier delivers less than the ordered quantity.
Late delivery	Supplier delivers late.
Incorrect items supplied	Supplier delivers the wrong items.
Causes of inaccurate stock records	
Items missing in BOM	BOM is not updated, which results in non-ordering of required items.
Insecure stores	Poor discipline or lack of security.
Poor transaction recording	Normally human error resulting from data transfer.
Causes of application of incorrect stock control rules	
Unexpected demand pattern changes	Dynamic demand renders current stock rule obsolete.
Demand/usage analysis not used to drive stock control rules	ABC or other analysis not used to manage and control item replenishment.
Causes of unexpected/urgent changes to production schedule	
Inaccurate forecast	Actual demand differs to forecasted demand.
Customer changes delivery lead-time	Customer expedites delivery.
Customer changes order quantity	Customer makes late change to order quantity.
Customer changes product ordered	Customer changes order to related product
Customer changes specified quality level	Customer requires more or less stringent quality level achieved.
Customer design changes during/after planning	Design change introduced by customer during/after planning.
Internal design changes during/after planning	Design change introduced by manufacturer during/after planning.

Table 4.1: Definitions of uncertainties in material shortages strand

4.2.3 Machine capacity shortages

The original business model considered only breakdown as a source of machine capacity shortages. Again, by reviewing through expert opinion, it was found that there were a number of underlying causes, which worked through the system to appear as a measurable machine capacity shortage. Breakdowns were just one of these. The full cause-and-effect diagram derived is shown in Figure 4.4. Table 4.3 provides a definition for each of the uncertainties identified.

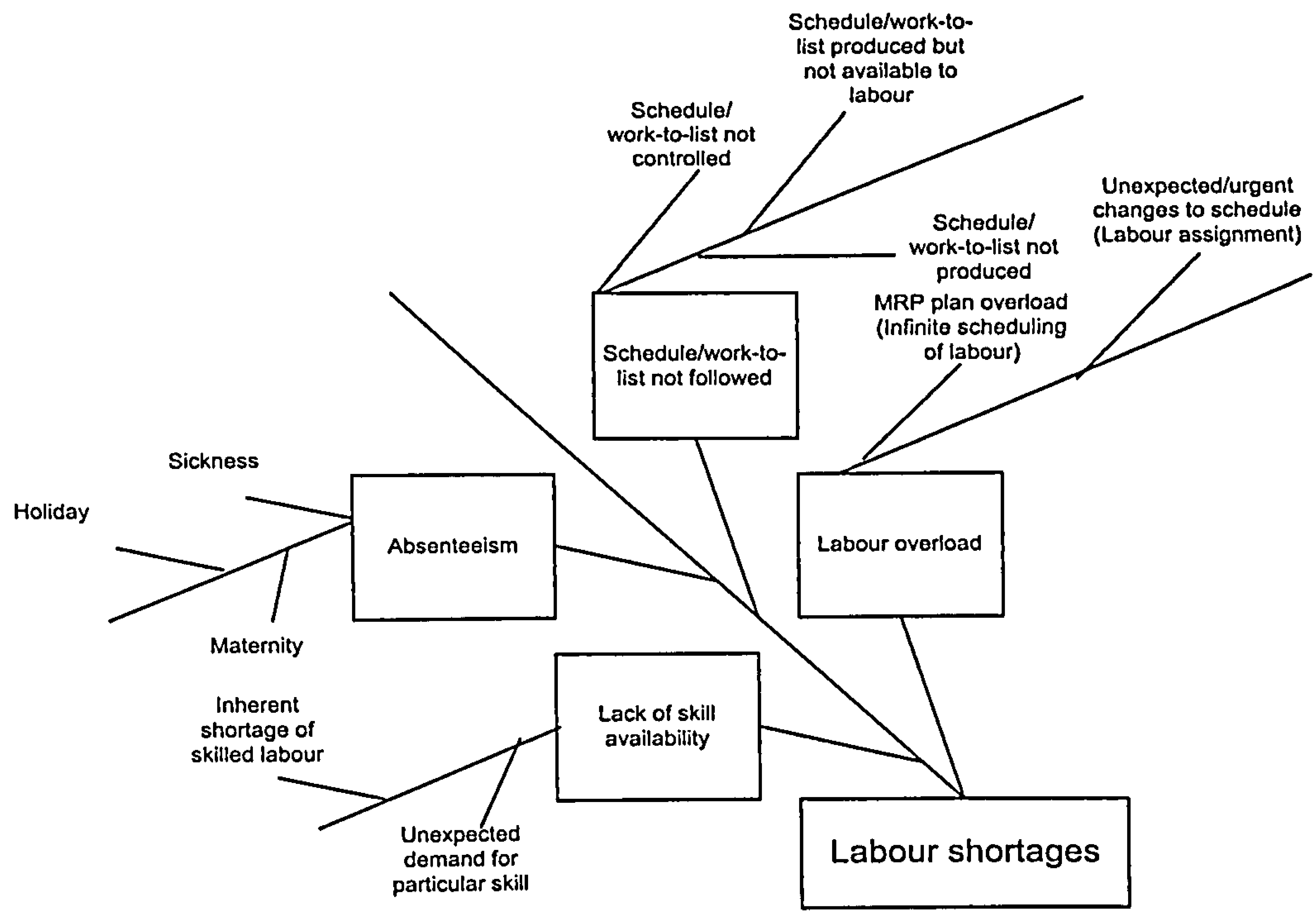

Figure 4.3: Labour shortages strand

Description	Definition
	Causes of labour shortages
Absenteeism	Labour not present for work.
Schedule/work-to-list not followed	Labour does not work according to schedule/work-to-list.
Lack of skill availability	Shortage of skill required making the product to customer specification.
Labour overload	Planned labour utilisation greater than 100%.
	Causes of absenteeism
Maternity	Labour not present for work due to pregnancy leave.
Sickness	Labour not present for work due to sickness.
Holiday	Labour not presents for work due to holiday.
	Causes of schedule/work-to-list not followed
Schedule/work-to-list not produced	List not issued after MRP run. Scheduling carried out in ad hoc manner.
Schedule/work-to-list not controlled	Lack of formal procedures to ensure adherence to schedule/work-to-list.
Schedule/work-to-list produced but not available to labour	List produced but not issued after MRP run.
	Causes of lack of skill availability
Inherent shortage of skilled labour	Under recruitment of required skills.
Unexpected demand for particular skill	Labour skills shortage caused by change in product mix.
	Causes of labour overload
MRP planned overload (Infinite scheduling of labour)	Infinite scheduling with no capacity planning carried out causing labour overload after MRP run.
Unexpected/urgent changes to schedule (Labour assignment)	Unplanned labour needs to expedite order at production stage.

Table 4.2: Definitions of uncertainties in labour shortages strand

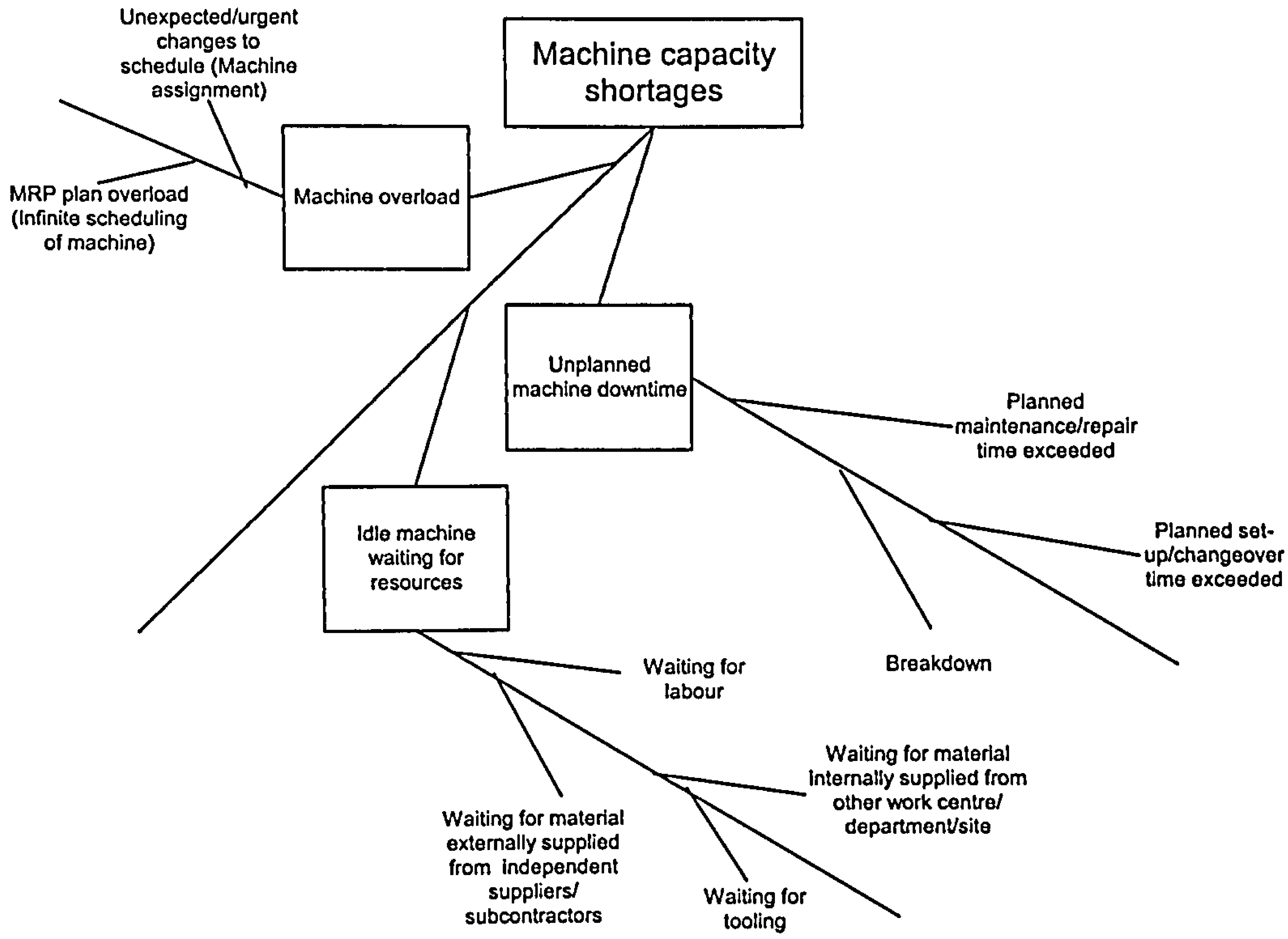

Figure 4.4: Machine capacity shortages strand

Description	Definition
Causes of machine capacity shortages	
Unplanned machine downtime	Unavailability of machine when required.
Machine overload	Planned machine utilisation greater than 100%.
Idle machine waiting for resources	Machine not usable when required due to unavailability of labour, material or tooling.
Causes of unplanned machine downtime	
Planned maintenance/repair time exceeded	Unexpected extension to planned maintenance/repair time.
Planned set-up/change-over time exceeded	Unexpected extension to planned set-up/change-over time.
Breakdown	Unplanned machine failure.
Causes of machine overload	
MRP plan overload (Infinite scheduling of machine)	Infinite scheduling with no capacity planning carried out causing machine overload after MRP run.
Unexpected/urgent changes to schedule (Machine assignment)	Unplanned machine needs to expedite order at production stage.
Causes of idle machine waiting for resources	
Waiting for labour	Work cannot be commenced due to waiting for labour.
Waiting for tooling	Work cannot be commenced due to waiting for tooling.
Waiting for material internally supplied	Work cannot be commenced due to waiting for material supplied internally.
Waiting for material externally supplied	Work cannot be commenced due to waiting for material supplied externally.

Table 4.3: Definitions of uncertainties in machine capacity shortages strand

4.2.4 Scrap/rework

The original business model showed engineering design changes as a cause of rework. In fact, under the general heading of rework (to include both scrap and rework), there were a considerable number of further causes. Figure 4.5 shows the full result of the analysis of this strand. Table 4.4 provides a definition for each of the uncertainties identified.

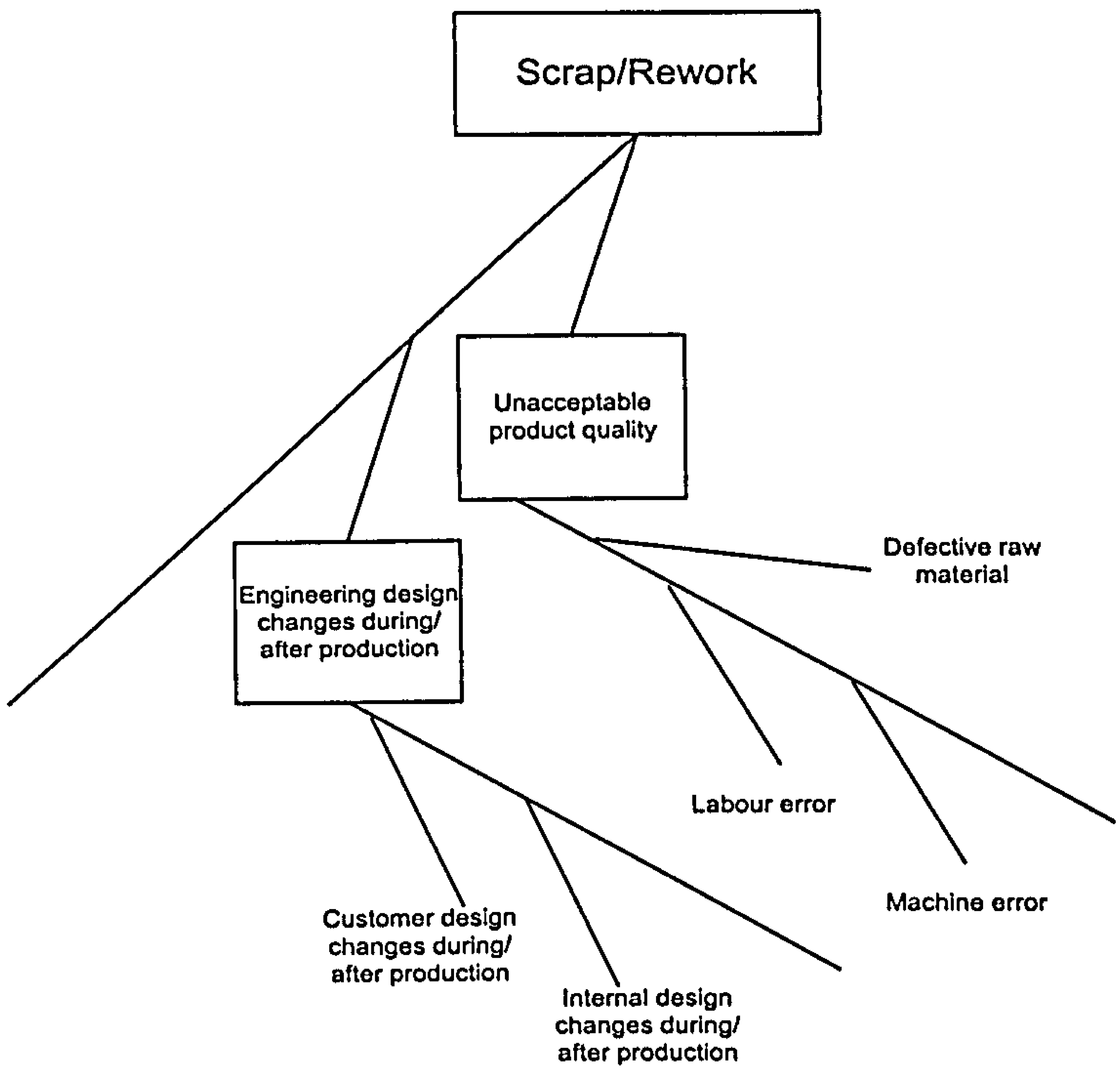

Figure 4.5: Scrap/rework strand

Description	Definition
Causes of scrap/rework	
Unacceptable product quality	Products that fail quality check from quality control or customer.
Engineering design changes during/after production	Late design changes instigated either by customer or internally.
Causes of unacceptable product quality	
Labour error	Unacceptable product quality caused by labour error.
Defective raw material	Unacceptable product quality caused by non-conforming raw material.
Machine error	Unacceptable product quality caused by machining/process error.
Causes of engineering design changes during/after production	
Customer design changes during/after production	Customer changes product design after the product is made or partially made.
Internal design changes during/after production	Design changes by manufacturer after the product is made or partially made.

Table 4.4: Definitions of uncertainties in scrap/rework strand

4.2.5 Finished product completed – not delivered

An additional group of causes of late delivery to customer was recognised that would not directly affect the efficient operation of MRP based systems. These causes fell into the general heading of finished product completed – not delivered and are shown in Figure 4.6. Table 4.5 provides a definition for each of the uncertainties identified.

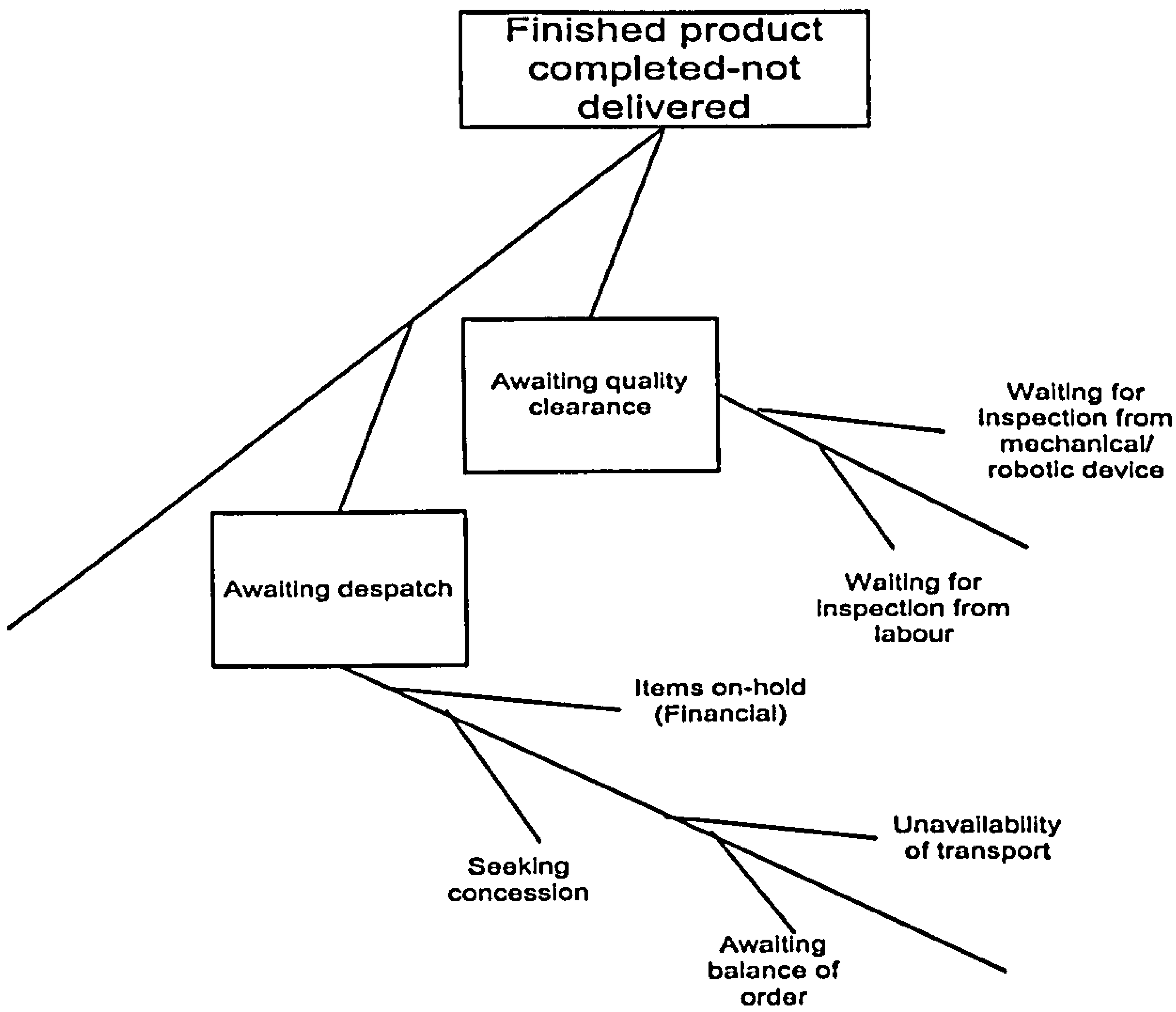

Figure 4.6: Finished product completed – not delivered strand

Description	Definition
Causes of finished product completed – not delivered	
Awaiting quality clearance	Delay in final quality control clearance.
Awaiting despatch	Despatch is carried out later than expected.
Causes of awaiting quality clearance	
Waiting for inspection from labour	Quality control labour is not available for finished product inspection.
Waiting for inspection from mechanical/robotic device	Mechanical/robotic device for finished product inspection is not available.
Causes of awaiting despatch	
Items on-hold (Financial)	Finished product not delivered awaiting financial clearance
Unavailability of transport	Finished product not delivered due to absence of delivery truck or inefficient logistics.
Awaiting balance of order	Finished product not delivered while waiting for other products to be completed.
Seeking concession	Finished product not delivered due to negotiation between manufacturer and customer, usually on price discount.

Table 4.5: Definitions of uncertainties in finished product completed-not delivered strand

4.3 Conclusions

All of the strands identified from expert opinion have the common ultimate effect of potentially causing a late delivery to the customer. Only the use of BAD approaches would prevent each uncertainty from directly resulting in late delivery. To see the overall business model, the individual strands were brought together in Figure 4.7.

To provide a clearer structure, the cause-and-effect diagram was transformed into a hierarchical model as shown in Figure 4.8, which would form the basis of subsequent modelling of causes and effects. The business model of uncertainty would be verified using industry data.

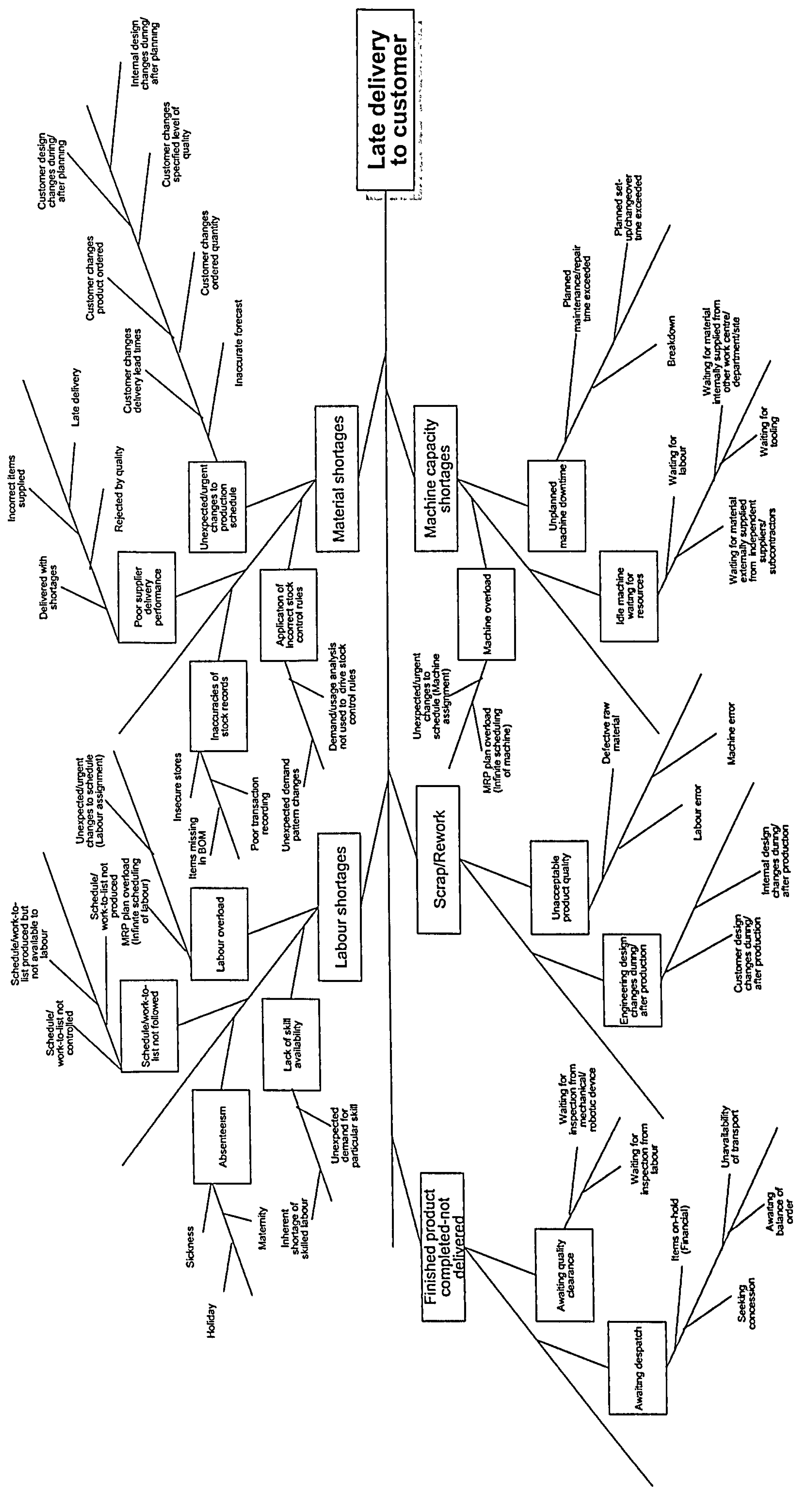

Figure 4.7: Cause-and-effect diagram of uncertainty

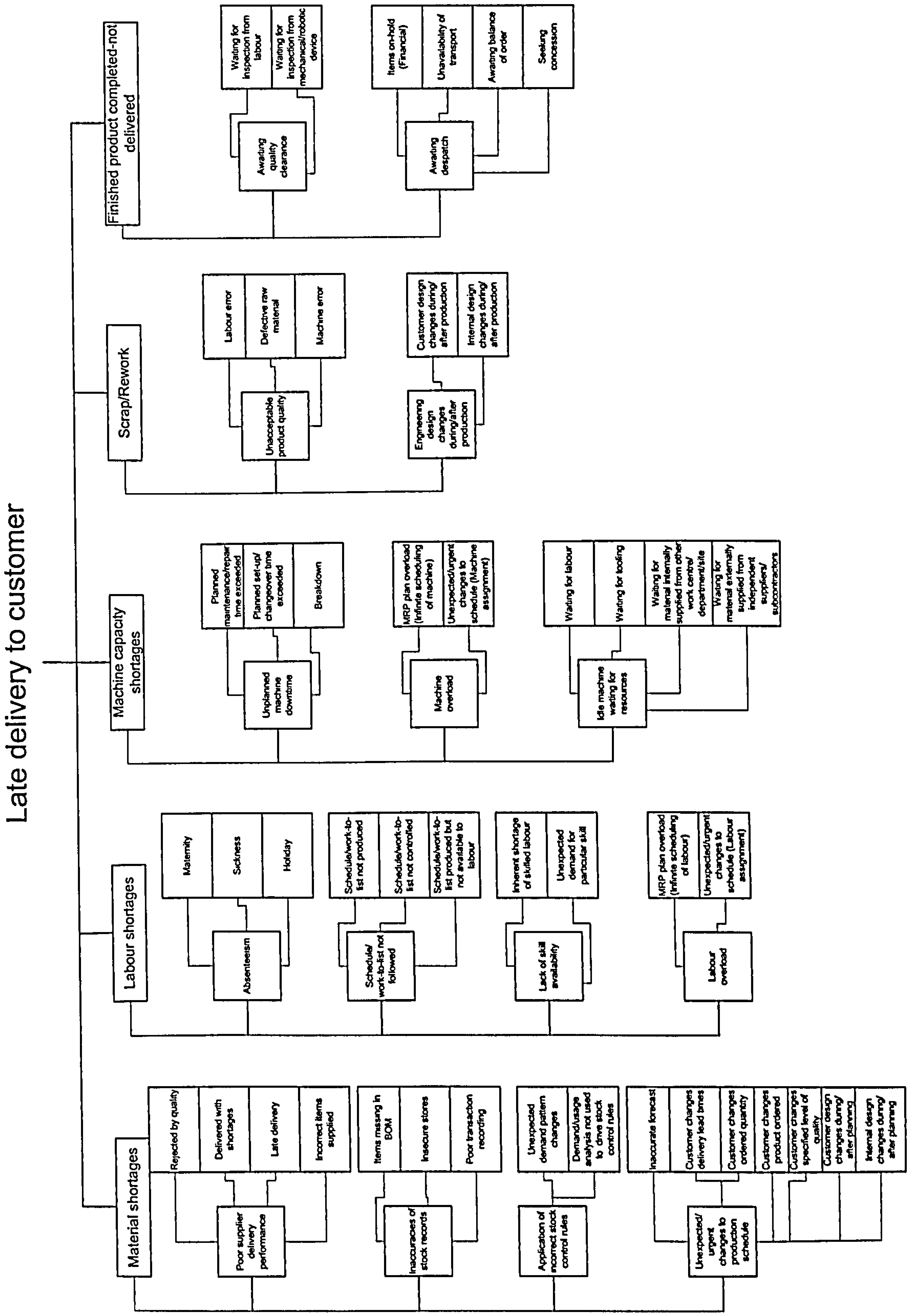

Figure 4.8: Hierarchy of uncertainty

Chapter 5: Comprehensive examination of uncertainty in industry

5.1 Introduction

This chapter discusses the design and application of a second postal questionnaire survey to verify the business model of uncertainty through comprehensive investigation of causes and effects. Using the responses gained, statistical analysis of the significance of uncertainties was carried out.

5.2 Design of second questionnaire survey

The questionnaire was structured into three sections. Section one examined respondents overall delivery performance and sought to identify which causes of late delivery to customer have been experienced at the top level of the hierarchy of uncertainty. Sections two and three examined the constituent uncertainties at each lower level in turn, with the responses in section three representing the underlying causes. Appendix 2 shows the design of the second questionnaire.

The design was also used to verify the business model of uncertainty as it sought responses according to the hierarchy of causes and effects developed. Failure to provide comprehensive information would invalidate the hierarchy. Correct completion would provide implicit verification of the hierarchy.

Objective responses were desired to establish the relative contribution of each effect of uncertainty within each strand of the hierarchy. However, it was recognised at the outset that many items of information might not be recorded. The option to provide an estimated measure was therefore allowed.

While every effort was made to ensure the completeness of the business model of uncertainty, it was still essential to allow refinement as a result of industry views. To gather such views, each question allowed inclusion of additional causes of uncertainty as specified by respondents. Also, examples were included within each question to aid understanding and to avoid ambiguous responses. A sample question showing all these features is shown in Figure 5.1.

2. What contribution does each of the following events make to orders that are not delivered on time, in the correct quantity or to a correct quality level?

	Example	Your %	Estimate
Material shortages	40%		
Labour shortages	30%		
Machine capacity shortages	15%		
Scrap/rework	10%		
Finished product completed – not delivered	5%		
Others, please specify	0%		
Total	100%	100%	100%

Figure 5.1: Sample question from the second questionnaire

The survey sample was restricted to companies that used MRP based systems. The first survey produced responses from a total of 126 MRP users, which formed the second survey sample population.

5.3 Results and analysis

An overall response rate of 56.35% was achieved with telephone follow-up. This was considered an excellent response rate. Table 5.1 shows the profile of the responses.

Operating environment	No. of respondents	% of sample	% of responses
Project	4	3.17	5.63
ATO/MTO	11	8.73	15.49
MTS	10	7.94	14.09
MM	44	34.92	61.97
Process	2	1.59	2.82
Total responses	71	56.35	-

Table 5.1: Second survey responses by operating environment

It was found that an overall majority of respondents operated in MM environment, with a much lower proportion operating in ATO/MTO and MTS environments. Only a very small proportion operated in process and project environments. Since MRP based systems were designed primarily for batch manufacturing, the responses from process and project based companies were excluded from further analysis.

The majority of respondents were unable to supply objective data, choosing instead to estimate the percentage contribution of causes to specified effects. A wide range of results was observed prompting a statistical analysis to assess the significance of each uncertainty.

5.3.1 Analysis of Variance

Analysis of Variance (ANOVA) is an established statistical technique used to uncover the main and interaction effects of independent variables on a dependent variable (Levin and Rubin, 1991). A main effect is a direct effect of an independent variable on the dependant variable, while an interaction effect is the joint effect of two or more independent variables on a dependant variable

A null hypothesis is made that samples are drawn from populations having the same mean while the alternative hypothesis is that they are not. If the null hypothesis is proven, then no significant main or interaction effects exist and *vice versa*. Hypothesis testing is carried out using the F-test, which is a comparison of two different estimates of the variance of a sample population, being the ratio of estimates of mean square between samples and mean square within samples. A p value is then calculated, which is an F probability distribution to indicate whether the variable analysed or interaction identified is significant. The computation for p value is:

$$FDIST = p(F_{table} < F_{observed}) \qquad ....[5.1]$$

Where,

FDIST = F probability distribution

F_{table} = Random variable that has an F distribution read from the F statistics table

$F_{observed}$ = Random variable that has an F distribution calculated from observed values

If:

$$p <= \alpha \qquad ....[5.2]$$

Where,

α = confidence level selected to limit the chance of finding an effect that does not really exist

then the uncertainty is significant with (1 - α) level of confidence.

The intention of this research is to establish the existence or otherwise of cause-and-effect relationships between uncertainties and their outcomes. The use of ANOVA was considered entirely appropriate for this purpose.

A normal distribution of the data set is a pre-requisite. The Central Limit Theorem states that for samples of a sufficiently large size, the distribution of sample means is approximately normal. A sample size of 30 is considered large enough for this purpose. Usable responses from the second survey totalled 65.

SPSS version 10.0 was the tool used to carry out the statistical analysis. To cater for the very large range of percentages recorded, it was necessary to convert continuous interval data into categorical data. As software constraints controlled the maximum number of categories a feasibility study was carried out using the available data to establish the maximum number possible within the limits of the software, which was found to be nine. Table 5.2 shows the resulting conversion scale from continuous interval to categorical units. All response data was converted to these categories prior to ANOVA execution.

Continuous interval (%)	Categorical unit
0-11	1
12-22	2
23-33	3
34-44	4
45-55	5
56-66	6
67-77	7
78-88	8
89-100	9

Table 5.2: Conversion scale from continuous interval to categorical unit

5.3.2 Analysis of Variance results

The data derived from the survey was largely based on estimates. This lack of definitive data created a concern that the estimates themselves were taken after the application of BAD approaches. In addition, many estimates might be beyond the scope of the respondents to assess either accurately or confidently. Therefore, a confidence level of just 80% ($\alpha = 0.20$) was set.

Tables 5.3 to 5.7 show the p values obtained for each individual uncertainty, presented according to the strand of uncertainty and type of operating environment, with p values representing significant uncertainties identified by an asterisk. Where a p value was not computed, it was due to an insufficient data set for ANOVA execution. The full ANOVA tables are shown in Appendix 3.

Uncertainty	ATO/ MTO	MM	MTS
Material shortages	--	0.016*	--
Causes of material shortages			
Poor supplier delivery performance	0.015*	0.031*	--
Inaccuracies of stock records	--	0.053*	--
Application of incorrect stock control rules	--	0.444	--
Unexpected/urgent changes to production schedule	0.019*	0.116*	--
Causes of poor supplier delivery performance			
Rejected by quality	0.909	0.345	--
Delivered with shortages	--	0.937	--
Late delivery	0.187*	0.181*	--
Incorrect items supplied	--	0.398	--
Causes of inaccuracies of stock records			
Items missing in BOM	--	0.253	1.000
Insecure stores	--	0.040*	--
Poor transaction recording	--	0.204	0.584
Causes of application of incorrect stock control rules			
Unexpected demand pattern changes	0.000*	0.918	--
Demand/usage analysis not used to drive stock control rules	--	0.700	--
Causes of unexpected/urgent changes to production schedule			
Inaccurate forecast	0.461	0.339	0.294
Customer changes delivery lead-time	--	0.885	--
Customer changes ordered quantity	--	--	--
Customer changes product ordered	--	0.766	--
Customer changes specified quality level	--	--	--
Customer design changes during/after planning	--	--	--
Internal design changes during/after planning	--	0.563	--

Table 5.3: p values of uncertainty within material shortages strand

Uncertainty	ATO/ MTO	MM	MTS
Labour shortages	0.071*	0.180*	--
Causes of labour shortages			
Absenteeism	0.423	0.835	--
Schedule/work-to-list not followed	1.000	1.000	--
Lack of skill availability	1.000	0.439	--
Labour overload	0.890	0.662	--
Causes of absenteeism			
Maternity	--	0.547	--
Sickness	--	0.762	0.178*
Holiday	--	0.982	1.000
Causes of schedule/work-to-list not followed			
Schedule/work-to-list not produced	0.604	0.138*	--
Schedule/work-to-list not controlled	0.623	0.065*	--
Schedule/work-to-list produced but not available to workforce	--	0.968	--
Causes of lack of skill availability			
Inherent shortage of skilled labour	0.117*	0.452	--
Unexpected demand for particular skill	0.447	0.147*	0.018*
Causes of labour overload			
MRP plan overload (Infinite scheduling of labour)	0.192*	0.002*	--
Unexpected/urgent changes to schedule (Labour assignment)	--	0.002*	--

Table 5.4: p values of uncertainty within labour shortages strand

Uncertainty	ATO/ MTO	MM	MTS
Machine capacity shortages	--	0.042*	--
Causes of machine capacity shortages			
Unplanned machine downtime	0.399	0.347	0.028*
Machine overload	--	0.137*	1.000
Idle machine waiting for resources	1.000	0.215	0.124*
Causes of unplanned machine downtime			
Planned maintenance/repair time exceeded	--	0.291	--
Planned set-up/changeover time exceeded	--	0.008*	--
Breakdown	--	0.000*	0.025*
Causes of machine overload			
MRP plan overload (Infinite scheduling of machine)	--	0.001*	--
Unexpected/urgent changes to schedule (Machine assignment)	--	0.005*	--
Causes of idle machine waiting for resources			
Waiting for labour	0.633	0.000*	--
Waiting for tooling	--	0.000*	--
Waiting for material internally supplied from other work centre/department/site	0.633	0.028*	--
Waiting for material externally supplied from independent suppliers/subcontractors	0.044*	--	--

Table 5.5: p values of uncertainty within machine capacity shortages strand

Uncertainty	ATO/ MTO	MM	MTS
Scrap/rework	--	0.089*	--
Causes of scrap/rework			
Unacceptable product quality	0.704	0.167*	0.315
Engineering design changes during/after production	--	0.879	0.291
Causes of unacceptable product quality			
Labour error	--	0.076*	--
Defective raw material	--	0.033*	0.685
Machine error	--	0.032*	--
Causes of engineering design changes during/after production			
Customer design changes during/after production	0.381	0.172*	--
Internal design changes during/after production	0.193*	0.456	0.078*

Table 5.6: p values of uncertainty within scrap/rework strand

Uncertainty	ATO/ MTO	MM	MTS
Finished product completed-not delivered	--	0.032*	--
Causes of finished product completed – not delivered			
Awaiting quality clearance	--	0.962	1.000
Awaiting despatch	0.77	0.118*	0.014*
Causes of awaiting quality clearance			
Waiting for inspection from labour	0.020*	0.000*	0.061*
Waiting for inspection from mechanical/robotic device	--	--	--
Causes of awaiting despatch			
Items on-hold (Financial)	0.148*	0.000*	--
Unavailability of transport	0.292	0.000*	0.170*
Awaiting balance of order	--	0.001*	--
Seeking concession	--	0.000*	0.806

Table 5.7: p values of uncertainty within finished product completed – not delivered strand

Tables 5.3 to 5.7 have shown that different uncertainties were significant in each operating environment. A total of 34 significant uncertainties were identified within MM operating environments, of which 23 were underlying causes. This compared to a total of 11 within ATO/MTO, of which 8 were underlying causes while MTS produced only 9, of which 6 were underlying causes. Both these factors produced a high likelihood that MM was the operating environment within which the hierarchy of uncertainty could be validated. Figure 5.2 shows the hierarchy of uncertainty with significant uncertainties identified from MM environment highlighted.

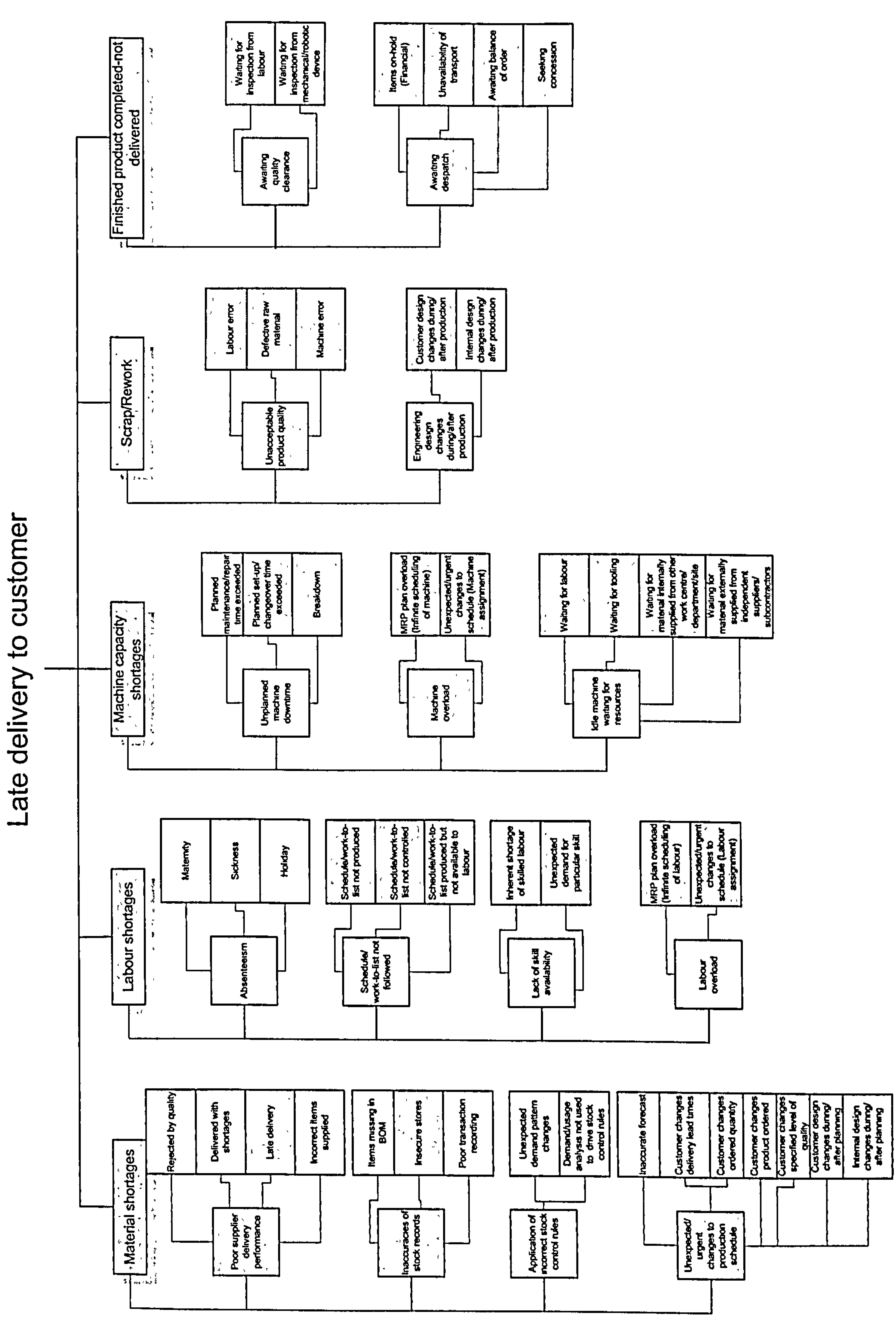

Figure 5.2: Hierarchy of uncertainty with significant uncertainty being highlighted

Within the interaction analysis for MM environment, eight two-way interactions between uncertainties were identified, of which three were significant. Such interactions implied the existence of an additional effect when the uncertainties occurred together. Table 5.8 shows the interactions identified in MM environment.

Interaction		
Material shortages	Machine capacity shortages	0.308
Material shortages	Scrap/rework	1.000
Poor supplier delivery performance	Inaccuracies of stock records	0.045*
Poor supplier delivery performance	Unexpected/urgent changes to production schedule	0.356
Inaccuracies of stock records	Unexpected/urgent changes to production schedule	0.387
Inaccurate forecast	Customer changes delivery lead-time	0.201
Sickness	Holiday	0.613
Schedule/work-to-list not controlled	Schedule/work-to-list produced but not available to workforce	0.185*

Table 5.8: Interactions between uncertainties in MM environment

5.4 Conclusions

The hierarchy of uncertainty has been verified from the responses received to the second questionnaire as respondents have satisfactorily quantified contributions of uncertainties at each level of the hierarchy.

The highest number of significant uncertainties was identified within MM environments. This was also the environment producing the greatest number of responses from both questionnaire surveys. ATO/MTO and MTS had a number of categories for which insufficient data was available to show normality. MM was therefore chosen as the focus of this research.

The existence of interactions was recognised but not examined in detail at this stage, as the intention was only to prove the existence of the hierarchy.

Chapter 6: Deterministic simulation model development

6.1 Introduction

The second questionnaire survey and subsequent ANOVA identified twenty-three significant underlying uncertainties in MM operating environments, which existed within a verified business model of uncertainty. To validate the cause-and-effect relationships within the hierarchy under ideal conditions, uncertainties could be examined within real companies using a case study approach, but the real-life imperative of satisfying customers would result in the use of BAD approaches that masked the true effects.

The first survey identified that companies applied a wide variety of BAD approaches with inconsistent results, it was therefore unlikely any company would be prepared to suppress the use of the approaches purely for experimental purposes. To overcome this limitation, simulation modelling was chosen to validate the business model.

This chapter describes the first step to validation of the business model of uncertainty, which was to simulate MRP deterministically i.e. in the absence of uncertainty, under MPS rules and logic, with an MM demand dataset. The simulation model was developed using SIMAN V programming language within ARENA simulation software. Operating logic was contained in a model file, with operating policies in an experiment file. Steady state and deterministic performance of the simulation model will then be presented.

6.2 Data collection

To fully represent an MRP system, there were a number of elements of detailed data required, being BOM data for product structures and assembly quantities, lead-time delay data for purchased and made parts and routing data for operation sequences of made parts. Resource volumes and capacities of work centres and labour were also required, along with MPS data for demand of finished products.

Knowing the characteristics of the operating domain and the data required for constructing the simulation model, the next step was to collect data. For modelling an MM environment, a variety of independent demand patterns for a range of finished products were required.

For the simulation model, data was derived from a real manufacturing company. Tunewell Transformers Ltd manufacture a wide range of industrial transformers and operate in a MM environment, using WinMan by TTW as their ERP system. The main modules of sales, inventory, purchasing, manufacturing and accounting have been implemented and are fully functional. The company was satisfied with the system performance, yet perceived that it was still incapable of coping with uncertainties. A variety of BAD approaches were used, such as overtime, subcontract and safety stock, to cope with uncertainties that could not be predicted and planned for in ERP. In fact, Tunewell is a typical MM manufacturer as identified from both questionnaire surveys.

A feature of the product range was that cycle times were relatively short, as were set-up and changeover times. This allowed a large number of batches to be modelled within any time frame set for the MPS. As many uncertainties may only exist and/or the effect be measured at very low levels, it was advantageous to have a large number of batches as it would increase the sensitivity of the simulation.

A sample range of products was chosen, as it was not practicable to model the entire product range of the company. In the simulation study, the products included in the MPS were classified as runners, repeaters and strangers (Parnaby, 1988). Runners were defined as products or parts produced at regular, short intervals such as every week. Repeaters were defined as products or parts produced regularly, but at longer time intervals. Strangers were defined as products or parts produced at irregular and possibly unpredictable time intervals. Analysis of the demand pattern and average volumes over a two-year period revealed a mix of three strangers, four repeaters and three runners as shown in Table 6.1.

Product number	Product class	Ave batch size per order
11	Repeater	89
12	Repeater	12
13	Runner	80
14	Runner	100
15	Stranger	175
16	Repeater	35
17	Repeater	40
18	Stranger	100
19	Stranger	32
20	Runner	75

Table 6.1: Product classification and batch size analysis

Indented explosions for each product BOM are included as Appendix 4. Table 6.2 shows types and capacities of resources available.

6.3 MRP domain

MRP is based on multi-product, multi-level dependent demand. An extensive search was carried out to establish whether such a simulation model had already been developed and was available within the public domain. This search was unsuccessful, requiring that the simulation model had to be developed from first principles.

Dependent demand dictates that a parent assembly cannot be started until all child parts are available as defined by the BOM. MRP back schedules from due date through the BOM to generate a POR report indicating the release date for each batch. A simulation model for an MRP domain must use the POR as the primary input.

Abbreviation	Resource	Types	Capacity
GUIL	Guillotine	Machine	1
BRKPRS	Break press	Machine	2
DRL	Drill	Machine	1
CLR	Coiler	Machine	5
ASS1	Assembler class one	Labour	24
ASS2	Assembler class two	Labour	1
ASS3	Assembler class three	Labour	1
ASS4	Assembler class four	Labour	2
FCLR	Finish coiler	Machine	1
TPCH	Turret punch press	Machine	2
WELD	Weld	Machine	5
DBRR	Deburr	Labour	1
SCLR	Sub-assembly coiler	Machine	1
MIX	Mix	Machine	6
SETTG	Settings	Machine	1
INS	Inspector	Labour	1
FIXA	Fixture A	Tool	1
FIXB	Fixture B	Tool	1
FIXC	Fixture C	Tool	2
FIXD	Fixture D	Tool	2

Table 6.2: Types and capacities of resources available

A spreadsheet MRP was developed as an alternative to the use of a commercial MRP package to provide greater flexibility when changing parameters and was used to model an MPS for the ten chosen products over a two-year period, measured as 550 working days, using a time bucket of one day. The resulting POR file included batch size and due date and was sequenced by release date then part number i.e. an exact replica of a POR without priorities other than due date. An example is shown in Appendix 5.

6.4 Simulation model logic

Simulation is carried out on a chronological basis, moving forward in time through a defined sequence of events. MRP uses backward scheduling with dependency protected in the logic of the program. It was necessary to introduce a method for ensuring dependency logic was included in the simulation model.

To ensure that when a child part was completed it could be attached to its parent, the POR file was interrogated to identify all parents, which were then released to the system and put into a holding area.

Parts were released for processing only on or after their release time. At that time, if the part were a child it would proceed through its manufacturing or purchase route, subject to availability of resources. When complete, it would look into the holding area for its parent, attach itself and be identified whether it was the last child required by the parent. If the part were a parent, it had first to identify if all its children were present. If so, it could proceed through its routing, subject to availability of resources. If all children were not available the part could not be released into the system, so staying in the holding area until all children were present. Figure 6.1 shows this release logic as a flow diagram.

Figures 6.2 and 6.3 show the development of this release logic into simulation logic and sub logic and were used to construct the model file shown in Appendix 6.

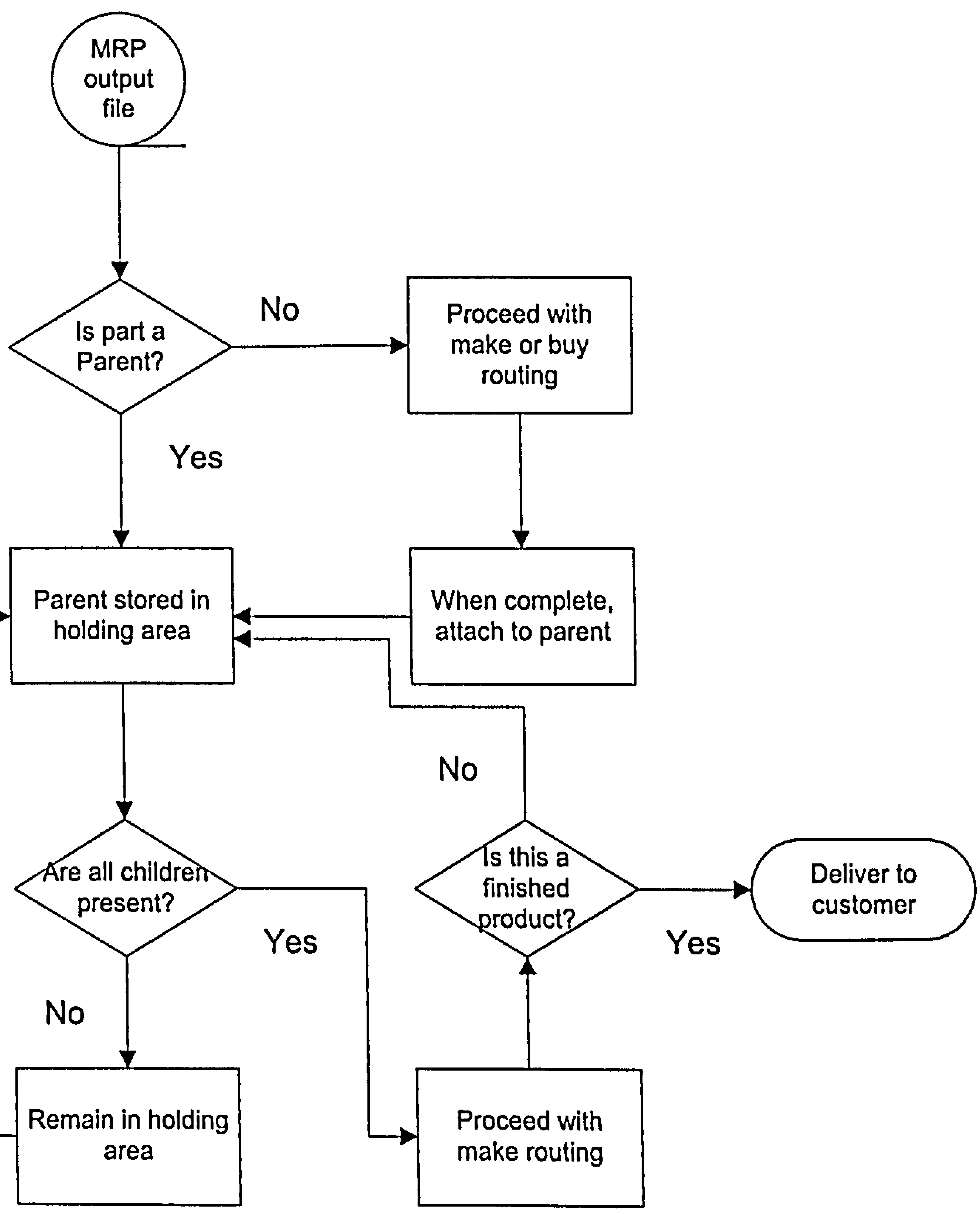

Figure 6.1: Flow diagram of MRP release logic

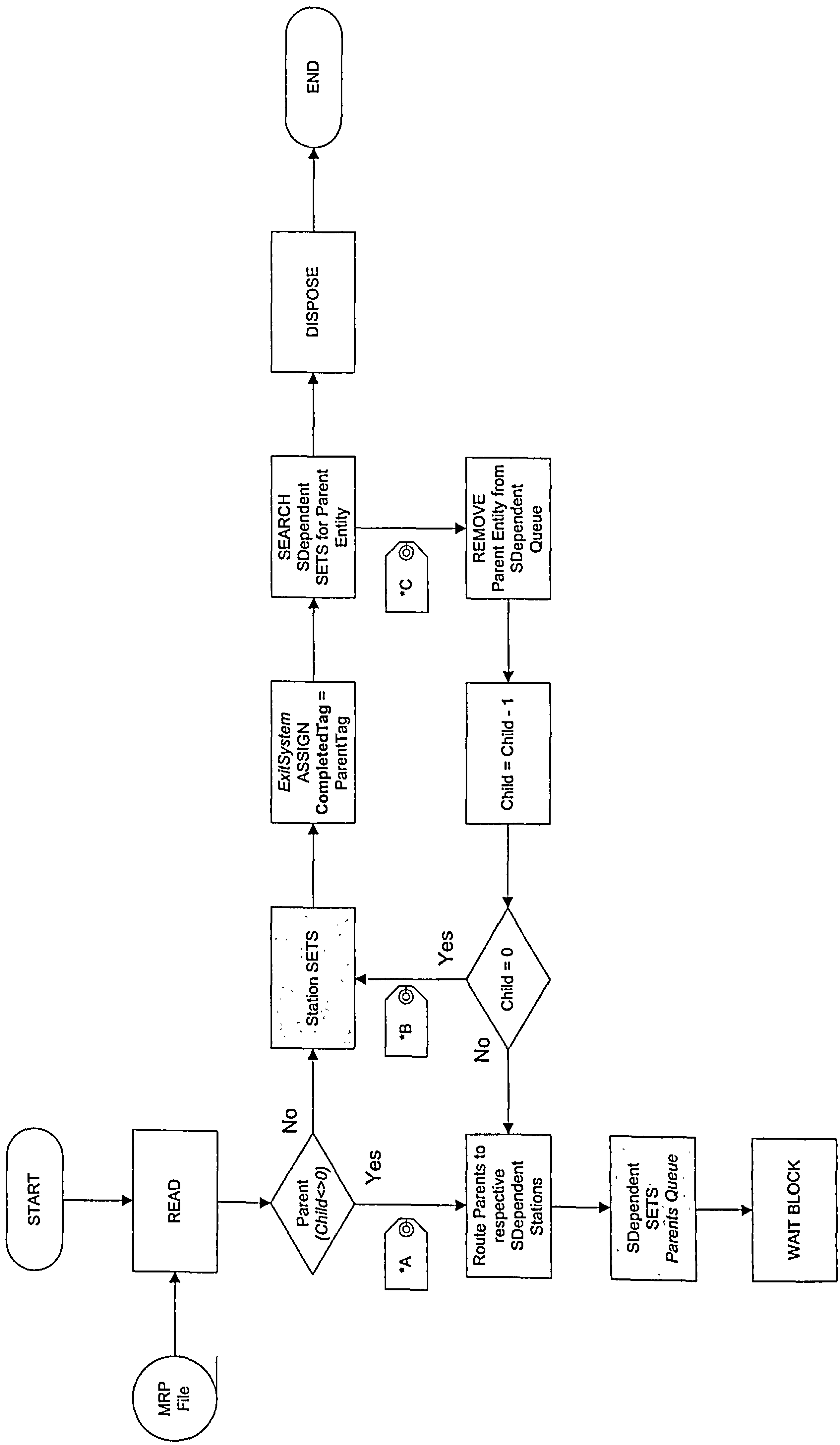

Figure 6.2: Flowchart of simulation model logic

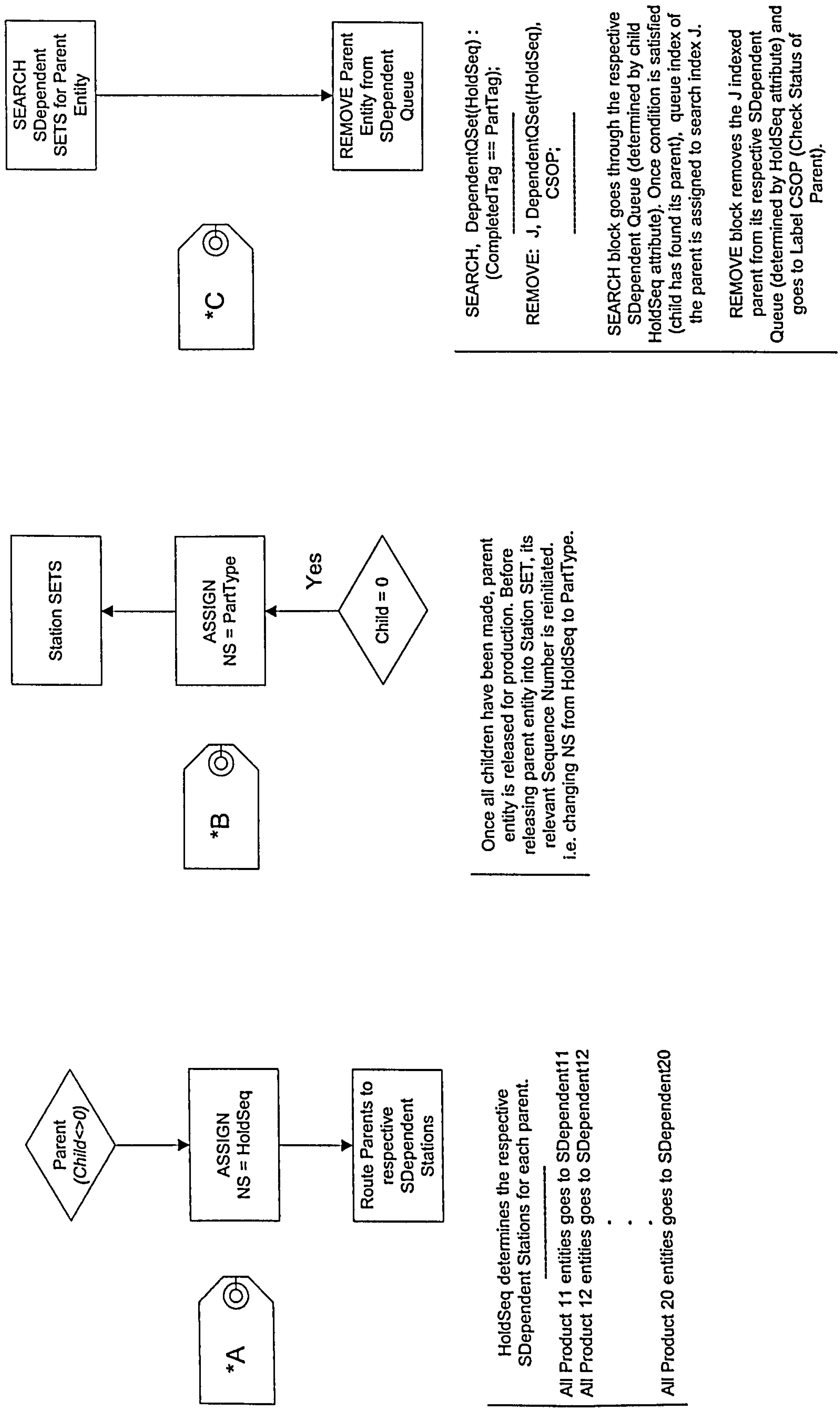

Figure 6.3: Simulation sub-model logic

6.5 Simulation model operating policies

Simulation models require operating policies to control their execution. Within this simulation model, the capacities and states of resources, queuing rules and part routings were established within the experiment file, as shown in Appendix 7. These policies would determine the performance of the simulation model and control the flow of events.

The queuing rule selected was First-In-First-Out (FIFO) as the rule followed by MRP logic in conditions of no uncertainty. Three different resource states were designated, namely idle, working and breakdown. In the deterministic domain, no failures were permitted, as breakdowns would be modelled in Chapter 7 as a form of uncertainty. When a resource was busy, its state would be reported as working, when not busy it would be reported as idle.

Part routings were modelled using the SEQUENCES element in the experiment file. For make parts, routing was sequenced by work centre with a set-up time per batch and operation time per unit. For buy parts, routing was sequenced through a station with a set-up time relating to the purchase lead-time and no operation time.

Specification of resources and capacities would be derived in Section 6.8 from a series of experiments to balance load with capacity.

6.6 Simulation model verification

To ensure the validity of results obtained from any simulation run, the simulation model was verified. There were a number of verification techniques that could be used. Whitner and Balci (1989) devised six different techniques, one of which, the dynamic technique, was employed. This technique was applied using a single product for debugging, top-down testing, bottom-up testing, execution tracing, stress testing and regression testing.

Debugging was carried out to ensure no errors in the programming. Within ARENA this process was carried out automatically. Top-down and bottom-up testing was performed to verify the dependent demand scenario. Top-down testing was performed by varying the values of attributes at the upper level, e.g. increasing the lead-time of a subassembly, and checking whether the related attributes at the lower level were updated correctly. Bottom-up testing checked the reverse scenario.

To ensure the simulation model executed as programmed, the TRACE element was included in the experiment file. While the simulation was running, random stops were made to check the flow.

Stress testing was carried out to check sensitivity by modelling extreme values of attributes. Responses were checked against expectations.

Regression testing was carried out by increasing and decreasing the values of attributes. Responses were examined for logicality.

6.7 Simulation model transient and steady state

With time-persistent statistics used as performance measures, the results from the transient period have to be discarded.

ARENA included an Output Analyser to produce graphical and/or statistical analysis of the output data collected. Figure 6.4 shows an example of the graphical output produced in this way for the performance measure of resource utilisation. Performance during the steady state was assessed by replication methods.

The procedure was carried out for all time-persistent measures, not all of which had identical transient periods. To resolve this issue, the longest transient period was used, guaranteeing a steady state for all measures. The transient period was calculated as 25000 minutes. If the performance measures used are not based on time-persistent statistics, e.g. count of parts leaving the system, the transient period was not required.

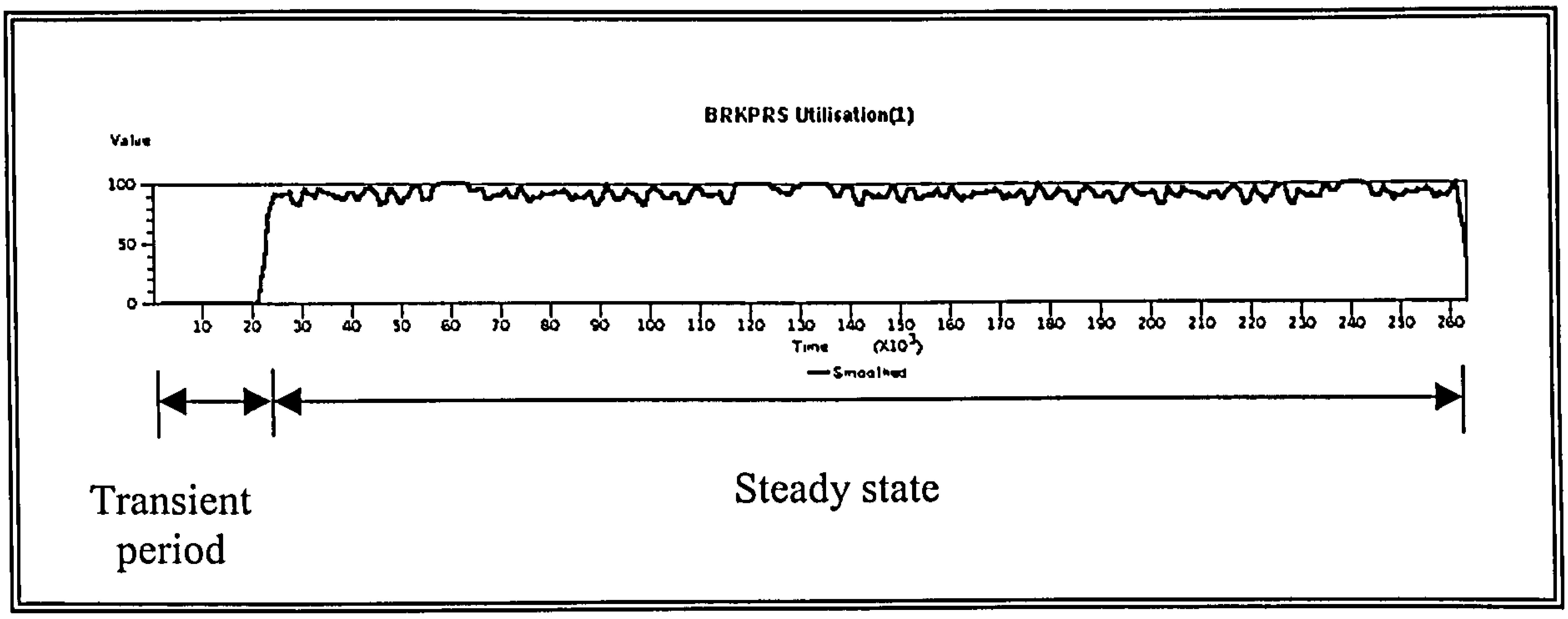

Figure 6.4: An example of the steady state of a measure

6.8 Deterministic domain

A completely balanced manufacturing system with no parts delivered late and 100% machine utilisation was the objective for the deterministic domain with no uncertainties. The deterministic domain would then become the datum for comparison when uncertainties were included.

It was not feasible to achieve exact balance in a finite capacity environment that modelled over 400 part numbers with a variety of demand patterns in nearly 50000 batches over 550 working days (2 years MPS).

As the selected products represented only a subset of the product range it was unknown how much actual manufacturing and assembly capacity would be required for their completion. To quantify resources required, the POR was first simulated with resources that were considered excessive and with no uncertainty to provide actual lead-times for each part produced. To eliminate lead-time dampening effects, all parts were allocated their actual lead-time and the process then repeated a number of times until lead-times were settled. To minimise available slack and Parts Delivered Early (PDE) and to maximize Parts Delivered on Time (POT), resources were gradually reduced in stages until minimum Finished Products Delivered Late (FPDL) and Parts Delivered Late (PDL) levels of 2.93% and 0.20% respectively were obtained. These represented the system datum values by which all results under uncertainty would be offset. A value of 0.18% PDE occurred at that level. Resources resulting, together with average utilisations, are shown in Table 6.3.

Resource	No. required	Ave Utilisation
GUIL	1	15.674
BRKPRS	1	83.998
DRL	1	11.547
CLR	4	80.452
ASS1	12	37.895
ASS2	1	33.439
ASS3	1	24.667
ASS4	2	82.640
FCLR	1	23.563
TPCH	2	45.055
WELD	3	78.306
DBRR	1	48.686
SCLR	1	2.5106
MIX	5	48.620
SETTG	1	51.280
INS	1	71.159
FIXA	1	Not measured
FIXB	1	Not measured
FIXC	2	Not measured
FIXD	2	Not measured

Table 6.3: Resources for deterministic domain

6.9 Simulation model validation

To validate the deterministic simulation model, the results were compared to those from commercially available MRP software (START MRP). The validation was carried out in two stages, the first to validate the POR input generated from the MRP spreadsheet, the second to validate the simulation results.

START MRP was set-up as a single company having the same part numbers, product structures and lead times as the MRP spreadsheet. Identical routings were specified and resources set to those derived for the deterministic domain. Once set-up, the two-year MPS was loaded and MRP run.

Release dates from both START MRP and MRP spreadsheet PORs were compared for a range of batches over the entire MPS period. In all cases exact matches were found thus validating the POR input to the simulation.

Validation of work centre utilisations was achieved by comparing averages from the simulation model, as shown in Table 6.3, against a daily average calculated from START MRP load profiles. This exercise was carried out with identical results.

The final step in validation was to compare simulation model PDL with the results from START MRP. However, the simulation model was a finite scheduling tool, while START MRP used infinite capacity. This made direct comparison impossible.

The simulation showed that 0.20% PDL occurred, even when overall utilisation appeared adequate. It was expected that PDL identified from the simulation model would be reflected in MRP work centre loadings as an overload.

An analysis was carried out to identify the parts involved and timing of PDL. For each part identified routings were established. From this, a total of five work centres were found to recur, which were those with the highest overall utilisations.

A spreadsheet was devised to plot PDL against work centre utilisation from START MRP. A five-day moving average was then calculated. This figure was selected to reflect typical industry planning time buckets as identified from the first survey. A section of the spreadsheet is shown as Figure 6.5.

The results broadly supported the expectation that PDL occurred in periods when there were a number of consecutive days of work centre overload that could not be recovered through the use of available slack in the system. Although a very few anomalies occurred, in the absence of MRP software that included finite scheduling this analysis provided the highest level of validation possible.

	BRKPRS				WELD				ASS4				INS				CLR			
	Utilisation		Part Number		Utilisation		Part Number		Utilisation		Part Number		Utilisation		Part Number		Utilisation		Part Number	
Day No	Daily	5 Day Ave	Due Date	Del Date	Daily	5 Day Ave	Due Date	Del Date	Daily	5 Day Ave	Due Date	Del Date	Daily	5 Day Ave	Due Date	Del Date	Daily	5 Day Ave	Due Date	Del Date
240	70	89			108	90			52	77			42	67			92	86		
241	115	93			95	89			111	89			106	78			76	88		
242	137	103	14037		149	107	14037		52	83			42	71			102	83		
243	105	112		14037	103	114		14037	117	82			92	71			100	89		
244	72	100	13038		90	109	13038		120	90			99	76			68	88		
245	161	118		13038	106	109		13038	80	96			86	85			101	89		
246	105	116	14037 17033		83	106	14037 17033		52	84			42	72			165	107		
247	96	108	14034 16035	14037 17033	60	88	14034 16035	14037 17033	111	96			106	85			133	113		
248	95	106	14034 14037	14034 16035	100	88	14034 14037	14034 16035	181	109			75	82			86	111	17002 18001	
249	92	110	14037	14034 14037	73	84	14037	14034 14037	90	103			186	99			118	121	14001	17002 18001
250	90	96	14034 14037 20023	14037	100	83	14034 14037 20023	14037	114	110	17 18 19		88	99	17 18 19		68	114	160022 0002	14001
251	129	100	17033 14034 14037	14034 14037 20023	113	89	17033 14034 14037	14034 14037 20023	80	115	14 16	17 18 19	75	106	14 16	17 18 19	83	98		160022 0002
252	61	93	14034 14037	17033 14034 14037	67	91	14034 14034	17033 14034 14037	52	103	13	14	42	93	13	14	118	95		
253	86	92	20023	14034 14037	60	83	20023	14034 14037	185	104		13 16	149	108		13 16	76	93	13001 17002	
254	90	91		20023	114	91		20023	52	97	13		53	81	13		68	83		13001 17002
255	95	92			68	84			80	90	17	13	75	79	17	13	100	89		
256	80	82			73	76			83	90	13	17	73	78	13	17	70	86		

Key: Shaded area shows periods of work centre overload

Figure 6.5: Comparison of MRP and simulation model PDL (partial)

6.10 Conclusions

No simulation model designed for true MRP operation under multi-product, multi-level dependant demand conditions using an MPS as a driver for POR and controlled by release time could be found in the public domain.

The required simulation model has been developed and approximately balanced using two years of real-life company data simulating a MM environment incorporating a product mix of runners, repeaters and strangers with varying batch sizes between products.

It was not possible to produce a MM simulation model capable of satisfying all customer orders. Residual values of 2.93% FPDL, 0.20% PDL and 0.18% PDE were the *optimum* achieved. It was concluded that even in the absence of uncertainty, infinite capacity planning with MRP was not capable of producing an acceptable POR to achieve 100% on-time delivery when scheduled finitely.

Chapter 7: Stochastic simulation model development

7.1 Introduction

This Chapter extends the work carried out in Chapter 6 to include development of a simulation model to incorporate uncertainty.

The original twenty-three uncertainties having statistical significance from the second survey were screened to establish suitability for simulation and identification of associated modelling techniques, each of which are discussed. For each uncertainty deemed suitable for simulation, algorithms were derived and explained.

Finally, design of experiments is introduced to include the nature of the experimental programme required, performance measures to be used and how many replications were needed.

7.2 Screening procedures for uncertainties

The second survey identified twenty-three significant uncertainties. Screening was required to ensure the uncertainties could be simulated and whether different uncertainties could use similar simulation modelling techniques. The initial screening recognised seven groups of simulation modelling techniques that could be applied. Table 7.1 shows the simulation groups and the uncertainties to which they relate.

Simulation technique	Uncertainty
Cycle time increment	Late delivery from supplier Insecure stores Planned set-up or change-over time exceeded Waiting for labour Waiting for tooling Waiting for inspection labour Waiting for material internally supplied Unexpected demand for particular skill (Labour)
Batch size increment	Unexpected/urgent changes to schedule (Machine assignment) Unexpected/urgent changes to schedule (Labour assignment)
Change to queuing rule	Schedule/work-to-list not controlled Schedule/work-to-list not produced
Mean Time Between Failure/Mean Time To Repair (MTBF/MTTR)	Breakdown
Alternative routing	Customer design changes
Probability (Pass/fail)	Labour error Defective raw material Machine error Items on-hold (Financial) Unavailability of transport Seeking concession Awaiting balance of order
Use of commercial MRP based system	MRP planned overload (Infinite scheduling of machine) MRP planned overload (Infinite scheduling of labour)

Table 7.1: Simulation techniques and associated uncertainties

7.2.1 Cycle time increment

Increasing cycle times produces a delay to procurement or completion of both the part itself and assemblies waiting for the affected part.

The uncertainties of late delivery from supplier, planned set-up or change-over time exceeded, waiting for labour, waiting for tooling, waiting for inspection labour and waiting for material internally supplied would logically use this technique.

An insecure stores could result in parts planned to be available not being found. This would force a delay while a search was carried out, complete re-manufacturing of a batch took place or a new purchase order was placed. In each case the effect would be to lengthen the cycle time. In the case of re-manufacture there would also be resource loading implications.

Unexpected demand for a particular skill (Labour) would cause affected parts to be delayed until suitable labour became available. This would only affect make items and the affected part would reside within the system as a queue, or WIP in exactly the same way as waiting for labour, therefore it would not be modelled separately.

Waiting for material internally supplied is similar to waiting for material from suppliers. It would only affect make parts and sub-assemblies and would be the result of another uncertainty that had already been modelled, for example a breakdown causing a part to be late, which then delayed the parent assembly. There was no requirement to model this uncertainty separately.

Cycle time increments could be modelled either by randomly increasing the set-up and/or operation time within the routing or by randomly delaying POR dates for the affected parts.

The use of a discrete probability distribution was chosen to delay POR dates as it permitted defined delays to be applied to a random selection of parts with comparative ease. Randomly increasing the set-up and/or operation times would produce the same effect, but would require the use of three probability distributions rather than just one.

7.2.2 Batch size increment

Increasing batch size would cause longer than planned lead-times in make parts by increasing the total operation time for the batch. Unexpected/urgent changes to schedule for machine and labour assignments could be simulated by increasing batch size and the number of batches affected.

The modelling technique chosen was to define a batch size multiplier coefficient and apply it to varying numbers of batches.

7.2.3 Change to queuing rule

There were a number of queuing rules that could be specified within the simulation model including FIFO, Last-In-First-Out (LIFO), Earliest Due Date (EDD), Shortest Processing Time and others. The rule applied by MRP based systems is FIFO.

If the schedule/work-to-list were in control then FIFO would be applied effectively. However, the existence of uncertainty could cause non-adherence to the schedule, for example parts unavailability forcing a change in sequence. Under such circumstances the uncertainty would be modelled elsewhere in the system.

There could still be occasions when, for example, a customer sought to expedite a particular job or an individual employee took a view as to the importance of a task. Those essentially random actions would be very difficult to simulate discretely, so alternative queuing rules (LIFO and EDD) would be applied.

If the schedule/work-to-list was not produced, the same analysis applied and it would therefore not be simulated separately.

7.2.4 MTBF/MTTR

Breakdown of a resource would have the effect of delaying completion of the part being processed, all subsequent parts waiting for the resource and sub-assemblies requiring the parts. Only if there were an amount of slack available after the breakdown would the system return to on-schedule. From the exercise carried out to balance the deterministic simulation model in Chapter 6 it was identified that many resources had spare capacity and thus this issue became of importance only for highly utilised resources.

Adjusting MTBF and MTTR allowed changes to be made to the reliability of the resources and was used to model breakdowns. Pedgen *et al.* (1995) showed that Exponential and Gamma distributions were widely accepted to model MTBF and MTTR respectively and they were therefore chosen.

7.2.5 Alternative routing

This would mainly be used to model customer design changes. Once such changes have happened a manufacturer would normally attempt to correct the affected batch. Depending on the extent of the change, the affected batch might be re-manufactured or some additional operations added to complete the new design. In the worst case the entire batch would be scrapped and re-manufactured under expediting rules. In such circumstances the rules involving scrap would be applied. For a change involving rework, simulation would be done by the inclusion of additional operations in the routing.

7.2.6 Probability (Pass/fail)

There were a number of events that could simply be defined in terms of the probability of success or failure. Seven uncertainties were identified, falling into two sub-groups, i.e. quality failures during production and finished product completed but not delivered.

In the case of quality failures during production in the absence of in-process inspection, failure would occur at final inspection. At that time, it may be too late to correct the error and the batch would be delivered late, even if rework were possible. If in-process inspection were available, then rework could be modelled for labour error, defective raw material and machine error. To model this would require three output branches, namely pass, fail or rework, with rework re-routing the batch back to the source work centre or a separate rework area. To simulate this effect would introduce major programming complications into the simulation model and the option was rejected.

The other group of finished product completed but not delivered occurred at the output stage and had no consequent effect on any part remaining in the manufacturing system and were therefore outside the scope of the required simulation and could safely be ignored.

7.2.7 Use of commercial MRP based system

The existence of the phenomenon of planned MRP overload was proved by the inability to construct a simulation model capable of satisfying 100% on-time delivery in a mixed mode environment. It followed that some overload naturally existed as a result of schedule imbalance as detailed in the validation process included in Chapter 6.

No further simulation modelling in this area was necessary as the existence of MRP planned overload would be catered for by offsetting all simulation results by the residual FPDL and PDL levels identified during validation.

7.3 Screening process results

After carrying out the uncertainties screening procedures, ten uncertainties were removed. Eleven uncertainties remained to be simulated using ARENA, while two had already been modelled within START MRP. Table 7.2 lists all thirteen uncertainties modelled and an abbreviation for each.

Abbreviation	Uncertainty
LDFS	Late delivery from supplier
INSC	Insecure stores
SWTLNC	Schedule/work-to-list not controlled
LA	Unexpected/urgent changes to schedule (Labour assignment)
MA	Unexpected/urgent changes to schedule (Machine assignment)
PSE	Planned set-up/change-over time exceeded
BD	Breakdown
WFL	Waiting for labour
WFT	Waiting for tooling
CDC	Customer design changes
WFINS	Waiting for inspection labour
OLAB*	MRP plan overload (Infinite scheduling of labour)
OMC*	MRP plan overload (Infinite scheduling of machine)

Key: * Uncertainties already modelled in START MRP

Table 7.2: Thirteen uncertainties screened for simulation

7.4 Stochastic simulation algorithms

The simulation algorithms written for the deterministic domain were extended to allow simulation of the eleven specified uncertainties to be modelled within ARENA. The complete model file is shown as Appendix 8, with the corresponding experiment file shown in Appendix 9. This section explains the logic of each algorithm, while the associated lines of code are shown in Appendix 10.

LDFS used a discrete probability distribution applied to a random selection of buy parts only. An attribute name and value of zero were assigned. The probability distribution was then described in terms of both frequency and magnitude. Frequency specified the percentage of batches that were subject to LDFS, while magnitude specified the minutes delay each affected batch would experience. The algorithm then offset the planned release time by the minutes delay experienced. The effect of this algorithm was that all affected parts exceeded their due date, with subsequent delays for parent parts.

For INSC, an almost identical sub-routine to LDFS was used. As INSC was applied to both make and buy parts, there was no need to specify the part range involved.

SWTLNC was modelled using the standard element QUEUES within the experiment file with a default rule of FIFO. Specifying either LIFO or EDD required only the addition of a RANKINGS element, which released entities from each queue according to the rule. These rules were applied only to resources with high utilisations.

LA was modelled using a specific batch size multiplier coefficient applied to make parts from a selection of orders for repeater products with a labour content. Only repeater products were subjected to LA as runners would be very tightly controlled and strangers, being irregular in nature, were assumed not to be subject to volume changes after MRP had been run. The algorithm first identified selected order numbers and associated part numbers having a labour content. The batch size multiplier coefficient was then used to increase the batch size by a chosen factor. The same sub-routine was applied to each repeater product in turn.

MA was modelled in the same way as LA, but identified only parts from selected orders that underwent machining.

PSE affected only work centres that included a set-up time and was applied through a discrete probability distribution (as for LDFS), to operations carried out on any one of them selected at random. Four work centres were identified within this category, being GUIL, CLR, TPCH and MIX. An attribute name and value of zero were assigned together with an Index Sequence number internally generated by ARENA, equating to the operation number within the routing sequence. Specifying the Index Sequence number ensured that delay was only applied to the first relevant work centre in the routing. The effect of this algorithm was that most affected parts exceeded their due date, with subsequent delays for parent parts although it was possible that some slack existed within the lead-time for these items, resulting in no overall delay.

The FAILURES element was used to model BD, which resulted in work being delayed causing subsequent delays to parts in the queue and all associated parent parts. Time-based distributions modelled MTBF, using an Exponential distribution and MTTR, using a Gamma distribution. The RESOURCES element allowed affected resources to be specified and rules governing actions in the event of breakdown to be stated for each resource. Only machines with high utilisation were subjected to BD, namely BRKPRS, CLR and WELD to increase the sensitivity of the simulation model. Low utilisation machines would have slack time available and hence a breakdown would not result in late delivery. The preempt rule was used to control actions in the event of breakdown. This caused the machine to stop immediately, irrespective of the stage reached in processing. The alternative approach was called ignore, which would cause any item to have its machining completed before the breakdown took effect. The inclusion of the state of working ensured that breakdowns could only occur when a machine was working, not when it was idle.

WFL was modelled in the same way as LDFS except that it applied to make rather than buy parts and included identification of the first operation in the routing sequence, to ensure only one occurrence of WFL per batch was modelled. The algorithm increased the operation time by the minutes delay experienced. Alternate routings of make parts were also included to ensure WFL could exist even when causes requiring alternative routings were present.

WFT had the same application and effect as WFL in that it only applied to make parts and caused a delay in processing. The major difference was that it only applied to those parts that used tooling identified by FIXA, FIXB, FIXC and FIXD.

CDC required an additional (or alternative) routing for affected parts that corresponded to the additional tasks required when such changes occurred. This would only affect make parts as it was assumed that buy items subject to change would be available when required. To model this required that alternative routings were available and a discrete probability distribution was applied to decide which route should be taken. Repeaters and strangers only were affected as it was assumed that changes to runners would occur as part of a formal design change procedure and not have immediate effect. The algorithm identified the part type, which equated directly to a routing number. The probability distribution was described in terms of frequency alone and when an alternative was required, assigned a new routing to that part.

WFINS used discrete probability distribution in the same way as for LDFS. As inspection activity was assumed to occur as the last operation for finished products, the algorithm identified the assigned machine number from the routing that related to inspection.

7.5 Simulation model verification and validation

Additional work was carried out to verify the stochastic algorithms. The same techniques as for the deterministic simulation model were adopted and were equally successful.

A further validation exercise was not considered necessary for two reasons. Firstly that the stochastic simulation model simply introduced verified algorithms to an already validated deterministic simulation model and secondly that no appropriate simulation model could be found for validation purposes.

7.6 Simulation model operating parameters

Before full experiments could be run, the parameters of the simulation model must be specified to define the complete simulation model domain. These are shown in Table 7.3. Limits to the parameters would be set within the experimental program.

No	System and operating parameters of the simulation model
	System parameters
1	A 550 working day (2 year) MPS.
2	Ten products using 434 part numbers generated 49659 POR batches through the MPS.
3	Part numbers were 60% buy parts, 40% make parts in 3-5 level BOMs
4	Residual levels of 2.93% FPDL, 0.20% PDL and 0.18% PDE resulted from the MPS adopted.
	Operating parameters
1	LDFS, INSC, PSE, WFL, WFT and WFINS were modelled using discrete probability distributions, specified in terms of frequency (%) and magnitude (mins.). CDC was only subject to distribution frequency (%).
2	Only buy parts were subject to LDFS.
3	Both make and buy parts were subject to INSC.
4	Only high utilisation resources (BRKPRS, CLR, ASS4, WELD, INS) were subject to SWTLNC.
5	Only make parts of specific repeater orders having operations through labour resources were subject to LA.
6	Only make parts of specific repeater orders involving operations through machine resources were subject to MA.
7	Only one occurrence per batch for operations through GUIL, CLR, TPCH and MIX were subject to PSE.
8	Only BRKPRS, CLR and WELD were subject to BD with Exponentially distributed MTBF and Gamma distributed MTTR.
9	Only make parts were subject to WFL with one occurrence per batch.
10	Only batches for operations through FIXA, FIXB, FIXC and FIXD were subject to WFT.
11	Only make parts of repeaters and strangers were subject to CDC.
12	Only batches that involve operations through INS were subject to WFINS.

Table 7.3: System and operating parameters of the stochastic simulation model

7.7 Simulation experiment design

It was identified from the screening procedures for uncertainties that eleven needed to be modelled. To ensure a robust approach to simulating this number of uncertainties and to ensure integrity of output and analysis, an experimental programme for the simulations had to be devised. During design of simulation experiments, there were a number of issues that needed to be addressed (Saad, 1994):

[1] What factors to be simulated?

[2] What are the appropriate performance measures?

[3] How many replications are required?

[4] Design of experiments

7.7.1 What factors to be simulated?

These have already been identified from the screening procedure for uncertainties and presented as Table 7.2

7.7.2 What are the appropriate performance measures?

Performance measures used to collect responses from a simulation model must be consistent with the objectives of the study. The literature review identified the need to establish a common performance measure and the first survey identified the level of late delivery to customer as the preferred measure, which has been specified as FPDL measured as a percentage of finished product batches made.

At a more detailed level, PDL as a percentage of total batches made has been used to provide insights to the effects of uncertainties on made-in parts, bought-out parts and finished products. Batches would only be counted late when more than one day difference was calculated between planned due date and actual delivery date.

7.7.3 How many replications are required?

The number of replications controls confidence in the results from an experiment. The higher the number of replications, the greater is the confidence achieved through removing the chance of statistical flukes, provided that results follow a normal distribution. Law and Kelton (2000) stated that for statistical reliability, five replications were considered satisfactory.

In this research, many of the distributions applied to simulate uncertainty were not themselves normal. Under these circumstances the number of replications had to be increased to create an approximation to normality. Pegden *et al.* (1995) stated that with data that may not be normally distributed, increasing the number of replications to ten would ensure that results would be approximately normal. This figure was chosen for initial pilot studies.

The distributions resulting from the pilot studies were then analysed to establish the confidence intervals achieved as measured by the half-widths (h) of the distributions. The formula to achieve this was:

$$h = t_{1-\alpha/2,\, n-1} \frac{S(x)}{\sqrt{n}} \qquad \text{.......................(7-1)}$$

Where: h = distribution half-width

$t_{1-\alpha/2,\, n-1}$ = standard deviate in t-distribution for α confidence level

$S(x)$ = an unbiased estimator of the standard deviation

n = number of replications

From the analysis it could be established whether any further replications were required to ensure an acceptable level of h value, considered to be less than 5% of the sample mean (Saad, 1994). The confidence level was set in all cases to 95%.

As an example, Table 7.4 shows the results for FPDL and PDL from a pilot run:

Replication No	PDL	FPDL
1	11.45	98.14
2	13.35	79.52
3	15.67	89.89
4	11.77	77.84
5	12.80	87.32
6	12.75	88.74
7	13.58	86.88
8	14.05	92.64
9	12.98	88.92
10	12.02	84.57
h	0.87	4.23
$t_{1-\alpha/2,\, n-1}$	2.26	2.26
$S(x)$	1.23	5.91
n	10	10
Mean ($\bar{X}$)	13.04	87.45

Table 7.4: Summary of results from ten replications

From these results it was possible to calculate upper and lower confidence intervals where:

$$\text{Confidence interval} = \bar{X} \pm h \qquad \text{.....................(7 - 2)}$$

To produce:

	PDL	FPDL
Lower confidence	12.17	83.22
Higher confidence	13.91	91.68

With a mean of 87.45, an acceptable h value for FPDL would be less than 4.37. With a computed value of 4.23, the 5% condition was satisfied and no further replications were required. However, an acceptable h value for PDL would be 0.65, but the computed value was 0.87, implying that further replications were required. To calculate the number of further replications required, the following equation was used:

$$n^* \geq n \left(\frac{h}{h^*}\right)^2 \qquad \text{.......................(7-3)}$$

Where: n^* = total replications required

n = initial number of replications

h = initial calculated half-width for n replications

h^* = desired distribution half width

Applying this formula yields:

$$n^* \geq 10\,(0.87 / 0.65)^2$$
$$\geq 17.91$$
$$\cong 18 \text{ replications}$$

Thus, an additional set of 8 independent replications was required, using a different starting seed. Alternatively it would be permissible to make a new study of 18 replications from the same seed. The additional replications would then be combined with the pilot run results and the h value recalculated. If the value were still not acceptable, the exercise would be repeated.

7.7.4 Design of experiments

'In simulation, experimental design provides a way of deciding before the runs are made which particular configurations to simulate so that desired information can be obtained with the least amount of simulating' (Law and Kelton, 2000).

For simulating few factors at few levels, full factorial designs modelling all possible combinations could be applied. For a two level full factorial experiment with k factors, 2^k gives the number of experiments required, e.g. two levels with three factors would require ($2^3 = 8$) experiments. For simulating the eleven uncertainties identified with two levels using full factorial design would require ($2^{11} = 2048$) experiments, each with a minimum of ten replications.

When the number of experiments required becomes too large, fractional factorial designs can be applied to reduce the number of experiments required by restricting simulation to a subset of all of the possible combinations. Reducing a two level simulation study to 2^{k-p} experiments would for a p value of one, halve the number and for a p value of three reduce it to one-eighth. However, reducing the number of experiments could cause misleading results as main effects and interactions could become confounded. The confounding effects are well known and understood and are described by a resolution number taken from standard tables and shown in Figure 7.1.

Resolution III is defined as main effects confounded, resolution IV has two-way interactions confounded, resolution V has three-way interactions confounded, while resolution VIII has up to three-way interactions not confounded (Croarkin and Tobias, 2001).

Available Factorial Designs (with Resolution)

Factors

Runs	2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	Full	[illegible]												
8		Full	IV	[illegible]	[illegible]	[illegible]								
16			Full	V	IV	IV	IV	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
32				Full	VI	IV	IV	IV	IV	IV	IV	IV	IV	IV
64					Full	VII	V	IV	IV	IV	IV	IV	IV	IV
128						Full	VIII	VI	V	V	IV	IV	IV	IV

Figure 7.1: Factorial designs showing resolution numbers (Source: Minitab Release 13)

An alternative approach to reduce the number of experiments is known as Taguchi orthogonal array design. It allows a mixture of levels of factors to be used, which would allow grouping of uncertainties. With factors grouped, the number of experiments would reduce significantly.

The effectiveness of the experimental design chosen would depend on the number of factors and the number of levels at each stage of the simulation study. Results would then be used to identify significant factors that required further simulation. This approach would tend to reduce the number of factors to be simulated as the study progressed, hence requiring different experimental designs. Both fractional factorial design and Taguchi orthogonal array design approaches would be used.

This study would use three experimental stages to simulate firstly discrete uncertainties, then a pilot study of all uncertainties in combination and finally detailed study of significant uncertainties in combination.

Simulation of all uncertainties discretely would establish the sensitivity of the simulation model and facilitate selection of parameter levels for later experiments.

The pilot study simulating all uncertainties in combination would use Taguchi orthogonal array design and subsequent ANOVA to establish uncertainties to be included in the detailed study of significant uncertainties in combination, using a minimum number of experiments.

Fractional factorial design and subsequent ANOVA would be used to simulate significant uncertainties in combination, from which research conclusions would be drawn.

7.8 Conclusions

All twenty-three uncertainties recognised as significant from the second survey could be modelled using seven different simulation techniques either within ARENA or START MRP.

A total of ten uncertainties either did not impact upon the manufacturing cycle as they occurred after product completion, were not considered suitable for modelling within the practical limits of this research or else were identified as a pseudo for other uncertainties already simulated and could be discarded from further detailed study. A further two uncertainties had already been modelled within START MRP and could also be excluded. A total of eleven uncertainties remained to be modelled both discretely and in combination.

It was possible to develop algorithms within ARENA and specify system and operating parameters that provided reasonable representations of the uncertainties modelled within a realistic operating environment using PDL and FPDL as performance measures.

Calculations would be required during detailed studies to establish the number of replications required to achieve an h value of less than 5% of the sample mean.

Experiments would be carried out in three stages to simulate firstly discrete uncertainties, then a pilot study of all uncertainties in combination and finally detailed study of significant uncertainties in combination, using both Taguchi orthogonal array and fractional factorial designs.

Chapter 8: Experiments, results and analysis

8.1 Introduction

This work has created, verified and validated a multi-level, multi product dependent demand simulation model that truly simulates MRP environments. This chapter will now examine and discuss the results of the experimental programme designed to test the stochastic simulation model under various types and levels of uncertainty.

Detailed design of experiments was applied to each of three experimental stages, namely sensitivity studies for discrete uncertainties, a pilot study of all uncertainties in combination and finally detailed study of significant uncertainties in combination.

Significant discrete uncertainties were first identified, then considered together with any significant interactions and discussed for relevance and realism.

The results from the experimental programme, together with further consideration of uncertainties modelled by START MRP, will be used to provide validation for the business model of uncertainty derived in this research.

8.2 Sensitivity studies for discrete uncertainties

Sensitivity studies were carried out to assess the dynamic response of the simulation model when subjected to uncertainty. A range of levels was applied to each uncertainty discretely and response profiles generated, providing empirical evidence from which low and high parameter levels for all subsequent experiments were set. The levels selected would reflect realistic limits for prevailing industrial expectations.

For uncertainties requiring distribution algorithms, 10 replications were made, from which sample means were computed. At a 95% confidence level, *h* values were calculated that in all cases were less than 5% of the sample mean, implying no additional replications were required.

For uncertainties that did not require distribution algorithms, single replications were sufficient, as identical results would be obtained irrespective of the number of replications.

8.2.1 Late delivery from supplier (LDFS)

Using a discrete probability distribution for modelling LDFS, simulations were run for frequencies of 1%, 2% and 5%, with 1, 3, 5 and 7 days as magnitudes. The results for FPDL and PDL are shown in Figures 8.1 and 8.2.

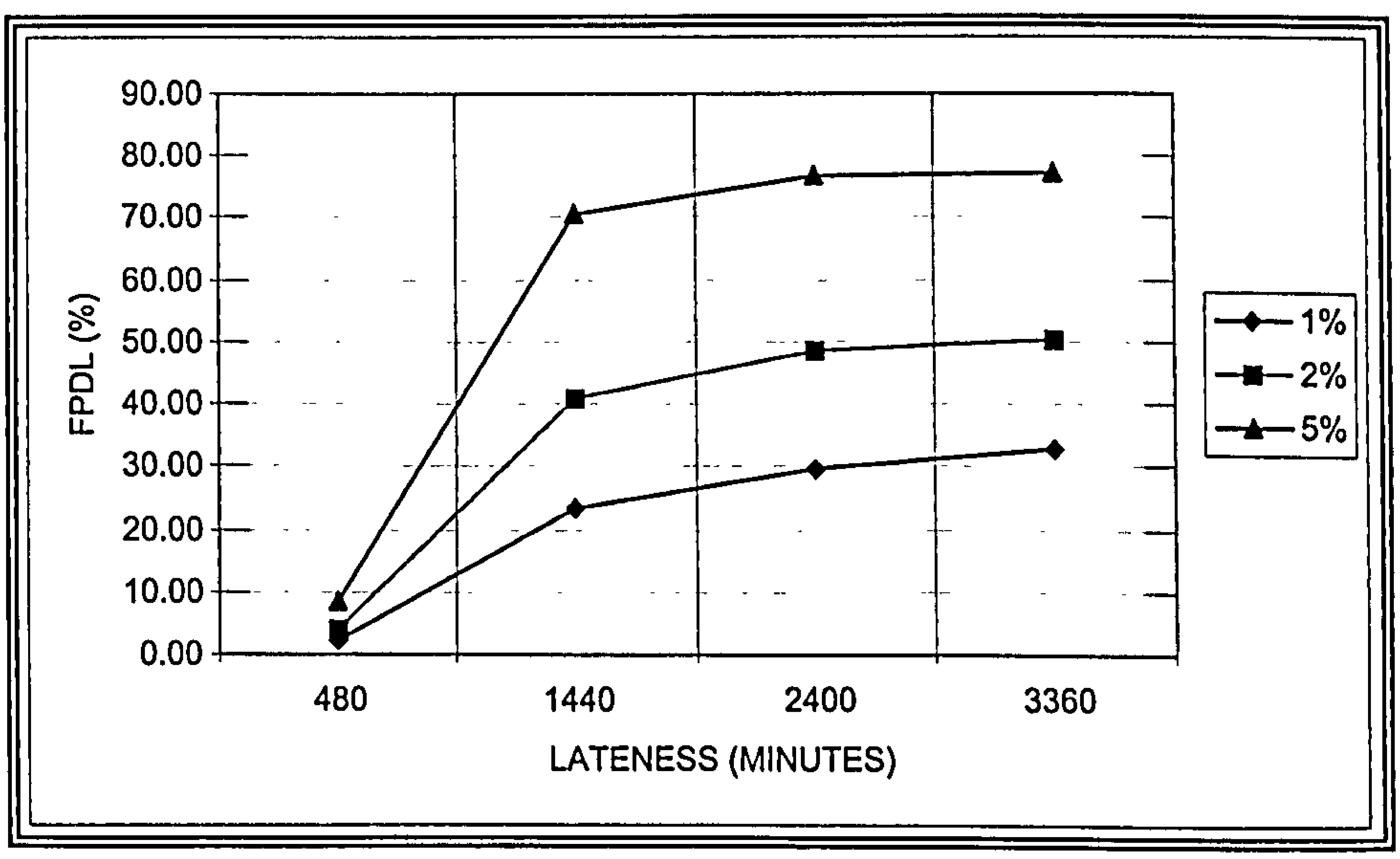

Figure 8.1: Sensitivity matrix for LDFS measured by FPDL

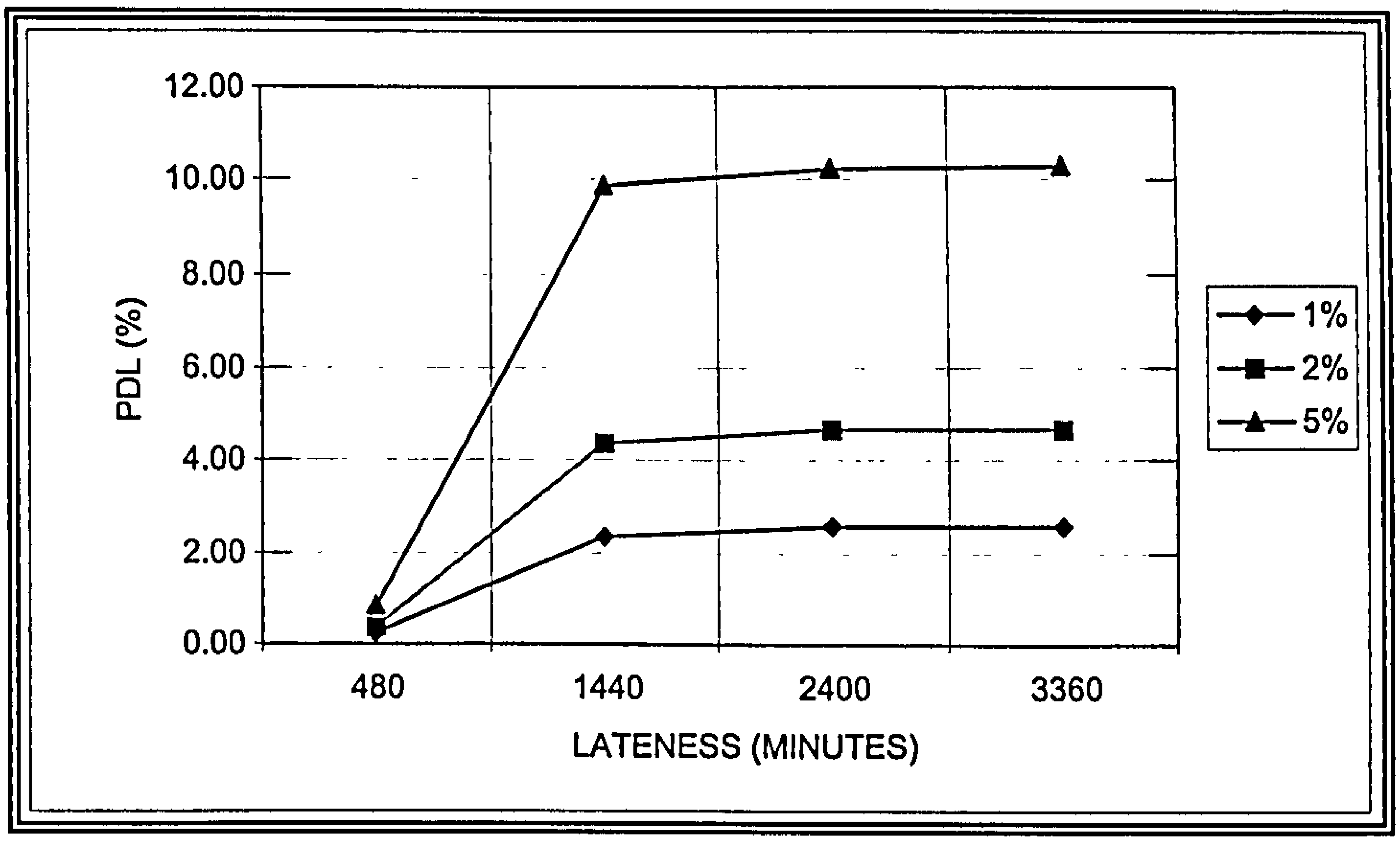

Figure 8.2: Sensitivity matrix for LDFS measured by PDL

Both matrices showed a similar profile of sensitivity. When either the frequency or the distribution magnitudes were increased, the PDL and FPDL increased. However, the order of magnitude of the responses was different, with PDL being about one-tenth of FPDL at the lower levels and one-seventh at the higher level.

The differences in magnitude of the responses were largely explained by considering the BOM in Figure 8.3.

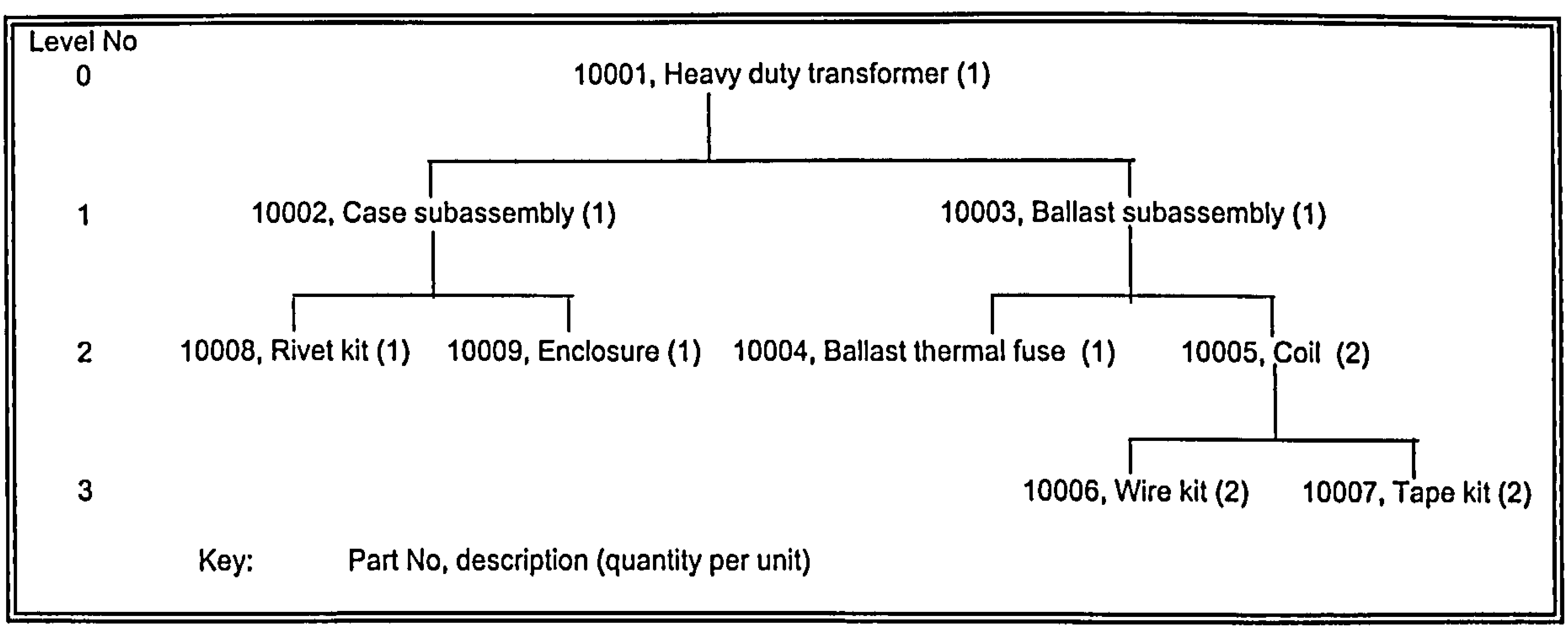

Figure 8.3: BOM for product 10001(heavy duty transformer)

The simulation model was designed for a manufacturing system with a broad balance between capacity and demand and hence no intentional slack anywhere in the system. From Figure 8.3 it is seen that if, for example, part number 10006 was delivered late, then in a system with no slack, part numbers 10005, 10003 and the final product 10001 would also be late. The effect would be 44.4% PDL (as there were nine parts), but 100% FPDL.

Irrespective of the number of parts late in a single BOM, no increase in FPDL could result. FPDL was therefore an insensitive measure and hence misleading when establishing which uncertainties were significant. PDL, on the other hand, measured the precise effect of uncertainties to a much higher level of sensitivity and was therefore chosen as the preferred measure for all experimental studies.

The lowest magnitude of lateness possible within an MRP based system based on release date was one day. From Figure 8.2 it was clearly seen that changing the frequency of LDFS for one day (480 mins) late produced very little effect on PDL. Detailed analysis showed this to be due to the existence of some residual slack in the system.

Increasing lateness to three days (1440 mins) caused a pronounced increase in PDL in approximate proportion to the frequency. PDL then levelled off as lateness was further increased. The conclusion was that any frequency of LDFS produced late delivery, but reducing magnitude (lateness) at any frequency was the key element in improving delivery performance.

This analysis applied to all uncertainties that used discrete probability distributions and was used to set parameters with fixed frequency and variable magnitude in all experiments.

The parameters of LDFS were set at 2% of parts affected with 480 minutes (1 day) and 1440 minutes (3 days) delay.

8.2.2 Insecure stores (INSC)

Using a discrete probability distribution for modelling INSC, simulations were run for frequencies of 1%, 2% and 5% of items not available when required, with 120, 240, 480, 960, 1440 and 2400 minutes lateness applied as magnitudes, representing the time taken to replace through emergency re-manufacture or purchase expediting. In this case magnitudes were expressed as minutes rather than days as INSC would cause a delay to issue of kits for assembly, hence delaying the start time for the first operation of the assembly. Figure 8.4 shows the sensitivity of PDL as a result of INSC.

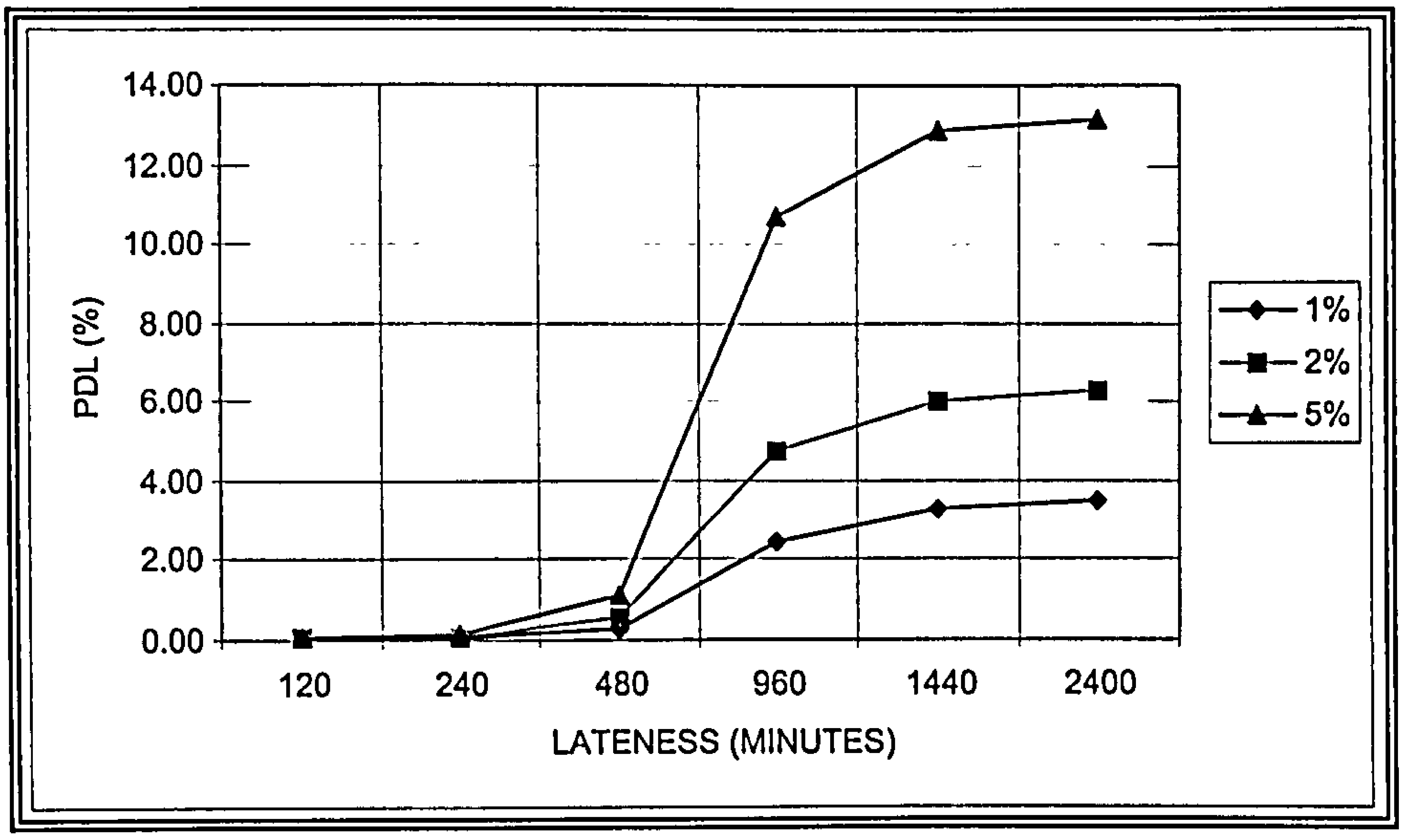

Figure 8.4: Sensitivity matrix for INSC

At very low lateness, PDL magnitude was also very low regardless of the frequency applied due to the effect of slack in the system. Figure 8.5 illustrates this by showing a sequence of orders to be processed through the CLR work centre on a single day, both before and after a delay has occurred. The upper plan was derived according to MRP rules and shows the slack existing in the work centre represented by the shaded areas between each order number.

The lower plan shows the effect of a delay of 120 minutes occurring at the beginning of the day. The existence of slack between orders 10 and 60 allowed the delay to be absorbed, no other parts were affected so all parts were still produced on the day intended. Under MRP reporting rules although a delay occurred none of the parts would be reported as late.

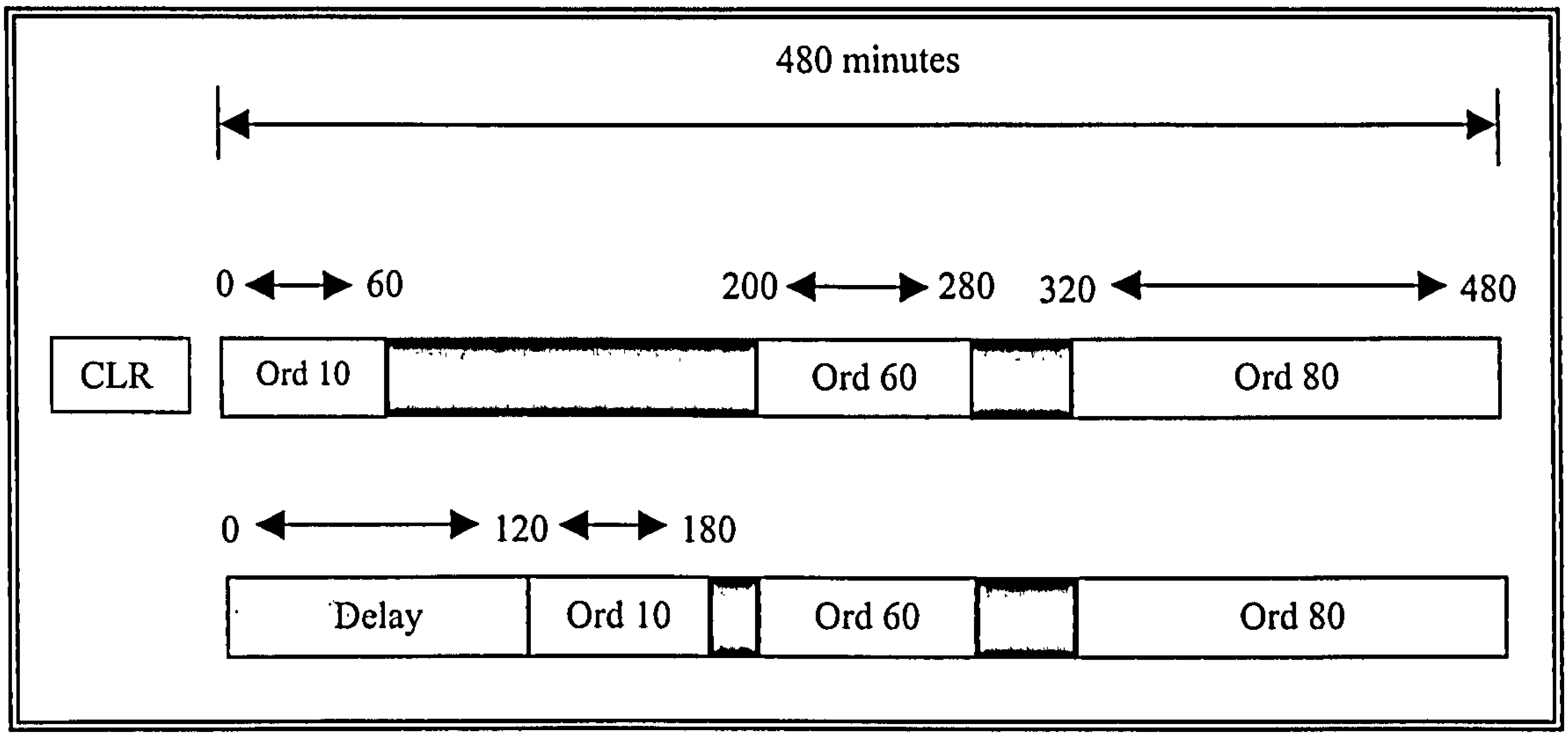

Figure 8.5: Schedule for CLR before and after delay applied

As delays increased, absorption of slack became more complete. Experimental results showed that as the magnitude reached 480 minutes (1 day), measurable responses were found. This was therefore chosen as the low level parameter. Beyond 1440 minutes, the rate of change of PDL reduced rapidly, so that level was chosen as the high level parameter. As with LDFS, a frequency of 2% was chosen.

8.2.3 Schedule/work-to-list not controlled (SWTLNC)

SWTLNC was discretely simulated using a variety of queuing rules: EDD, FIFO and LIFO. These experiments were not replicated, as the rules did not require a distribution. It was recognised in Section 7.2.3 that to accurately simulate SWTLNC was not feasible within the limits of this study and so it was only necessary to establish which scheduling rule produced the best and worst results to set low and high parameter levels. Figure 8.6 shows the sensitivity of PDL as a result of SWTLNC.

The default rule for MRP is FIFO. Using this approach in the deterministic domain produced a balanced system with a low residual level of PDL. Applying EDD produced no measurable improvement in PDL. As no particular benefit came from EDD it was decided to use the default of FIFO as the low level parameter, i.e. low level equalled zero uncertainty in the simulation model. The use of LIFO deteriorated the performance of the system and was used as the high level parameter.

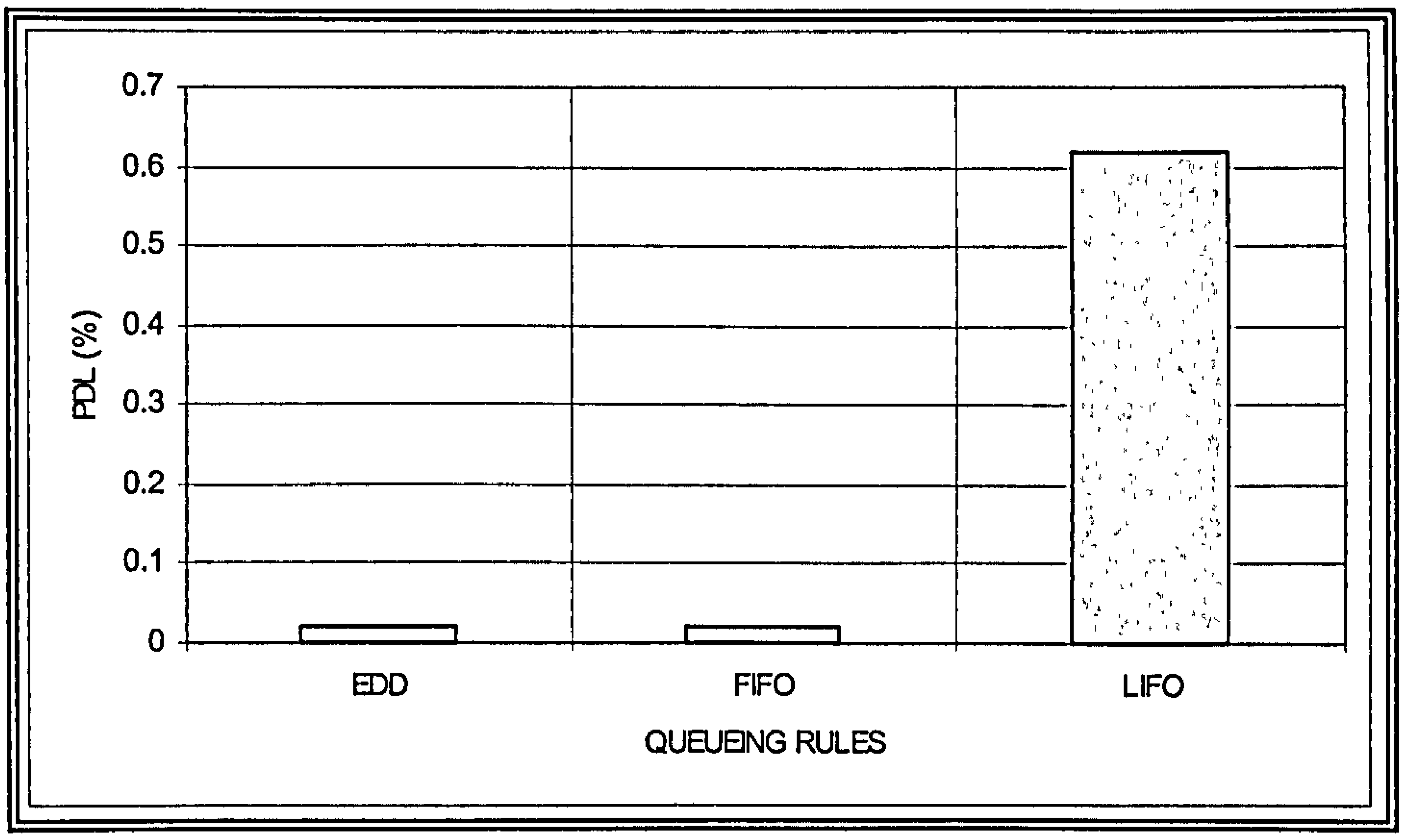

Figure 8.6: Sensitivity of SWTLNC

8.2.4 Unexpected/urgent changes to schedule affecting labour (LA) or machine (MA)

Both LA and MA were simulated together applied to make parts for repeaters and not using a probability distribution. The simulation model required that a specific number of batches of each part number be selected and 1, 4, 7 and 10 were chosen. These equated to 7%, 26%, 46% and 63% respectively of all repeater batches made. Batch size multiplier coefficients were used of 10%, 20%, 40%, 60%, 80% and 100%. Figure 8.7 shows the sensitivity of PDL as a result of LA and MA.

Increases in PDL occurred as both batch size multiplier and number of batches affected increased. The effect on PDL was very low which, to get measurable results, would encourage the use of 1 and 10 batches as the low and high parameter levels. Also, by the same reasoning, the doubled batch size increment would be used to obtain measurable results.

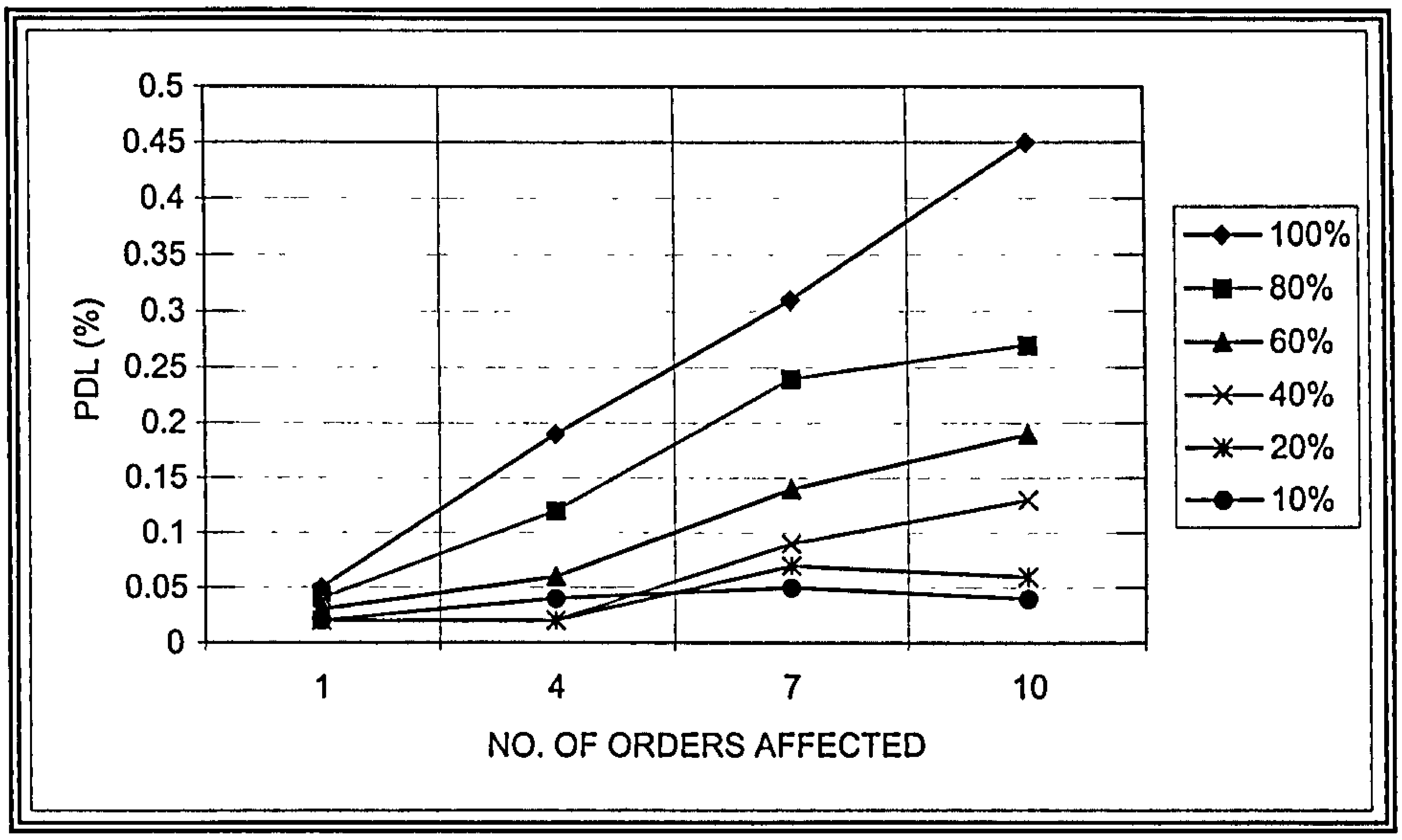

Figure 8.7: Sensitivity matrix for LA and MA

As a further analysis, each of LA and MA were considered separately to establish any significant difference in the responses of the simulation model. Derived parameter settings were applied with results as shown in Figure 8.8.

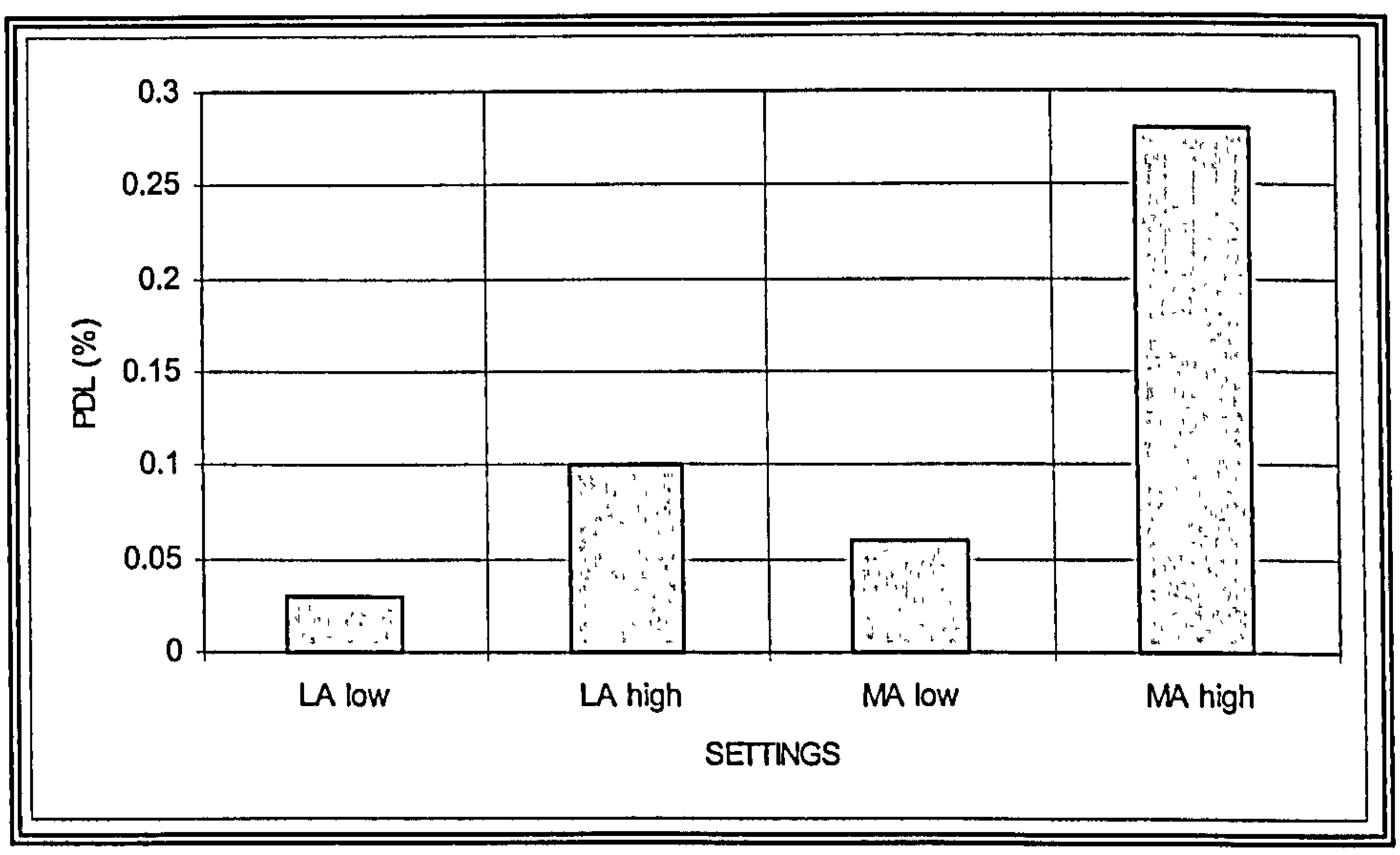

Figure 8.8: Discrete effect of LA and MA using selected settings

It was seen that different responses occurred as a result of both LA and MA, even when applied at the same levels. For this reason it was decided to model each of these uncertainties separately in subsequent experiments.

8.2.5 Planned set-up/changeover time exceeded (PSE)

Using a discrete probability distribution for modelling PSE, simulations were run with 1%, 5% and 10% of batches having a set-up time applied as frequencies and 15, 45, 120, 240 and 480 minutes extension to set-up/changeover time applied as magnitudes. Beyond 480 minutes was unlikely to be an extension to planned set-up/changeover times, but was more likely to be attributable to some other cause, for example waiting for tooling. Figure 8.9 shows the sensitivity of PDL as a result of PSE.

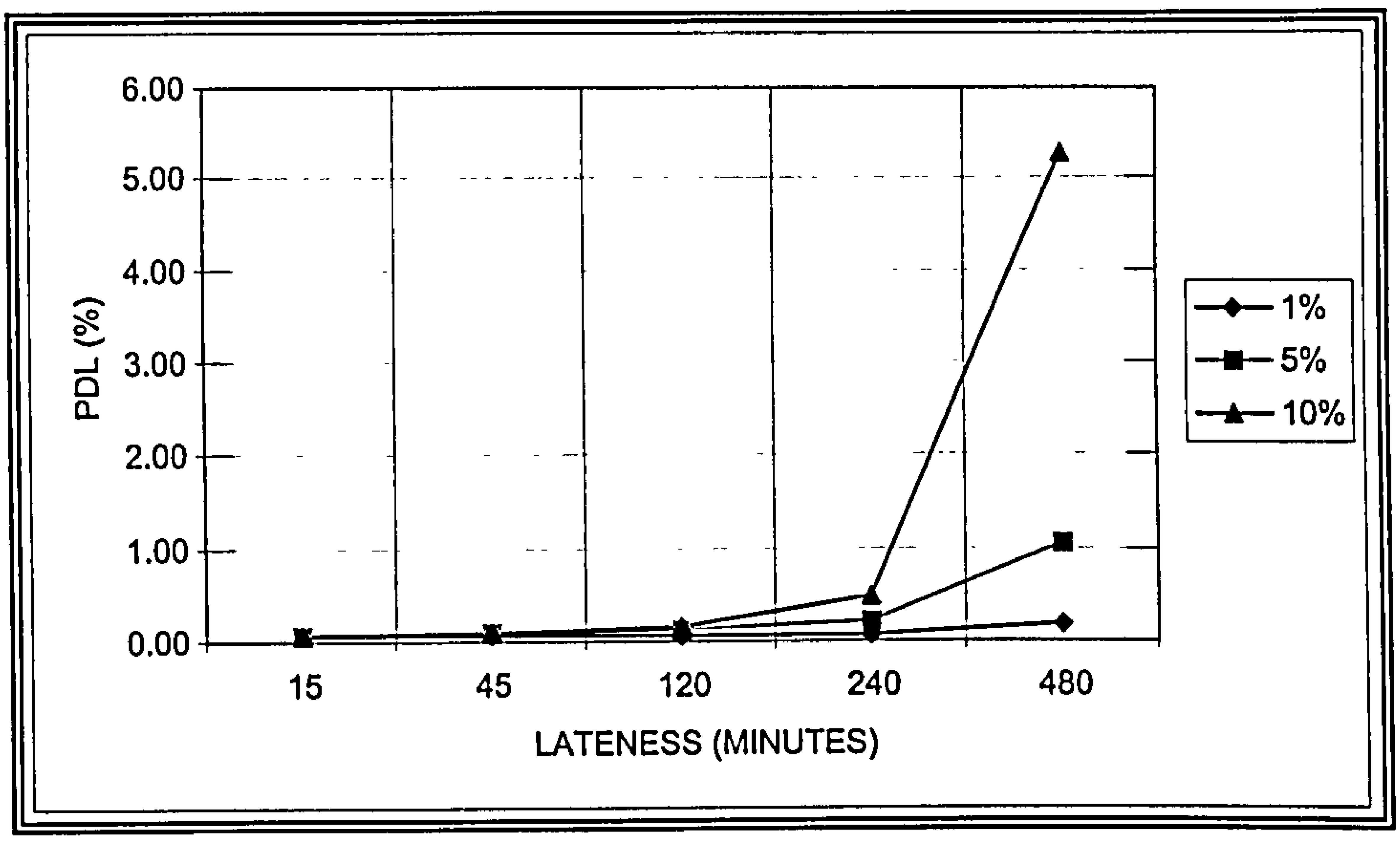

Figure 8.9: Sensitivity matrix for PSE

At very low magnitudes, PDL was very low, regardless of the frequency applied, due to the effects of slack in the system as previously explained in Section 8.2.2.

In reality, PSE would normally be a matter of minutes or, occasionally, a few hours, hence 15 and 240 minutes were chosen as the low and high levels parameters for magnitude of time exceeded. The frequency would be set to 5% to produce measurable effects for PDL.

8.2.6 Breakdown (BD)

BD was modelled using two probability distributions simultaneously, namely an Exponential distribution for MTBF and a Gamma distribution for MTTR. With two distributions modelled simultaneously, varying both would result in a very large variance and a questioning of the assumption of normality in the results. To avoid this issue and to reduce the expected variance, the distribution for MTBF would use fixed levels, while a range of levels was applied to MTTR.

Values of MTBF for the high utilisation machines of BRKPRS, CLR and WELD were set to 60,000, 24,000 and 30,000 minutes respectively, relating to a range of between 50 and 125 days. To model MTTR using a Gamma distribution, values for shape parameter (α) and scale parameter (β) were specified. It was recognised that as the machine ages, time to repair would reduce due to learning curve effects. A Gamma distribution curve with α equal to two would represent such a case. Five sets of β values were tested for the machines, shown in Table 8.1. Figure 8.10 shows the sensitivity of PDL as a result of BD.

	Experiment indicators				
Machines	EX1	EX2	EX3	EX4	EX5
BRKPRS	300	600	1200	2400	3000
CLR	120	240	1200	2400	3000
WELD	150	300	1200	2400	3000

Table 8.1: Configuration of β values tested for modelling MTTR

Up to a β value of 1200, PDL increased rapidly, tailing off after that point. EX3 was therefore chosen as the high level parameter, corresponding to a MTTR of 2400 minutes, or five days. The low level parameter was set as EX1, being the lowest measurable response achieved. This corresponded to a minimum MTTR of 240 minutes or half a day.

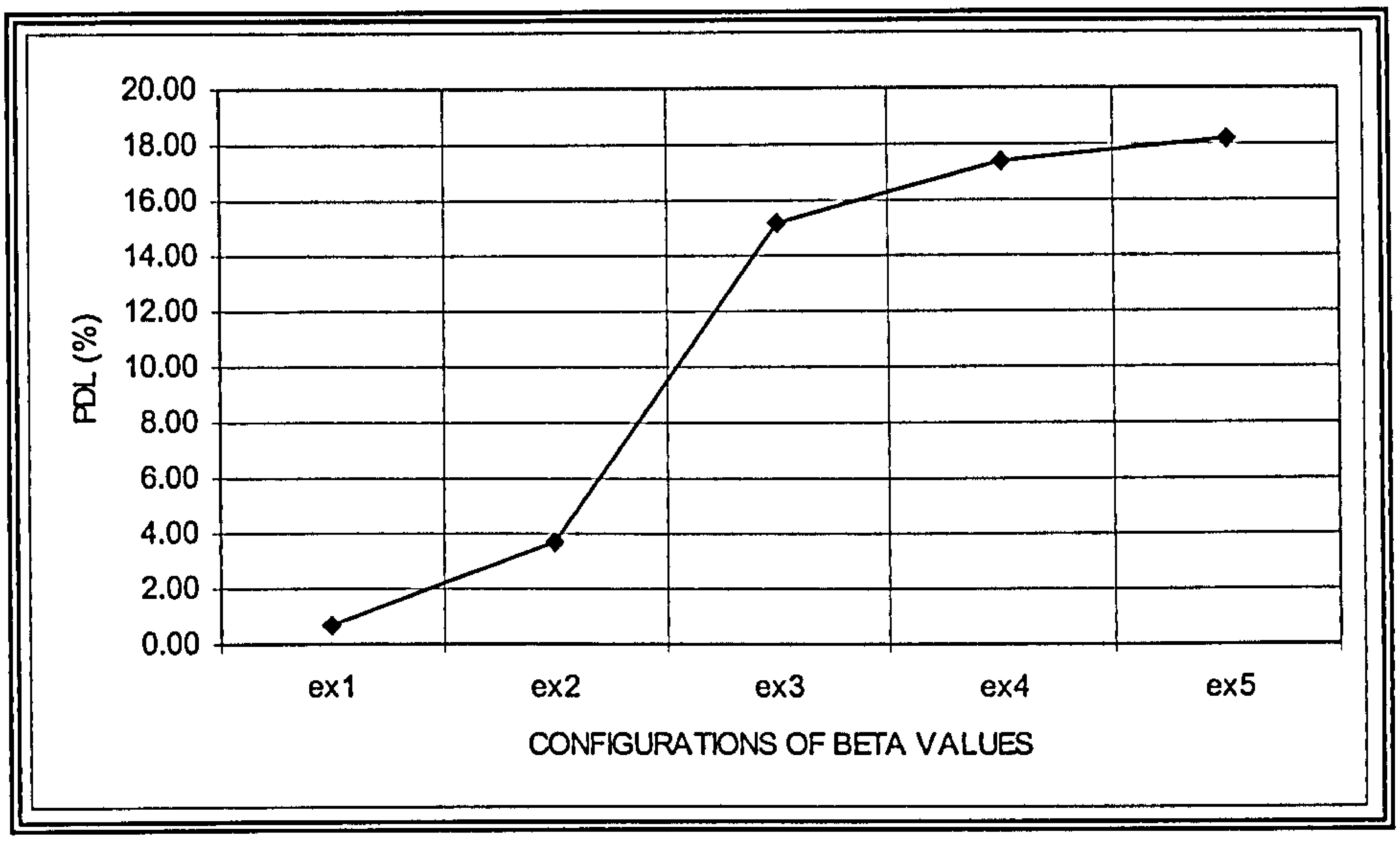

Figure 8.10: Sensitivity matrix for BD measured by PDL

8.2.7 Waiting for labour (WFL)

Using a discrete probability distribution for modelling WFL, simulations were run with 1%, 5% and 10% of all make batches having a wait for labour applied as frequencies and 15, 60, 120, 240 and 480 minutes delay applied as magnitudes. Beyond 480 minutes was unlikely to be WFL, but more likely to be attributable to some other cause, for example labour absenteeism. Figure 8.11 shows the sensitivity of PDL as a result of WFL

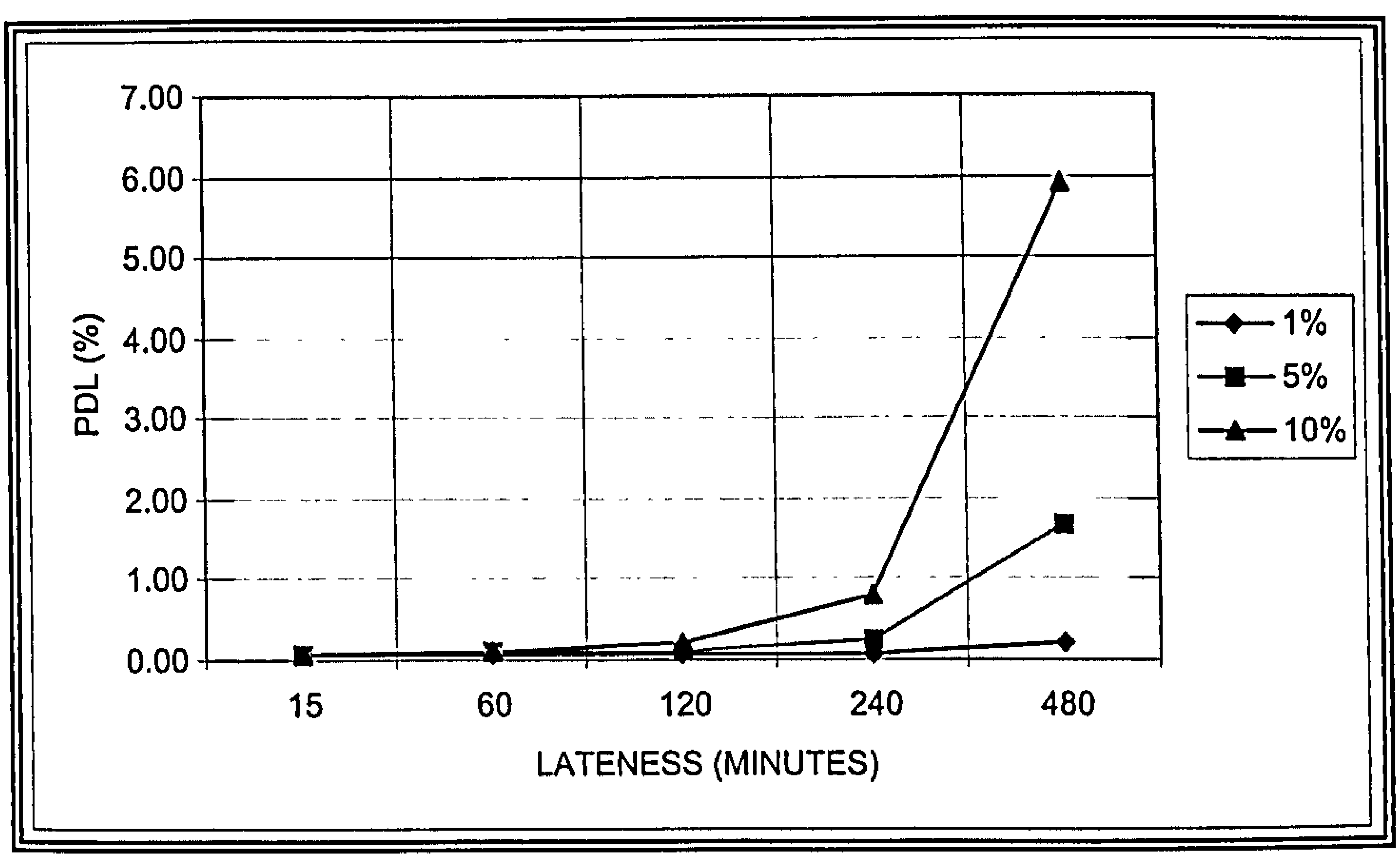

Figure 8.11: Sensitivity matrix for WFL measured by PDL

The results showed a similar profile to PSE, but with slightly raised levels of PDL due to a small increase in the number of parts affected.

WFL would normally be a matter of minutes or, occasionally, a few hours, hence 15 and 240 minutes were chosen as the low and high levels for magnitude. The frequency would be set to 5% to produce measurable effects for PDL.

8.2.8 Waiting for tooling (WFT)

WFT was modelled in the same way as WFL, but only applied to make parts that used tooling resources. 1%, 5% and 10% were applied as frequencies and 30, 120, 240 and 480 minutes delay applied as magnitudes. Beyond 480 minutes would be unlikely to be WFT, but more likely to be attributable to some other cause, for example late delivery from supplier. Figure 8.12 shows the sensitivity of PDL as a result of WFT.

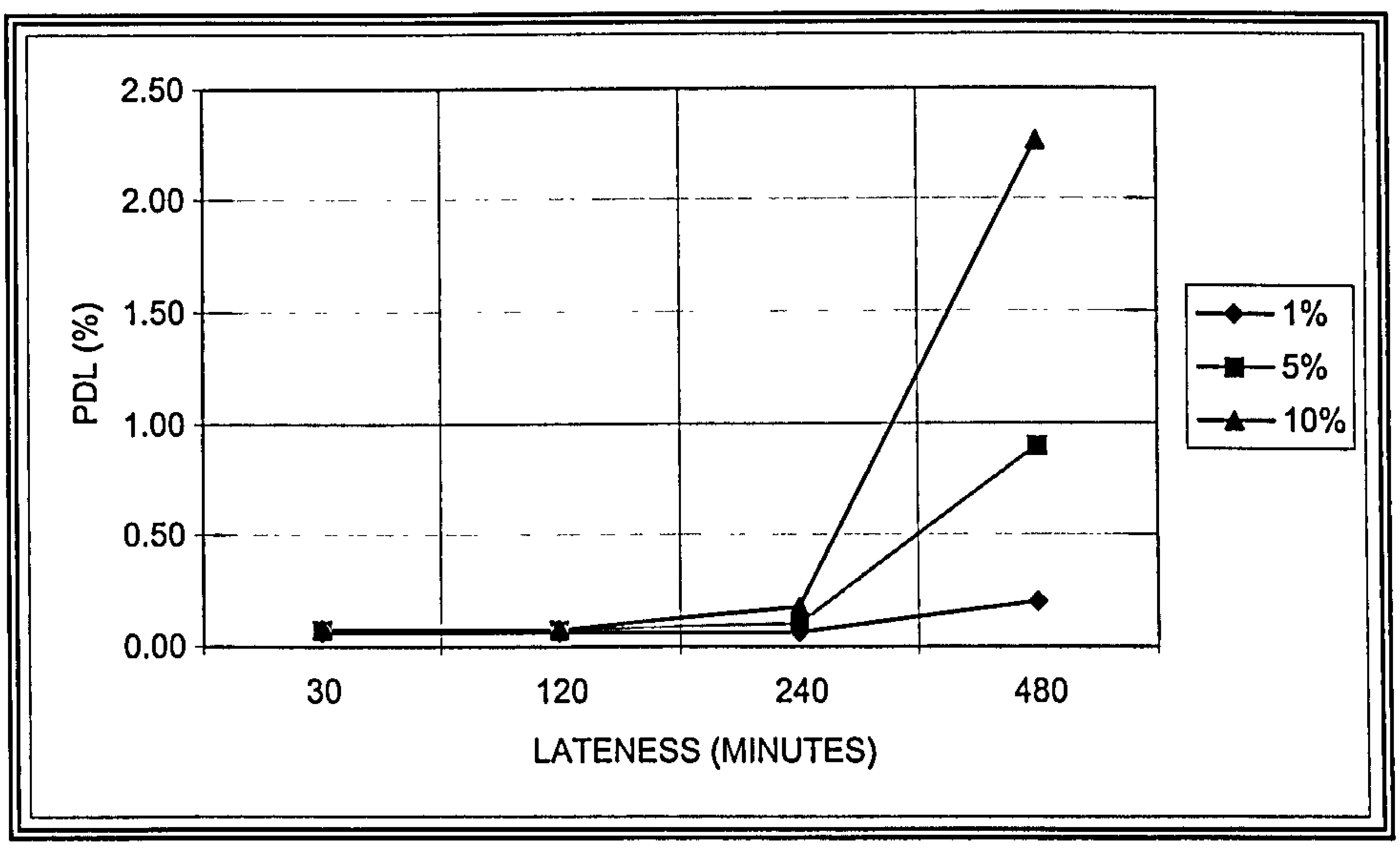

Figure 8.12: Sensitivity matrix for WFT measured by PDL

The results were similar to other causes modelled in the same way except that as the number of make parts affected was very low, the percentage of PDL was also very low.

WFT would normally be a matter of minutes or occasionally up to a day, hence 30 and 480 minutes were chosen as the low and high levels for magnitude. The distribution frequency would be set to 5% to produce measurable effects for PDL.

8.2.9 Customer design changes (CDC)

Simulations were run testing discrete frequency for CDC at 1%, 4%, 7%, 10% and 20% of all make batches, resulting in an approximate linear relationship between frequency and PDL. Figure 8.13 shows the sensitivity of PDL as a result of CDC. To model CDC realistically, 4% and 10% would be set as low and high levels sufficient to produce a measurable result.

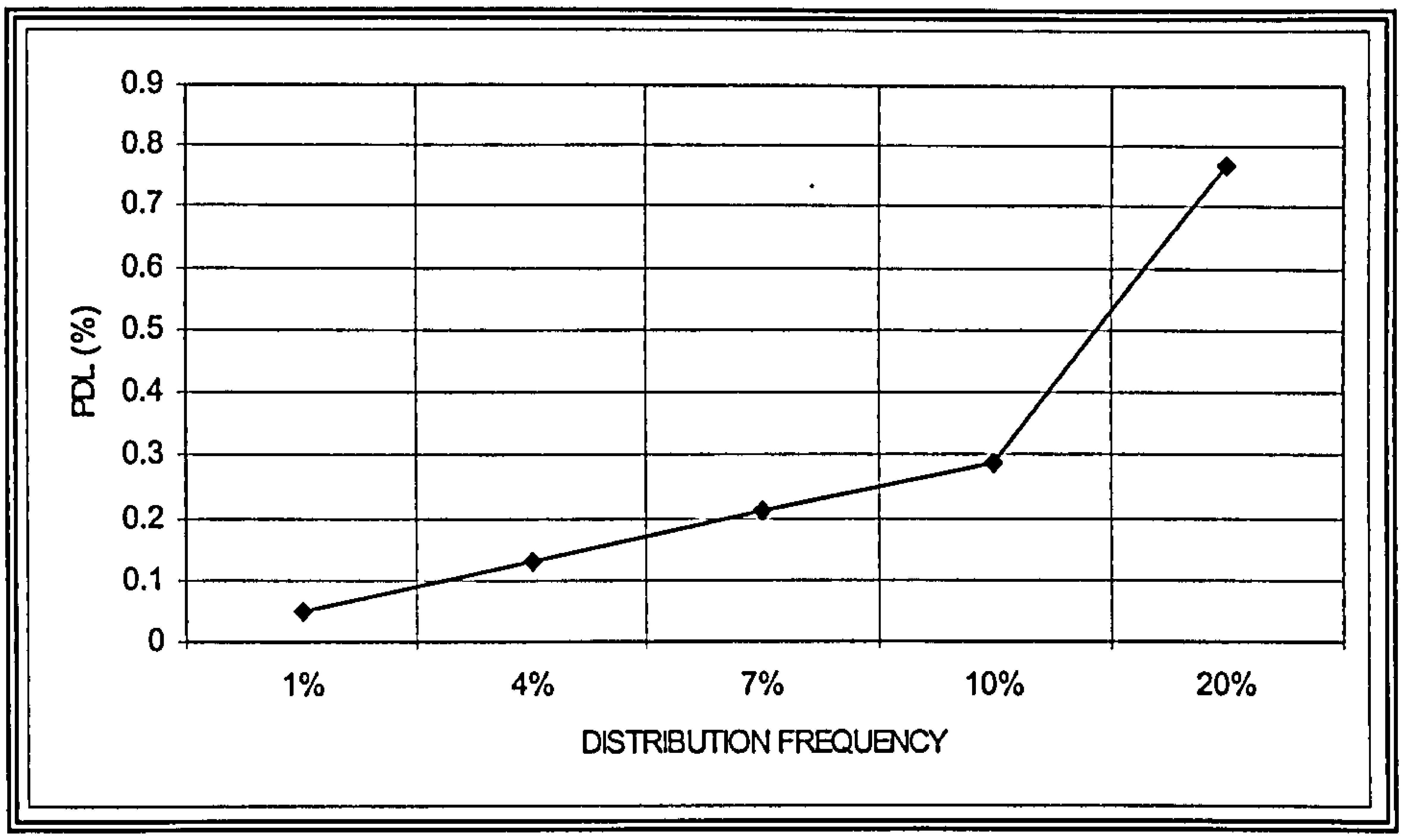

Figure 8.13: Sensitivity matrix for CDC measured by PDL

8.2.10 Waiting for inspection labour (WFINS)

Using a discrete probability distribution for modelling WFINS, simulations were run with 1%, 5% and 10% of all finished products applied as frequencies and 15, 60, 120, 240 and 480 minutes delay applied as magnitudes. It was assumed that operator inspection occurred for in-process inspection. Figure 8.14 shows the sensitivity of PDL as a result of WFINS and showed that as with uncertainties modelled in a similar way, at very low levels of delay the magnitude of PDL was very low, regardless of the frequency applied.

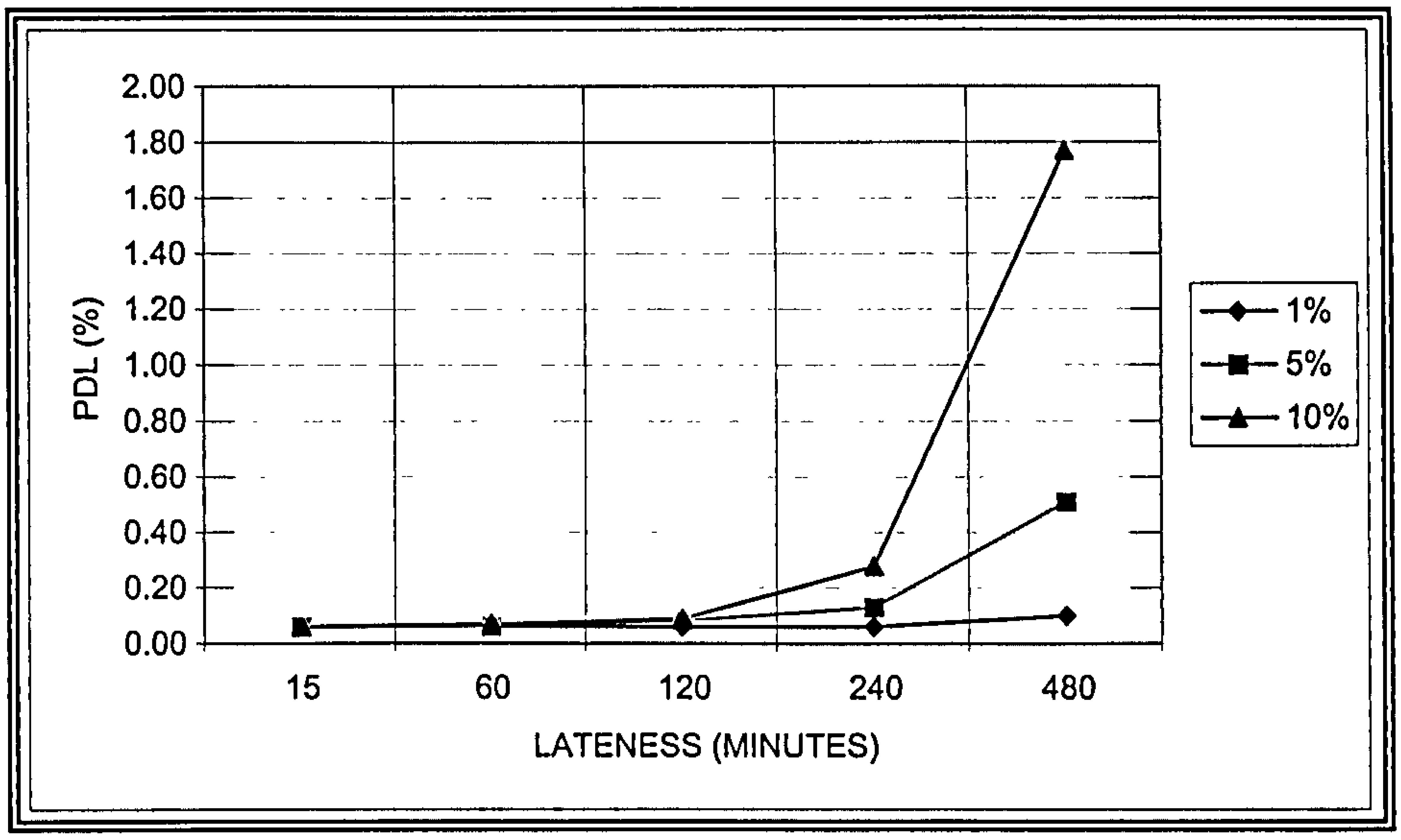

Figure 8.14: Sensitivity matrix for WFINS measured by PDL

WFINS would normally be a matter of minutes or, occasionally, a few hours, hence 15 and 240 minutes were chosen as the low and high levels for magnitude of delay. The distribution frequency would be set to 5% to produce measurable effects for PDL

8.3 Pilot study of all uncertainties in combination

8.3.1 Experimental design

A full factorial design would examine all uncertainties in all possible combinations. Eleven uncertainties each modelled at two levels would require $2^{11} = 2048$ experiments. To reduce the number of experiments for a pilot study to identify only significant main effects, it was decided to employ an alternative approach.

A fractional factorial design with resolution IV would use a value of p = 6, resulting in $2^{11-6} = 32$ experiments. Law and Kelton (2000) developed a factor screening strategy that combined uncertainties into groups to reduce the number of groups (uncertainties) to be designed. An examination of the uncertainties showed that they could be formed into seven groups, mainly corresponding to the strands of the hierarchy of uncertainty developed, with each group having one or more uncertainties that required experiment at both low and high levels. A single uncertainty required two levels; two uncertainties required four levels, resulting in a mixed level design as shown in Table 8.2.

Group	Uncertainty	No of levels
G1	LDFS	4
	INSC	
G2	SWTLNC	4
	LA	
G3	PSE	4
	BD	
G4	WFL	4
	WFT	
G5	MA	2
G6	CDC	2
G7	WFINS	2

Table 8.2: Factor screened groups

Taguchi orthogonal array design allows mixed level design and produced an experimental design matrix within Minitab Release 13 of (L_{16} (4**4 2**3)) = 16 experiments required. This design produced a resolution IV configuration (Peace, 1993) and was chosen for the pilot study. Table 8.3 shows the experimental configurations.

Exp No.	Group						
	G1	G2	G3	G4	G5	G6	G7
1	LL	LL	LL	LL	L	L	L
2	LL	HL	HL	HL	L	H	H
3	LL	LH	LH	LH	H	L	H
4	LL	HH	HH	HH	H	H	L
5	HL	LL	HL	LL	H	H	L
6	HL	HL	LL	HL	H	L	H
7	HL	LH	HH	HH	L	H	H
8	HL	HH	LH	LH	L	L	L
9	LH	LL	LH	HH	L	H	H
10	LH	HL	HH	LH	L	L	L
11	LH	LH	LL	HL	H	H	L
12	LH	HH	HL	LL	H	L	H
13	HH	LL	HH	HL	H	L	H
14	HH	HL	LH	LL	H	H	L
15	HH	LH	HL	HH	L	L	L
16	HH	HH	LL	LH	L	H	H

Key: L = Low level parameter, H = High level parameter

Table 8.3: Experiment configuration for pilot study

The chosen parameter levels from the sensitivity study that corresponded to each of the experimental configurations are shown in Table 8.4.

Gp	Uncertainty	Four parameter levels			
		LL	HL	LH	HH
G1	LDFS	Discrete probability distribution			
		Freq = 2.00% Mag = 480mins	Freq = 2.00% Mag = 1440mins	Freq = 2.00% Mag = 480mins	Freq = 2.00% Mag = 1440mins
	INSC	Discrete probability distribution			
		Freq = 2.00% Mag = 480mins		Freq = 2.00% Mag = 1440mins	
G2	SWTLNC	Queuing rule			
		FIFO	LIFO	FIFO	LIFO
	LA	Batch size multiplier: Freq = 100%			
		Orders affected = 1		Orders affected = 10	
G3	PSE	Discrete probability distribution			
		Freq = 5.00% Mag = 15mins	Freq = 5.00% Mag = 240mins	Freq = 5.00% Mag = 15mins	Freq = 5.00% Mag = 240mins
	BD	MTBF: Exponential distribution: BRKPRS = 60000mins, CLR = 24000mins, WELD = 30000mins			
		MTTR: Gamma distribution			
		BRKPRS = (300mins, 2) CLR = (120mins, 2) WELD = (150mins, 2)		BRKPRS = (1200mins, 2) CLR = (1200mins, 2) WELD = (1200mins, 2)	
G4	WFL	Discrete probability distribution			
		Freq = 5.00% Mag = 15mins	Freq = 5.00% Mag = 240mins	Freq = 5.00% Mag = 15mins	Freq = 5.00% Mag = 240mins
	WFT	Discrete probability distribution			
		Freq = 5.00% Mag = 30mins		Freq = 5.00% Mag = 480mins	

Gp	Uncertainty	Two parameter levels	
		L	H
G5	MA	Batch size multiplier: Freq = 100%	
		Orders affected = 1	Orders affected = 10
G6	CDC	Discrete probability distribution	
		Freq = 4.00%	Freq = 10.00%
G7	WFINS	Discrete probability distribution	
		Freq = 5.00% Mag = 15mins	Freq = 5.00% Mag = 240mins

Key: Freq = Frequency, Mag = Magnitude

Table 8.4: Parameter settings for pilot study

To begin the experimental programme, each of the sixteen experiments was run with a total of ten replications each. The results were collected and h values calculated. For six of the experiments h values greater than 5% of the sample mean were found, requiring additional replications to be run. Results both before and after the additional replications are shown in Table 8.5.

Exp No.	After original runs			After additional runs			
	$\bar{X}$	Desired h	Actual h	Replications	$\bar{X}$	Desired h	Actual h
1	2.28	0.11	0.20	31	2.23	0.11	0.10
2	3.34	0.17	0.25	22	3.36	0.17	0.15
3	15.95	0.80	1.55	38	16.52	0.83	0.59
8	15.61	0.78	1.04	18	16.45	0.82	0.73
10	18.17	0.91	1.02	13	18.81	0.94	0.93
11	9.39	0.47	0.63	18	9.30	0.47	0.45

Table 8.5: Experiments with additional replications

8.3.2 Results, analysis and discussion

Results from all replications were analysed using ANOVA. Table 8.6 shows the main effect results using PDL as the dependant variable, with p values of significant uncertainties at 95% confidence level asterisked.

Source	SS	*df*	MS	F	p
Corrected Model	10119.865	15	674.658	144.608	.000
Intercept	35766.591	1	35766.591	7666.303	.000
G1	1012.289	3	337.430	72.326	.000*
G2	10.994	3	3.665	.785	.503
G3	2111.090	3	703.697	150.832	.000*
G4	88.217	3	29.406	6.303	.000*
G5	74.423	1	74.423	15.952	.000*
G6	22.202	1	22.202	4.759	.030*
G7	.503	1	.503	.108	.743
Error	1045.056	224	4.665		
Total	48200.120	240			
Corrected Total	11164.921	239			

Table 8.6: ANOVA output for main effects

Five groups consisting of LDFS, INSC, PSE, BD, WFL, WFT, MA and CDC were found to have a significant effect on PDL. Of these, MA and CDC were significant in their own right, but it was not known if any or all individual uncertainties within groups were themselves significant, only that the group as a whole was significant.

8.4 Detailed study of significant uncertainties in combination

8.4.1 Experimental design

Detailed study was carried out using all individual uncertainties identified in the pilot study as significant either in their own right or as part of a group. For the total of eight uncertainties identified, a full factorial design of two levels for each would require $2^8 = 256$ experiments. To reduce the number of experiments a half factorial design was chosen having a resolution VIII configuration requiring $2^{8-1} = 128$ experiments.

Parameter levels from the sensitivity study were used as shown in Table 8.7, applied to the experimental configurations shown in Table 8.8.

Uncertainty	Parameter level	
	L	H
LDFS	Discrete probability distribution	
	Freq = 2.00% Mag = 480mins	Freq = 2.00% Mag = 1440mins
INSC	Discrete probability distribution	
	Freq = 2.00% Mag = 480mins	Freq = 2.00% Mag = 1440mins
PSE	Discrete probability distribution	
	Freq = 5.00% Mag = 15mins	Freq = 5.00% Mag = 240mins
BD	MTBF: Exponential distribution: BRKPRS = 60000mins CLR = 24000mins WELD = 30000mins	
	MTTR: Gamma distribution	
	BRKPRS = (300mins, 2) CLR = (120mins, 2) WELD = (150mins, 2)	BRKPRS = (1200mins, 2) CLR = (1200mins, 2) WELD = (1200mins, 2)
WFL	Discrete probability distribution	
	Freq = 5.00% Mag = 15mins	Freq = 5.00% Mag = 240mins
WFT	Discrete probability distribution	
	Freq = 5.00% Mag = 30mins	Freq = 5.00% Mag = 480mins
MA	Batch size multiplier: Freq = 100%	
	Orders affected = 1	Orders affected = 10
CDC	Discrete probability distribution	
	Freq = 4.00%	Freq = 10.00%

Key: Freq = Frequency, Mag = Magnitude

Table 8.7: Parameters settings for detailed study

Exp No.	Uncertainty								Exp No.	Uncertainty								Exp No.	Uncertainty							
	LDFS	INSC	PSE	BD	WFL	WFT	MA	CDC		LDFS	INSC	PSE	BD	WFL	WFT	MA	CDC		LDFS	INSC	PSE	BD	WFL	WFT	MA	CDC
1	L	L	L	L	L	L	L	L	44	H	H	L	H	L	H	L	L	87	L	H	H	L	H	L	H	L
2	H	L	L	L	L	L	L	H	45	L	L	H	H	L	H	L	H	88	H	H	H	L	H	L	H	H
3	L	H	L	L	L	L	L	H	46	H	L	H	H	L	H	L	L	89	L	L	L	H	H	L	H	H
4	H	H	L	L	L	L	L	L	47	L	H	H	H	L	H	L	L	90	H	L	L	H	H	L	H	L
5	L	L	H	L	L	L	L	H	48	H	H	H	H	L	H	L	H	91	L	H	L	H	H	L	H	L
6	H	L	H	L	L	L	L	L	49	L	L	L	L	H	H	L	L	92	H	H	L	H	H	L	H	H
7	L	H	H	L	L	L	L	L	50	H	L	L	L	H	H	L	H	93	L	L	H	H	H	L	H	L
8	H	H	H	L	L	L	L	H	51	L	H	L	L	H	H	L	H	94	H	L	H	H	H	L	H	H
9	L	L	L	H	L	L	L	H	52	H	H	L	L	H	H	L	L	95	L	H	H	H	H	L	H	H
10	H	L	L	H	L	L	L	L	53	L	L	H	L	H	H	L	H	96	H	H	H	H	H	L	H	L
11	L	H	L	H	L	L	L	L	54	H	L	H	L	H	H	L	L	97	L	L	L	L	L	H	H	L
12	H	H	L	H	L	L	L	H	55	L	H	H	L	H	H	L	L	98	H	L	L	L	L	H	H	H
13	L	L	H	H	L	L	L	L	56	H	H	H	L	H	H	L	H	99	L	H	L	L	L	H	H	H
14	H	L	H	H	L	L	L	H	57	L	L	L	H	H	H	L	H	100	H	H	L	L	L	H	H	L
15	L	H	H	H	L	L	L	H	58	H	L	L	H	H	H	L	L	101	L	L	H	L	L	H	H	H
16	H	H	H	H	L	L	L	L	59	L	H	L	H	H	H	L	L	102	H	L	H	L	L	H	H	L
17	L	L	L	L	H	L	L	H	60	H	H	L	H	H	H	L	H	103	L	H	H	L	L	H	H	L
18	H	L	L	L	H	L	L	L	61	L	L	H	H	H	H	L	L	104	H	H	H	L	L	H	H	H
19	L	H	L	L	H	L	L	L	62	H	L	H	H	H	H	L	H	105	L	L	L	H	L	H	H	H
20	H	H	L	L	H	L	L	H	63	L	H	H	H	H	H	L	H	106	H	L	L	H	L	H	H	L
21	L	L	H	L	H	L	L	L	64	H	H	H	H	H	H	L	L	107	L	H	L	H	L	H	H	L
22	H	L	H	L	H	L	L	H	65	L	L	L	L	L	L	H	H	108	H	H	L	H	L	H	H	H
23	L	H	H	L	H	L	L	H	66	H	L	L	L	L	L	H	L	109	L	L	H	H	L	H	H	L
24	H	H	H	L	H	L	L	L	67	L	H	L	L	L	L	H	L	110	H	L	H	H	L	H	H	H
25	L	L	L	H	H	L	L	L	68	H	H	L	L	L	L	H	H	111	L	H	H	H	L	H	H	H
26	H	L	L	H	H	L	L	H	69	L	L	H	L	L	L	H	L	112	H	H	H	H	L	H	H	L
27	L	H	L	H	H	L	L	H	70	H	L	H	L	L	L	H	H	113	L	L	L	L	H	H	H	H
28	H	H	L	H	H	L	L	L	71	L	H	H	L	L	L	H	H	114	H	L	L	L	H	H	H	L
29	L	L	H	H	H	L	L	H	72	H	H	H	L	L	L	H	L	115	L	H	L	L	H	H	H	L
30	H	L	H	H	H	L	L	L	73	L	L	L	H	L	L	H	L	116	H	H	L	L	H	H	H	H
31	L	H	H	H	H	L	L	L	74	H	L	L	H	L	L	H	H	117	L	L	H	L	H	H	H	L
32	H	H	H	H	H	L	L	H	75	L	H	L	H	L	L	H	H	118	H	L	H	L	H	H	H	H
33	L	L	L	L	L	H	L	H	76	H	H	L	H	L	L	H	L	119	L	H	H	L	H	H	H	H
34	H	L	L	L	L	H	L	L	77	L	L	H	H	L	L	H	H	120	H	H	H	L	H	H	H	L
35	L	H	L	L	L	H	L	L	78	H	L	H	H	L	L	H	L	121	L	L	L	H	H	H	H	L
36	H	H	L	L	L	H	L	H	79	L	H	H	H	L	L	H	L	122	H	L	L	H	H	H	H	H
37	L	L	H	L	L	H	L	L	80	H	H	H	H	L	L	H	H	123	L	H	L	H	H	H	H	H
38	H	L	H	L	L	H	L	H	81	L	L	L	L	H	L	H	L	124	H	H	L	H	H	H	H	L
39	L	H	H	L	L	H	L	H	82	H	L	L	L	H	L	H	H	125	L	L	H	H	H	H	H	H
40	H	H	H	L	L	H	L	L	83	L	H	L	L	H	L	H	H	126	H	L	H	H	H	H	H	L
41	L	L	L	H	L	H	L	L	84	H	H	L	L	H	L	H	L	127	L	H	H	H	H	H	H	L
42	H	L	L	H	L	H	L	H	85	L	L	H	L	H	L	H	H	128	H	H	H	H	H	H	H	H
43	L	H	L	H	L	H	L	H	86	H	L	H	L	H	L	H	L									

Key: L = Low level parameter, H = High level parameter

Table 8.8: Experiment configuration of detailed study

To begin the experimental programme, each of the 128 experiments was run with a total of ten replications each. The results were collected and h values calculated. For 34 of the experiments h values greater than 5% of the sample mean were found, requiring additional replications to be run. Results both before and after the additional replications are shown in Table 8.9.

	After original runs			After additional runs			
Exp No.	$\bar{X}$	Desired h	Actual h	Replications	$\bar{X}$	Desired h	Actual h
9	13.04	0.65	0.87	18	13.12	0.66	0.58
12	17.00	0.85	1.06	16	17.76	0.89	0.87
13	14.98	0.75	0.94	16	15.07	0.75	0.72
14	16.27	0.81	0.95	14	16.49	0.82	0.72
25	15.48	0.77	0.94	15	15.25	0.76	0.71
27	16.87	0.84	1.00	14	16.71	0.84	0.60
28	17.18	0.86	1.38	26	16.95	0.85	0.80
29	14.79	0.74	1.09	22	14.29	0.71	0.64
30	17.06	0.85	1.08	16	17.15	0.86	0.86
43	15.13	0.76	1.00	17	15.97	0.80	0.65
45	15.11	0.76	0.98	17	15.43	0.77	0.60
47	14.96	0.75	1.04	19	15.67	0.78	0.76
48	18.09	0.90	1.12	15	17.61	0.88	0.77
58	16.67	0.83	1.02	15	16.57	0.83	0.69
59	14.01	0.70	0.80	13	14.16	0.71	0.63
62	16.99	0.85	1.03	15	17.34	0.87	0.80
63	11.47	0.57	0.64	12	11.90	0.60	0.60
64	15.93	0.80	0.88	12	16.06	0.80	0.77
73	15.25	0.76	1.15	23	15.31	0.77	0.74
78	17.45	0.87	1.29	22	17.86	0.89	0.84
90	17.89	0.89	1.32	22	18.30	0.92	0.89
91	14.05	0.70	0.95	18	14.61	0.73	0.69
93	13.87	0.69	0.96	19	14.63	0.73	0.71
94	16.58	0.83	1.01	15	17.94	0.90	0.83
95	15.87	0.79	1.00	16	16.64	0.83	0.77
96	17.45	0.87	1.28	22	17.93	0.90	0.87
105	14.76	0.74	1.02	19	15.34	0.77	0.73
106	17.26	0.86	1.05	15	17.69	0.88	0.84
107	14.29	0.71	0.85	14	14.57	0.73	0.68
109	14.60	0.73	1.11	23	15.06	0.75	0.72
110	16.66	0.83	1.00	14	17.00	0.85	0.80
121	15.75	0.79	1.33	29	16.81	0.84	0.79
122	17.68	0.88	1.00	13	18.41	0.92	0.88
125	14.90	0.75	1.00	18	15.73	0.79	0.78

Table 8.9: Experiments with additional replications

8.4.2 Results, analysis and discussion

Results from all replications were analysed using ANOVA, which together with analysis and discussion, would be presented under the following headings:

[1] Significant uncertainties

[2] Two-way interactions

[3] Three-way interactions

[4] Validation of the business model of uncertainty

For all ANOVA results, p values of significant uncertainties at 95% confidence level were asterisked. Table 8.10 shows header and footer summary output from the complete analysis.

Source	SS	*df*	MS	F	p
Corrected Model	57225.029	92	622.011	98.463	.000
Intercept	149609.592	1	149609.592	23682.779	.000
Error	9103.130	1441	6.317		
Total	256965.068	1534			
Corrected Total	66328.159	1533			

Table 8.10: ANOVA header and footer summary output

Resolution VIII configuration ensured only up to three-way interactions were not confounded, therefore higher order interactions were excluded from the analysis.

8.4.2.1 Significant uncertainties

From the main effect results shown in Table 8.11, it was identified that only four uncertainties were significant, namely LDFS, BD, MA and CDC.

Source	SS	*df*	MS	F	p
LDFS	3705.849	1	3705.849	586.626	.000*
INSC	19.618	1	19.618	3.105	.078
PSE	6.953	1	6.953	1.101	.294
BD	50881.286	1	50881.286	8054.365	.000*
WFL	.240	1	.240	.038	.846
WFT	.532	1	.532	.084	.772
MA	378.375	1	378.375	59.896	.000*
CDC	53.634	1	53.634	8.490	.004*

Table 8.11: ANOVA results for main effects

It was shown in Section 8.2.1 that any delay affecting a part within a BOM was propagated up through the BOM chain to cause additional lateness unless slack existed to recover the delay. The extent of lateness and the number of parts affected would depend upon the BOM level at which the uncertainty applied. The term 'knock-on effect' was coined to explain this phenomenon.

Where a delay occurred on a resource, it affected not only the batch being processed, but also every batch held in the queue for the resource. This queue could contain batches from a number of different BOMs thus delays were propagated across products, which created consequent knock-on effects in the products concerned unless slack existed to recover the delay. The term 'compound effect' was coined to explain this phenomenon.

LDFS affected buy parts that occurred at the lowest BOM level and caused primary knock-on effects. When a delayed part eventually arrived, it could affect subsequent processing depending upon resource loading at that time causing a secondary compound effect.

In real life, whenever a BD occurred the batch that was currently being processed, together with all batches in the queue, could be routed to other machines to prevent significant delay. As use of such spare capacity was a form of BAD approach, it was not modelled. Within the simulation model, BD produced a compound effect.

When a batch was subject to MA the increase in batch size caused an extended stay within all work centres visited. With CDC additional operations were introduced to a batch. In both cases a compound effect occurred.

From the pilot study it was expected that at least one of the uncertainties from G4 (WFL and WFT) would be significant when analysing the main effects, but results showed neither was significant. The grouping used within the Taguchi design required both uncertainties to be modelled simultaneously implying the significance found was due to the effects of grouping. As the fractional factorial design considered each separately, it would take precedence.

8.4.2.2 Two-way interactions

The results for two-way interactions from ANOVA are shown in Table 8.12, which identified only two significant two-way interactions, namely LDFS* BD and BD*MA.

Source	SS	*df*	MS	F	p
LDFS * INSC	3.741	1	3.741	.592	.442
LDFS * PSE	3.500	1	3.500	.554	.457
LDFS * BD	238.565	1	238.565	37.764	.000*
LDFS * WFL	2.790	1	2.790	.442	.506
LDFS * WFT	7.019E-02	1	7.019E-02	.011	.916
LDFS * MA	18.429	1	18.429	2.917	.088
LDFS * CDC	.304	1	.304	.048	.826
INSC * PSE	6.159	1	6.159	.975	.324
INSC * BD	.441	1	.441	.070	.792
INSC * WFL	18.540	1	18.540	2.935	.087
INSC * WFT	8.060	1	8.060	1.276	.259
INSC * MA	7.424	1	7.424	1.175	.279
INSC * CDC	3.170	1	3.170	.502	.479
PSE * BD	.743	1	.743	.118	.732
PSE * WFL	8.382	1	8.382	1.327	.250
PSE * WFT	1.695	1	1.695	.268	.605
PSE * MA	7.012	1	7.012	1.110	.292
PSE * CDC	.857	1	.857	.136	.713
BD * WFL	2.185	1	2.185	.346	.557
BD * WFT	14.844	1	14.844	2.350	.126
BD * MA	38.791	1	38.791	6.140	.013*
BD * CDC	6.730	1	6.730	1.065	.302
WFL * WFT	5.890E-02	1	5.890E-02	.009	.923
WFL * MA	12.627	1	12.627	1.999	.158
WFL * CDC	12.763	1	12.763	2.020	.155
WFT * MA	5.120	1	5.120	.810	.368
WFT * CDC	3.107	1	3.107	.492	.483
MA * CDC	13.499	1	13.499	2.137	.144

Table 8.12: ANOVA results for two-way interactions

Having identified these interactions, it was required to consider whether they could logically be correct or whether they were the result of a statistical fluke.

Interaction between LDFS and BD could only happen when LDFS, which affected only buy parts at the lowest level of each BOM chain, was followed by BD. On its own, LDFS would have a knock-on effect, but when BD subsequently occurred in the same BOM chain the batches affected would be subject to a compound effect as well.

Both BD and MA, when acting separately, produced a compound effect. It was logically possible for both to affect the same batch or parts in the same BOM chain.

8.4.2.3 Three-way interactions

If an uncertainty was not identified as significant from the main effect results, it did not imply that any interactions with other uncertainties were also not significant. Thus it was possible to have significant interactions between uncertainties that were themselves not significant. The results for three-way interactions from ANOVA are shown in Table 8.13 which identified only four significant three-way interactions, namely LDFS*PSE*WFL, INSC*PSE*MA, INSC*BD*WFL and WFL*WFT*MA. Having identified these interactions, it was again required to consider whether they could logically be correct or whether they were the result of a statistical fluke.

LDFS*PSE*WFL, INSC*PSE*MA and INSC*BD*WFL each consisted of the knock-on effect of LDFS or INSC and additional compound effects. In all cases it was logically possible for each uncertainty to occur on the same batch or on parts within the same BOM chain.

WFL*WFT*MA consisted only of the compound effects of each and it was logically possible for each uncertainty to occur on the same batch or on parts within the same BOM chain.

8.4.2.4 Validation of the business model of uncertainty

Results from the second survey verified the business model of uncertainty, which now required validation. One way of achieving this was to compare second survey results with output from the simulation model.

An additional experiment was devised to model all eleven uncertainties from the discrete study simultaneously using the second survey results to obtain single parameter levels that would produce reported FPDL for each uncertainty. The parameter levels identified are shown in Table 8.14.

Source	SS	*df*	MS	F	p
LDFS * INSC * PSE	3.746	1	3.746	.593	.441
LDFS * INSC * BD	2.905	1	2.905	.460	.498
LDFS * INSC * WFL	7.418	1	7.418	1.174	.279
LDFS * INSC * WFT	1.787	1	1.787	.283	.595
LDFS * INSC * MA	17.826	1	17.826	2.822	.093
LDFS * INSC * CDC	.504	1	.504	.080	.778
LDFS * PSE * BD	1.922	1	1.922	.304	.581
LDFS * PSE * WFL	25.076	1	25.076	3.970	.047*
LDFS * PSE * WFT	.120	1	.120	.019	.890
LDFS * PSE * MA	7.984	1	7.984	1.264	.261
LDFS * PSE * CDC	2.925	1	2.925	.463	.496
LDFS * BD * WFL	2.285	1	2.285	.362	.548
LDFS * BD * WFT	3.499E-02	1	3.499E-02	.006	.941
LDFS * BD * MA	5.894	1	5.894	.933	.334
LDFS * BD * CDC	4.889	1	4.889	.774	.379
LDFS * WFL * WFT	1.390	1	1.390	.220	.639
LDFS * WFL * MA	4.289	1	4.289	.679	.410
LDFS * WFL * CDC	4.337	1	4.337	.687	.407
LDFS * WFT * MA	1.072	1	1.072	.170	.680
LDFS * WFT * CDC	5.557	1	5.557	.880	.348
LDFS * MA * CDC	2.810	1	2.810	.445	.505
INSC * PSE * BD	1.149E-02	1	1.149E-02	.002	.966
INSC * PSE * WFL	5.699	1	5.699	.902	.342
INSC * PSE * WFT	6.791E-03	1	6.791E-03	.001	.974
INSC * PSE * MA	43.305	1	43.305	6.855	.009*
INSC * PSE * CDC	3.237	1	3.237	.512	.474
INSC * BD * WFL	29.125	1	29.125	4.610	.032*
INSC * BD * WFT	1.551	1	1.551	.245	.620
INSC * BD * MA	.309	1	.309	.049	.825
INSC * BD * CDC	4.253	1	4.253	.673	.412
INSC * WFL * WFT	8.392	1	8.392	1.328	.249
INSC * WFL * MA	14.411	1	14.411	2.281	.131
INSC * WFL * CDC	7.622E-02	1	7.622E-02	.012	.913
INSC * WFT * MA	16.836	1	16.836	2.665	.103
INSC * WFT * CDC	5.130	1	5.130	.812	.368
INSC * MA * CDC	7.289E-03	1	7.289E-03	.001	.973
PSE * BD * WFL	9.729	1	9.729	1.540	.215
PSE * BD * WFT	2.459	1	2.459	.389	.533
PSE * BD * MA	8.607	1	8.607	1.363	.243
PSE * BD * CDC	.474	1	.474	.075	.784
PSE * WFL * WFT	1.353	1	1.353	.214	.644
PSE * WFL * MA	17.624	1	17.624	2.790	.095
PSE * WFL * CDC	14.235	1	14.235	2.253	.134
PSE * WFT * MA	1.964	1	1.964	.311	.577
PSE * WFT * CDC	5.912	1	5.912	.936	.334
PSE * MA * CDC	7.584	1	7.584	1.201	.273
BD * WFL * WFT	1.766	1	1.766	.280	.597
BD * WFL * MA	.779	1	.779	.123	.726
BD * WFL * CDC	6.426	1	6.426	1.017	.313
BD * WFT * MA	2.190	1	2.190	.347	.556
BD * WFT * CDC	5.017	1	5.017	.794	.373
BD * MA * CDC	.179	1	.179	.028	.866
WFL * WFT * MA	30.846	1	30.846	4.883	.027*
WFL * WFT * CDC	9.779	1	9.779	1.548	.214
WFL * MA * CDC	8.887	1	8.887	1.407	.236
WFT * MA * CDC	2.675	1	2.675	.424	.515

Table 8.13: ANOVA results for three-way interactions

Uncertainty	Parameter level
LDFS	Discrete probability distribution
	Frequency = 1.22% Magnitude = 960mins
INSC	Discrete probability distribution
	Frequency = 1.00% Magnitude = 240mins
SWTLNC	FIFO default
	LIFO for BRKPRS, ASS1, ASS4, DBRR, FCLR, SCLR, DRL
LA	Batch size multiplier
	Frequency = 29.00% Orders affected = 10
PSE	Discrete probability distribution
	Frequency = 5.00% Magnitude = 45mins
BD	MTBF: Exponential distribution: BRKPRS= 60000mins CLR = 24000min WELD = 30000mins
	MTTR: Gamma Distribution BRKPRS = (300mins, 2) CLR = (120mins, 2) WELD = (150mins, 2)
WFL	Discrete probability distribution
	Frequency = 5.00% Magnitude = 15mins
WFT	Discrete probability distribution
	Frequency = 0.25% Magnitude = 5mins
MA	Batch size multiplier
	Frequency = 22.50% Orders affected = 10
CDC	Discrete probability distribution
	Frequency = 1.00%
WFINS	Discrete probability distribution
	Frequency = 10.00% Magnitude = 300mins

Table 8.14: Parameter settings for additional experiments

Figure 8.15 shows the results for this additional experiment indicating that the parameter levels modelled resulted in very significantly higher FPDL than that actually reported. It was a self evident truth that no company would be prepared to remove its BAD approaches in order to test the significance of uncertainties as the price in missed due dates would be too high. The difference in results from the experiment and those actually reported was therefore assumed to be due to the use of BAD approaches within a company.

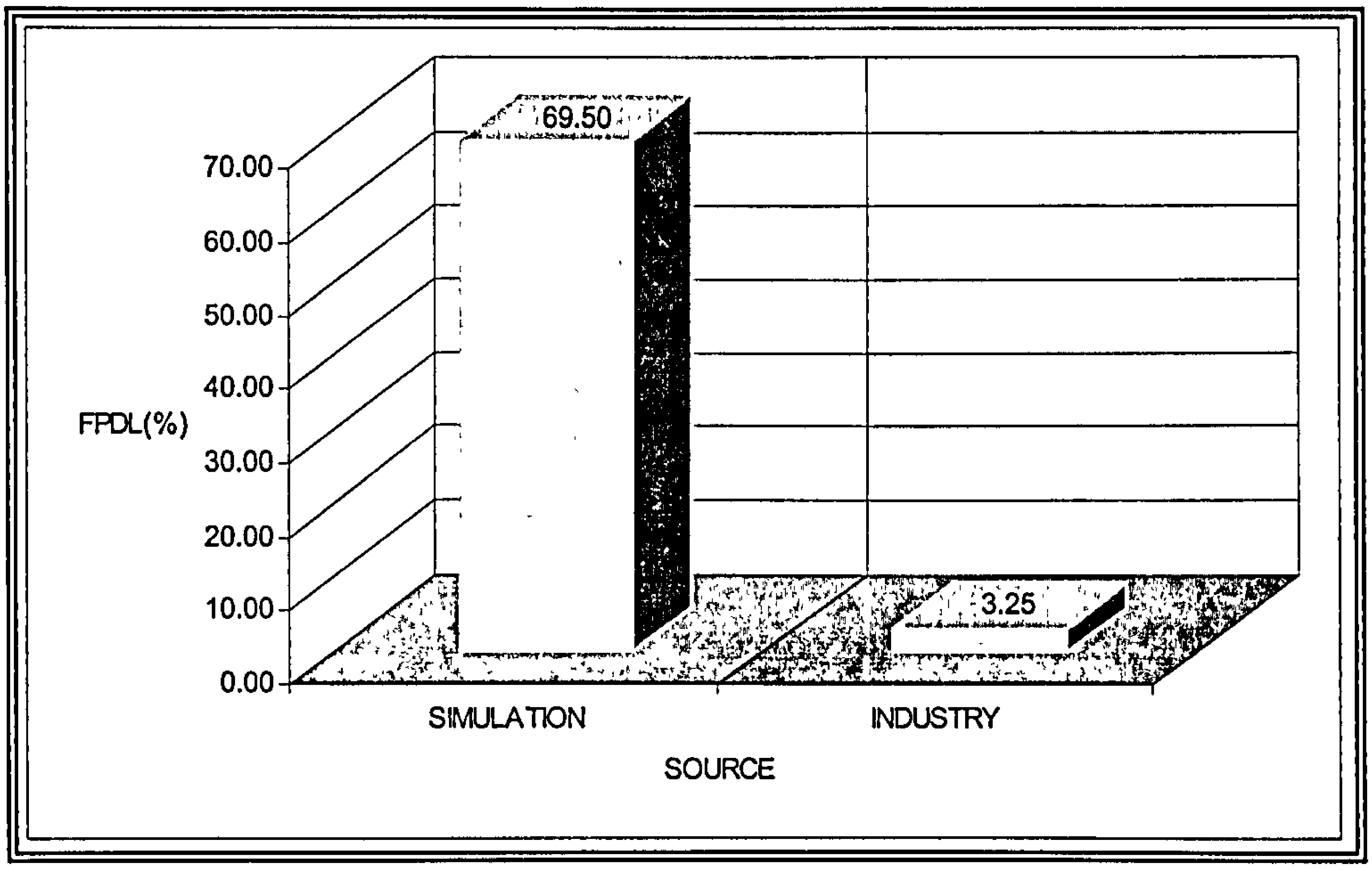

Figure 8.15: Validation experiment results

Due to the masked nature of the industry data, the results did not provide the validation required so an alternative two-stage approach was therefore invoked. The first stage sought to validate the hierarchical structure of the business model of uncertainty by proving the existence of cause-and-effect relationships. The second stage sought to validate the relationship between levels of uncertainties, FPDL and PDL.

The detailed studies of significant uncertainties in combination were chosen as the validation platform for the business model of uncertainty because they provided the highest level of confidence in results obtained within a robust experimental design having sufficient replications.

As the simulation results showed that the eight uncertainties induced late delivery, the cause-and-effect relationships were proven and hence the general structure of the business model of uncertainty was validated. However, results from ANOVA showed some significant interactions between uncertainties. These findings did not imply that the interactions negated the cause-and-effect relationship; rather they meant that additional late delivery would occur as a result of the interactions.

Using particular results from the detailed study, values of FPDL and PDL were taken that corresponded to each of four scenarios: all uncertainties set to low parameter levels; all uncertainties set to high parameter levels; significant uncertainties set to low with non significant uncertainties set to high parameter levels and significant uncertainties set to high with non significant uncertainties set to low parameter levels. The results were plotted in Figure 8.16 and showed that a proportional relationship between parameter levels set and FPDL and PDL did exist, hence satisfying the second stage of validation.

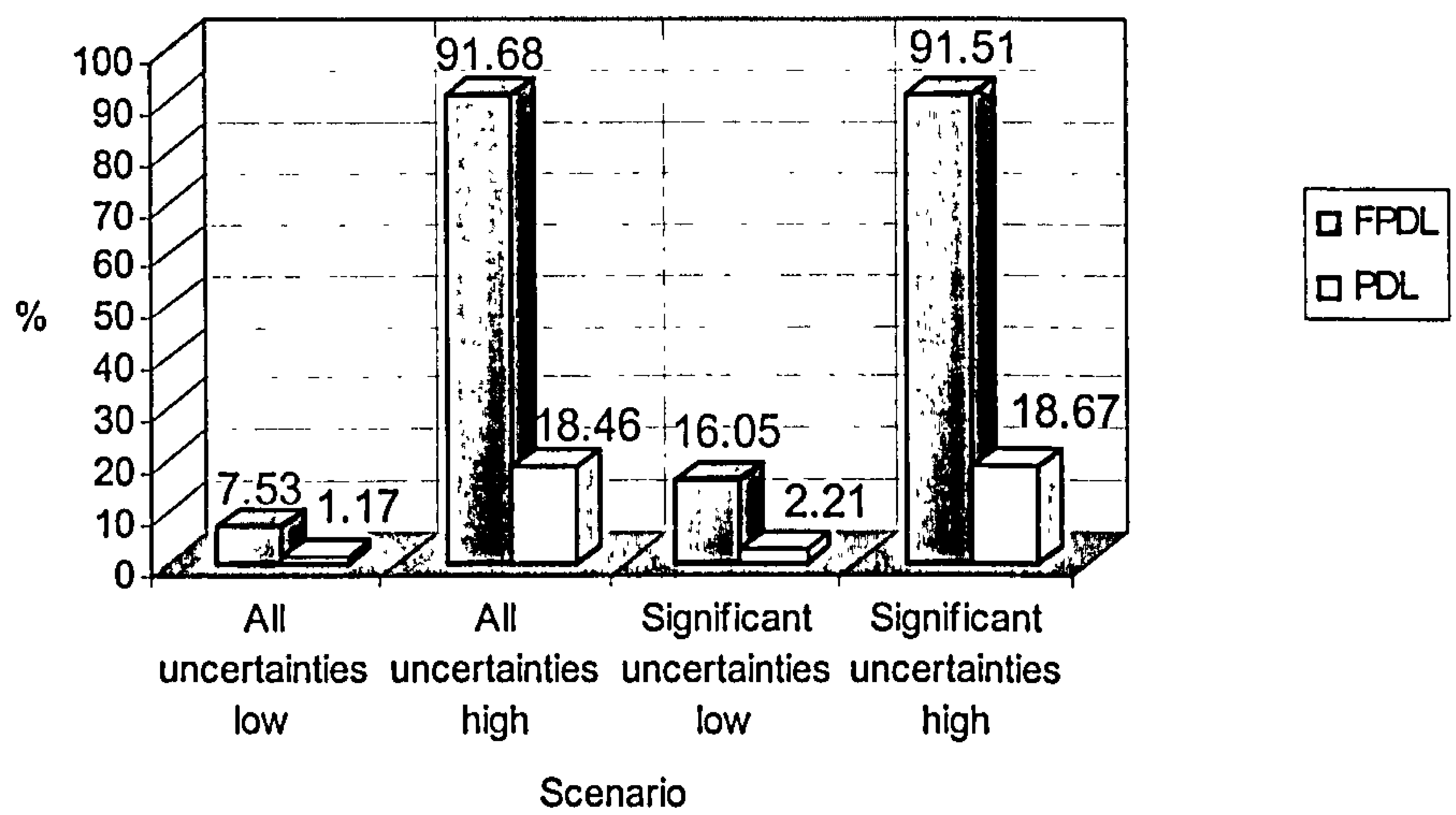

Figure 8.16: Relationship between parameter levels and FPDL and PDL

In spite of the fact that not all identified uncertainties were modelled, an examination of the behaviour of the business model of uncertainty through simulation and validation led to a high degree of confidence that results and validations obtained were extendable to the business model of uncertainty as a whole. To model the entire structure would require an experimental programme well beyond the practical limits of this research.

8.5 MRP planned overload

The general outcome from the simulation model showed 0.20% PDL occurred even when overall capacity appeared adequate. From this it was concluded that MRP planned overload did exist as an uncertainty even when it could not be easily recognised except through finite scheduling. To investigate this phenomenon the MPS used for simulation modelling was run through START MRP.

An analysis of loading was carried out for identified high utilisation resources. The correlation between periods of excess utilisation and PDL was reported in Chapter 6 as part of the validation process for the simulation model and showed the existence of MRP planned overload.

An additional finding from the analysis was that PDL occurred even when MRP planned overload was not identified when using resource loadings based on five-day time buckets. Figure 8.17 shows a section of the analysis that supported this event.

	BRKPRS				WELD				ASS4				INS				CLR			
	Utilisation		Part Number		Utilisation		Part Number		Utilisation		Part Number		Utilisation		Part Number		Utilisation		Part Number	
Day No	Daily	5 Day Ave	Due Date	Del Date	Daily	5 Day Ave	Due Date	Del Date	Daily	5 Day Ave	Due Date	Del Date	Daily	5 Day Ave	Due Date	Del Date	Daily	5 Day Ave	Due Date	Del Date
428	95	90			100	85			90	91			58	78			68	81		
429	92	95			73	83			80	83			75	73			118	91		
430	90	89			100	83			114	89			88	74			68	90		
431	129	98			113	89			80	95	16		75	80	16		83	88		
432	61	93	13035		67	91	13035		52	83		16	42	68		16	118	91		
433	86	92		13035	60	83		13035	185	102			149	86			76	93		
434	90	91			114	91			52	97			53	81			68	83		
435	95	92			68	84			80	90			75	79			100	89		
436	80	82			73	76			83	90			73	78			70	86		
437	110	92			94	82			80	96			75	85			102	83		
438	61	87			67	83			105	80			63	68			92	86		

Figure 8.17: Comparison of MRP and simulated PDL data (partial)

This finding was perhaps the most interesting in that it showed working in time buckets within an infinite scheduling based MRP system could well disguise a problem that only appeared as a result of real (finite) scheduling. In a very small number of cases it was identified that even in the presence of MRP planned overload, PDL did not necessarily occur, implying it was protected by the existence of slack.

8.6 Conclusions

After comprehensive experimentation and analysis, the business model of uncertainty was validated and represented a practical and pragmatic attempt to provide a usable tool to diagnose underlying uncertainties and their consequent effects on PDL. All uncertainties simulated were shown to affect delivery performance with different levels of magnitude. Conclusions from the experimental programmes were drawn and summarised as follows:

[1] Only four uncertainties were ultimately found to be significant in the simulation model, namely LDFS, BD, MA and CDC. The interactions analysis identified significant two-way interactions between LDFS*BD and BD*MA and significant three-way interactions between LDFS*PSE*WFL, INSC*PSE*MA, INSC*BD*WFL and INSC*WFT*MA, all of which were logically possible, highlighting the fact that additional PDL did occur as a result of such interactions.

[2] Any frequency of uncertainty was undesirable and produced PDL. However, at any frequency level, reduction in magnitude of lateness would reduce PDL significantly, particularly when magnitudes were beyond the ability of slack to absorb the lateness.

[3] Considerable evidence was found for the existence of knock-on and compound effects. Knock-on effects were created by uncertainties delaying the issue of batches affecting a particular BOM chain, i.e. LDFS and INSC. Compound effects were caused by uncertainties affecting resource availability and were identified as PSE, BD, MA, WFL, WFT and CDC.

[4] FPDL was shown to be an insensitive measure of delivery performance but was a useful measure of a manufacturing system as a whole. Of greater use when considering appropriate BAD approaches was PDL, which was more sensitive for diagnosis of significant uncertainties.

[5] The business model of uncertainty was validated with simulation evidence showing that uncertainties affected delivery performance. This conclusion was not invalidated by the existence of some significant interactions.

[6] The results from the overloading analysis showed that MRP planned overload resulted in late delivery. An interesting finding was that late delivery could also occur when no planned overload existed.

Chapter 9: Conclusions

9.1 Introduction

This chapter summarises how the research objectives were achieved, the research contribution made and the conclusions drawn from the development process. It then considers areas for further research and finally the potential impact of the business model of uncertainty on company performance will be discussed.

9.2 Achievement of research objectives

A comprehensive literature review was undertaken covering MRP capability and performance and uncertainty in MRP environments, which satisfied the first research objective. Conducting an industrial survey and analysing the results satisfied the second objective of investigating how MRP performs in industry in the presence of uncertainty. The third objective of developing a business model of uncertainty in MRP environments was achieved through the application of theory and expert opinion. This business model was verified through the use of a second industrial survey to satisfy objective four. The final objective of validating the business model was satisfied through an extensive experimental programme involving design of experiments and analytical and simulation modelling.

9.3 Research contribution

The main contribution from this research was the origination of a business model to be used as a diagnostic tool for identifying underlying uncertainties that significantly affect delivery performance in MRP environments driven by MM independent demand patterns and the development of a multi-product, multi-level dependant demand simulation model driven by POR.

A classification system was designed to provide structure to the literature review, which identified uncertainties as *input*, *process* or *output*. The need for a business model using a structured and systematic approach to deal with uncertainty and the need for consistent performance measures to allow comparison of research results was identified.

A categorisation system for companies was developed to relate levels of uncertainty experienced to the industrially preferred performance measure of due date adherence. Companies at the extremes of performance levels were recognised to be either Good, Poor, Laggard or Improver and the BAD approaches used by each category were identified.

A major concern was identified in that objective data was not widely available, questionnaire respondents supplying mainly estimates. The clear implication was that industry did not measure most uncertainties.

9.4 Summary of conclusions

At the completion of the reviews and experimental programmes, the following conclusions were drawn:

[1] MRP has been in existence for almost forty years and in widespread use throughout the industrialised world. In spite of this, MRP has continued to under perform for a very large number of users.

[2] The literature review showed uncertainty within MRP environments had been researched in depth. However, the focus of most past research was the

use of BAD approaches to cope with discrete or simple combinations of uncertainty. No evidence could be found for the existence of either a structured and/or systematic approach to the study of uncertainty in MRP environments that sought to diagnose and act upon the underlying causes of uncertainty.

[3] The type of operating environment, e.g. MTS and MTO has been largely ignored as a factor in the study of uncertainty. The implicit assumption was that characteristics of specific operating environments were not seen to be important in examining the effects of uncertainty and BAD approaches.

[4] The BAD approaches proposed for coping with uncertainty were *sub-optimal* because most researchers had concentrated on their use within either independent demand or single-level dependent demand environments. No evidence could be found that such approaches were used within multi-product, multi-level dependent demand environments controlled by POR. Dependent demand was at the heart of MRP and if this dependency was not modelled then results obtained from partial dependent or independent demand environments were representative only. Although the logic of MRP was well known and understood, no simulation representing this logic in its entirety could be found. Although some claims were made, they were unsupported. Past research mainly simulated free flow of materials into the manufacturing system and subsequent matching for assembly operations, controlled by process times rather than by MRP planned lead times.

[5] The literature review highlighted a variety of performance measures used to assess the effects of uncertainty and the effectiveness and efficiencies of BAD approaches in coping with them. With different measures, comparison of the effects of uncertainty and the effectiveness of BAD approaches used between researches was not valid. This led to the need for a representative

measure of MRP performance. The primary measure of performance used by industry was FPDL, which was proved an insensitive measure due to the existence of knock-on and compound effects. PDL should be used to provide a more sensitive measure.

[6] Survey results showed wide ranges and levels of uncertainty experienced by industry. Under-performance was noted even after BAD approaches were applied, but no evidence could be found for their effectiveness as inconsistency was encountered in their application across Good, Poor, Laggard and Improver companies. This conclusion provided empirical evidence to support the non-existence of a structured and systematic approach to cope with uncertainty.

[7] Survey results found that MRP based systems were mainly used in MM operating environments. Industry did not measure causes of uncertainty directly, but some measures were taken of the effects of uncertainty. The conclusion was that causes of uncertainty were either difficult to measure or were not considered important. When effects of uncertainty were measured, it was too late to impact upon the cause. Measurement at the level of causes would enable BAD approaches to be applied at that level preventing the effects from propagating to the finished products level.

[8] The second survey verified the business model of uncertainty by providing empirical evidence to show that causes and effects of uncertainty affected delivery performance. The hierarchy created provided a framework within which diagnosis of significant uncertainty within companies was viable.

[9] Two years of real-life company data was used to simulate a MM environment incorporating a product mix of runners, repeaters and strangers with varying batch sizes between products. Under those conditions it was not possible to produce a simulation model capable of satisfying all

customer orders. It was concluded that even in the absence of uncertainty, infinite capacity planning with MRP was not capable of producing an acceptable POR to achieve 100% on-time delivery when scheduled finitely.

[10] Simulation exposed a number of significant interactions, all of which were feasible. The additional effects did not undermine the hierarchy of uncertainty but showed that care must be taken when quantifying the effects of applying BAD approaches.

[11] The business model of uncertainty was validated and represented a practical and pragmatic attempt to provide a usable tool to diagnose underlying uncertainties and their consequent effects on PDL. All uncertainties simulated were shown to affect delivery performance with different levels of magnitude. Any frequency of uncertainty was undesirable and produced PDL. However, at any frequency level, reduction in magnitude of lateness would reduce PDL significantly, particularly when magnitudes were beyond the ability of slack to absorb the lateness.

9.5 Further research

Limitations within this research gave rise to aspects of further research required.

No published or private record could be found of MRP users in the UK. The research was therefore based upon correct identification of a population of MRP users. While the sample size was considered sufficient, it would be useful to undertake a complete survey of MRP applications within UK industry to reinforce the profile of results used in this research. An influential body such as Government best carries out such work in order to elicit accurate responses.

The second questionnaire survey produced results that were largely estimated. The statistical analysis of the responses utilised a comparatively low confidence level of 80% as many responses were based on estimates. Further work could usefully increase the confidence level achieved either by detailed case study work or by further detailed questionnaire work, perhaps incorporating a larger sample size. If such work was undertaken, the results could well impact upon the nature of the significant uncertainties recognised. This would not invalidate the business model developed, but would allow a more accurate picture of the relative effect of the uncertainties to be drawn.

It was recognised that commercial MRP systems often incorporate single and multi-level pegging ability. This facility would largely satisfy the need to recognise potential knock-on effects when faced with uncertainty. It would be useful to develop algorithms for use within both finite and infinite scheduling software to enable interrogation of queues existing at the point of delay in order to establish potential compound effects and their subsequent knock-on effects.

Last but not least, the MPS data used in this research was not truly stochastic. Although mixes of runners, repeaters and strangers were used, their demand intervals and volumes were fixed. Further research could be carried out varying both these parameters to assess their impact upon delivery performance.

9.6 Potential impact on company performance

The primary objective in developing the business model of uncertainty was to provide a tool to enable companies using MRP based systems to diagnose the causes of uncertainty that would significantly affect their ability to provide on-time delivery to customers.

For MM companies, the business model of uncertainty enables recognition of the range of factors that contribute to FPDL. From this, encouragement would be given to create empirical measures for each of the factors, which would then act as both a datum for improvement programmes and as a benchmark against other companies. A simulation model could be used at that stage to quantify the effect of each uncertainty for a particular company enabling priorities for improvement to be set, with the aim of removing or reducing levels of uncertainty.

If uncertainty cannot be removed or reduced, then once individual significances have been established suitable BAD approaches could be applied more effectively to cope. The use of PDL would provide an ultimate performance measure against which to monitor improvement.

As company performance changed over time, the process would be repeated as a continuous improvement programme.

For the first time, the business model of uncertainty would allow a company to recognise that uncertainty occurs throughout the organisation and cannot be adequately managed and controlled except through a holistic approach. By focussing on the true causes of FPDL at their root level, the need for the indiscriminate and expensive use of random BAD approaches would be eliminated and the cost effectiveness of each BAD approach used may be accurately assessed.

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This is the first survey that forms one part of my research programme. I am not acting on behalf of a professional body to find out the integrity of your business. However, the completion of this questionnaire is a favour that enables me to draw a general conclusion of MRP performance in industry. It only takes approximately 30 minutes to complete the questionnaire and the outcome of the research might be useful for your company future development.

Note: The contents of this form are absolutely confidential. Information identifying the respondent will not be disclosed under any circumstances. If you have any difficulties in completing the questionnaire, please don't hesitate to contact me. My contact details are in the enclosed cover letter and at the end of this Questionnaire.

Instruction: Please fills in the blank(s) or tick the appropriate box(es) in every question or sub-section if applicable.

Section 1: Company details

1.1 Company name: ______________________

1.2 Company address: ______________________

1.3 Tel.: ____________ Fax: ____________ Email: ____________

1.4 Contact name: ____________ 1.5 Position held: ____________

1.6 Company size: -
Number of employees: ☐1-49 ☐50-249 ☐250+
Turnover: ☐Less than £2.8 million ☐Less than £11.2 million ☐ More than £11.2 million

1.7 Main products or services: ______________________

1.8 What percentage of your products are: -
Custom made ________%
Assembled or made to order with standard parts from stock ________%
Standard products delivered from stock ________%

1.9 Do you use Material Requirements Planning (MRP) type systems?
☐ Yes {Please continue to Section 2 overleaf}
☐ No {Please briefly describe the method(s) you do use} ______________________

{Thanks for your time in completing the Questionnaire. Please return the completed Questionnaire to the contact address}

Section 2: Expected vs. Actual success levels of MRP systems

2.1 Name your MRP package and it's vendor (e.g. R/3 -SAP): ______________________

2.2 What is your degree of success from MRP systems?
This is to examine the successes you have achieved from your MRP implementation. Please rate your success level against your initial expectations by using the following scale.

1 Need major improvement
2 Need significant improvement
3 Need on-going improvement
4 Need little improvement
5 Need no improvement

	1	2	3	4	5
Stock planning and scheduling	☐	☐	☐	☐	☐
Stock accuracy	☐	☐	☐	☐	☐
Stock turns	☐	☐	☐	☐	☐
Bill Of Material accuracy	☐	☐	☐	☐	☐
Customer delivery lead times	☐	☐	☐	☐	☐
Work In Progress levels	☐	☐	☐	☐	☐
Paperwork processing	☐	☐	☐	☐	☐
Set-up and change over costs	☐	☐	☐	☐	☐
Master Production Schedule accuracy	☐	☐	☐	☐	☐
Information sharing and communication	☐	☐	☐	☐	☐

Section 3: Performance assessment of MRP

3.1 How often is your MRP run?
☐ Daily
☐ Weekly
☐ Monthly
☐ Quarterly
Other, please specify ____________

3.2 What is the period for which the resultant schedule is fixed?
☐ Daily
☐ Weekly
☐ Monthly
☐ Quarterly
Other, please specify ____________

3.3 What percentage of your MRP run policies are of this type?
☐ Net change ________%
☐ Regenerative ________%
Other, please specify ____________

3.4 Do you use Rough Cut Capacity Planning in master production scheduling?
☐ Yes
☐ No

3.5 What is the percentage of the number of levels in your product structure?
________% of the products with 1 to 3 levels
________% of the products with 4 to 6 levels
________% of the products with 7 to 9 levels
Other, please specify ____________

3.6 What is the percentage of bought -out parts, made -in parts, and subcontract parts?
_________% bought -out _________% made -in _________% subcontract

3.7 How is your schedule executed?

- ☐ Work-to list
- ☐ Kanban card
- ☐ Availability of kitted parts

Other, please specify ____________________

3.8 What are the following manufacturing performance levels in your company?

	<2%	2%-5%	6%-15%	16%-30%	>30%
Late delivery to customer	☐	☐	☐	☐	☐
Late delivery from supplier	☐	☐	☐	☐	☐

3.9 What percentage of your orders are affected by the following events?

	<2%	2%-5%	6%-15%	16%-30%	>30%
Engineering design changes	☐	☐	☐	☐	☐
Rework	☐	☐	☐	☐	☐
Machine breakd own	☐	☐	☐	☐	☐
Materials/subassemblies shortage	☐	☐	☐	☐	☐
Labour shortage	☐	☐	☐	☐	☐
Customer order changes	☐	☐	☐	☐	☐
Changes to Master Production Schedule	☐	☐	☐	☐	☐

3.10 Rank the relative significance of the following performance measures in achieving the organisational goals. Fill in the boxes provided with: Most significant = 1, Next significant = 2 and so on until all measures you use are ranked.

Efficiency in production planning and control	☐	Reduction in Work In Progress value	☐
Improvement in procurement	☐	Reduction in non -added value activity	☐
Reduction in stock value	☐	Reduction in supply and manufacture total lead times	☐
Improvement in parts tracking	☐	Improvement in forecast accuracy	☐
Improvement in meeting customer's due date	☐	Total enterprise integration	☐
Other, please specify ________	☐	________	☐
	☐		☐

Section 4: Other media to support MRP performance

This is to pinpoint the usage of other approaches in industry to increase MRP performance in production planning, control and scheduling.

4.1 Do you use any of the following to make your systems work well?

- ☐ Overtime
- ☐ Subcontract
- ☐ Outsourcing
- ☐ Reschedule for manufacturing and purchasing
- ☐ Just In Time (JIT)
- ☐ Drum Buffer Rope (DBR)
- ☐ Safety stock for finished products
- ☐ Safety stock for parts
- ☐ Increase in lead time for manufacturing and purchasing
- ☐ Spare capacity for manufacturing
- ☐ Spare worker for manufacturing
- ☐ Plan-for-extra in master production planning
- ☐ Over-planning for scrap allowance
- ☐ Supplier partnership and vendor rating
- ☐ Preventive maintenance
- ☐ Multi-skilling labour
- ☐ Training for planner or scheduler that operates MRP systems
- ☐ Forecast improvement for demand
- ☐ Product standardisation for reducing number of parts
- ☐ Process standardisation
- ☐ Procedure standardisation for routing
- ☐ Pareto or other focusing rule for lot-sizing in manufacturing and purchasing
  Other, please specify ________
- ☐ Performance review for manufacturing and purchasing
- ☐ Re-routing
- ☐ Shorten lead times for manufacturing and purchasing (If it is not used skip the following sub-section,)
  - ☐ Fast set-up
  - ☐ Small process batch
  - ☐ Small transfer batch
  - ☐ JIT purchasing
  - Other, please specify ________
- ☐ Volume flexibility for manufacturing and purchasing
- ☐ Business Process Reengineering (BPR) for total integration
- ☐ Other, please specify ________

☐ ***Please tick this box if you wish to receive further information on the results of the survey.***

Thanks for your time in completing the Questionnaire. Please return the completed Questionnaire to the following address.

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Instructions:
Please consider your company performance over the last 6 months, and answer the following questions using factual data, i.e. any measured or calculated form of data that exists in your company. In the absence of factual data, please use your professional judgement to answer the question or part of the question. In this case, please tick the 'Estimate' box.

Examples are enclosed to guide you in answering the questions. You will notice that all your answers in each question must add up to 100%. Please try to avoid 'rounding' errors. If you have any difficulties with the questions, please do not hesitate to contact me. I am very keen to establish the most accurate data possible, so please feel free to discuss the answer with an appropriate colleague.

Enjoy answering……Start here.

Section 1:
This section is designed to examine your company's overall customer delivery performance and to highlight the occurrence of *events* in manufacturing environments, which contribute to late deliveries.

1. In an average *week/month* (delete as appropriate), what percentage of your customer orders are delivered on time, in the correct quantity, and to a correct quality level?

Who?	% of the time	Estimate
Example	90%	
You		

2. What contributions do each of the following events make to those orders which are not delivered on time, in the correct quantity and to a correct quality level?

	Example	Your %	Estimate
Material shortages	40%		
Labour shortages	30%		
Machine capacity shortages	15%		
Scrap/rework	10%		
Finished product completed-not delivered	5%		
Others, please specify	0%		
Total	100%	100%	

Section 2:
This section is designed to identify the *causes* of each event, highlighted in question 2, affecting deliveries to customers.

3. What contributions do each of the following causes make to your total of material shortages?

Causes of material shortages	Example	Your %	Estimate
Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items	45%		
Stock-out due to inaccuracies of stock records	30%		
Stock-out caused by application of incorrect stock control rules	15%		
Stock-out caused by unexpected/urgent changes to production schedule	10%		
Others, please specify	0%		
Total	100%	100%	

4. What contributions do each of the following causes make to your total of labour shortages?

Causes of labour shortages	Example	Your %	Estimate
Absenteeism	45%		
Schedule/work-to-list not followed	30%		
Lack of skill availability	15%		
Labour overload	10%		
Others, please specify	0%		
Total	100%	100%	

5. What contributions do each of the following causes make to your total of machine capacity shortages?

Causes of machine capacity shortages	Example	Your %	Estimate
Unplanned machine downtime	55%		
Machine overload	30%		
Idle machine waiting for resources (Labour/material/tooling not available)	15%		
Others, please specify	0%		
Total	100%	100%	

6. What contributions do each of the following causes make to your total of <u>scrap/rework</u>?

Causes of scrap/rework	Example	Your %	Estimate
Unacceptable product quality	70%		
Engineering design changes during/after production	30%		
Others, please specify	0%		
Total	100%	100%	

7. What contributions do each of the following causes make to your total of <u>finished product completed-not delivered</u>?

Causes of finished product completed-not delivered	Example	Your %	Estimate
Awaiting for quality clearance	70%		
Awaiting for despatch	30%		
Others, please specify	0%		
Total	100%	100%	

Section 3:

This section is designed to comprehend the *factors* affecting the causes in section 2.

8. What contributions do each of the following factors make to your total of <u>poor supplier delivery performance</u>?

Factors affecting poor supplier delivery performance	Example	Your %	Estimate
Rejected by quality	45%		
Delivered with shortages	30%		
Late delivery	15%		
Incorrect items supplied	10%		
Others, please specify	0%		
Total	100%	100%	

9. What contributions do each of the following factors make to your total of <u>inaccuracies of stock records</u>?

Factors affecting inaccuracies of stock records	Example	Your %	Estimate
Items missing in Bill of Material (BOM)	55%		
Insecure stores	30%		
Poor transaction recording	15%		
Others, please specify	0%		
Total	100%	100%	

10. What contributions do each of the following factors make to your total of <u>application of incorrect stock control rules</u>?

Factors affecting application of incorrect stock control rules	Example	Your %	Estimate
Unexpected demand pattern changes	70%		
Demand/usage analysis not used to drive stock control rules	30%		
Others, please specify	0%		
Total	100%	100%	

11. What contributions do each of the following factors make to your total of <u>unexpected/urgent changes to production schedule</u>?

Factors affecting unexpected/urgent changes to production schedule	Example	Your %	Estimate
Inaccurate forecast	30%		
Customer changes delivery lead-time	30%		
Customer changes ordered quantity	15%		
Customer changes product ordered	10%		
Customer changes specified level of quality	5%		
Customer design changes during/after planning	5%		
Internal design changes during/after planning	5%		
Others, please specify	0%		
Total	100%	100%	

12. What contributions do each of the following factors make to your total of <u>absenteeism</u>?

Factors affecting absenteeism	Example	Your %	Estimate
Maternity	55%		
Sickness	30%		
Holiday	15%		
Others, please specify	0%		
Total	100%	100%	

13. What contributions do each of the following factors make to your total of <u>schedule/work-to-list not followed</u>?

Factors affecting schedule/work-to-list not followed	Example	Your %	Estimate
Schedule/work-to-list not produced	55%		
Schedule/work-to-list not controlled	30%		
Schedule/work-to-list produced but not available to workforce	15%		
Others, please specify	0%		
Total	100%	100%	

14. What contributions do each of the following factors make to your total of <u>lack of skill availability</u>?

Factors affecting lack of skill availability	Example	Your %	Estimate
Inherent shortage of skilled labour	70%		
Unexpected demand for particular skill	30%		
Others, please specify	0%		
Total	100%	100%	

15. What contributions do each of the following factors make to your total of <u>labour overload</u>?

Factors affecting labour overload	Example	Your %	Estimate
Material Requirements Planning (MRP) planned overload (Infinite scheduling of labour)	70%		
Unexpected/urgent changes to schedule (Labour assignment)	30%		
Others, please specify	0%		
Total	100%	100%	

16. What contributions do each of the following factors make to your total of <u>unplanned machine downtime</u>?

Factors affecting unplanned machine downtime	Example	Your %	Estimate
Planned maintenance/repair time exceeded	55%		
Planned set-up/changeover time exceeded	30%		
Breakdown	15%		
Others, please specify	0%		
Total	100%	100%	

17. What contributions do each of the following factors make to your total of <u>machine overload</u>?

Factors affecting machine overload	Example	Your %	Estimate
Material Requirements Planning (MRP) planned overload (Infinite scheduling of machine)	70%		
Unexpected/urgent changes to schedule (Machine assignment)	30%		
Others, please specify	0%		
Total	100%	100%	

18. What contributions do each of the following factors make to your total of <u>idle machine waiting for resources (Labour/material/tooling not available)</u>?

Factors affecting idle machine waiting for resources (Labour/material/tooling not available)	Example	Your %	Estimate
Waiting for labour	45%		
Waiting for tooling	30%		
Waiting for material internally supplied from other work centre/department/site	15%		
Waiting for material externally supplied from independent supplier/subcontractor	10%		
Others, please specify	0%		
Total	100%	100%	

19. What contributions do each of the following factors make to your total of unacceptable of product quality?

Factors affecting unacceptable of product quality	Example	Your %	Estimate
Labour error	55%		
Defective raw material	30%		
Machine error	15%		
Others, please specify	0%		
Total	100%	100%	

20. What contributions do each of the following factors make to your total of engineering design changes during/after production?

Factors affecting engineering design changes during/after production	Example	Your %	Estimate
Customer design changes during/after production	70%		
Internal design changes during/after production	30%		
Others, please specify	0%		
Total	100%	100%	

21. What contributions do each of the following factors make to your total of awaiting for quality clearance?

Factors affecting awaiting for quality clearance	Example	Your %	Estimate
Waiting for inspection labour	70%		
Waiting for inspection from mechanical/robotic device	30%		
Others, please specify	0%		
Total	100%	100%	

22. What contributions do each of the following factors make to your total of awaiting for despatch?

Factors affecting awaiting for despatch	Example	Your %	Estimate
Items on-hold (Financial)	45%		
Unavailability of transport	30%		
Awaiting balance of order	15%		
Seeking concession	10%		
Others, please specify	0%		
Total	100%	100%	

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Please feel free to comment about the contents of this questionnaire.

Thank you very much for your time and effort in completing the questionnaire.
Please return the completed questionnaire using the addressed and pre-paid envelope.

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Note: Those uncertainties with no output are not shown here. Asterisked p values indicate the significance with 80% confidence level.

3.1 ATO/MTO operating environments

Dependent Variable: Late delivery to customer

Source	SS	df	MS	F	p
Corrected Model	29.742	7	4.249	4.025	.140
Intercept	30.592	1	30.592	28 982	.013
Labour shortages	8.000	1	8.000	7.579	.071*
Error	3.167	3	1.056		
Total	81.000	11			
Corrected Total	32.909	10			

Dependent Variable: Material shortages

Source	SS	df	MS	F	p
Corrected Model	93.136	8	11.642	46.568	.021
Intercept	226.078	1	226.078	904.313	.001
Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items	50.300	3	16.767	67.067	.015*
Stock-out caused by unexpected/urgent changes to production schedule	12.500	1	12.500	50.000	.019*
Error	.500	2	.250		
Total	349.000	11			
Corrected Total	93.636	10			

Dependent Variable: Labour shortages

Source	SS	df	MS	F	p
Corrected Model	31.682	8	3.960	.196	.963
Intercept	33.092	1	33.092	1.634	.329
Absenteeism	20.250	1	20.250	1.000	.423
Schedule/work-to-list not followed	.000	1	.000	.000	1.000
Lack of skill availability	.000	1	.000	.000	1.000
Labour overload	.500	1	.500	.025	.890
Error	40.500	2	20.250		
Total	129.000	11			
Corrected Total	72.182	10			

Dependent Variable: Machine capacity shortages

Source	SS	df	MS	F	p
Corrected Model	12.909	6	2.152	.478	.800
Intercept	24.572	1	24.572	5.460	.080
Unexpected machine downtime	4.000	1	4.000	.889	.399
Idle machine waiting for resources	.000	1	.000	.000	1.000
Error	18 000	4	4.500		
Total	71.000	11			
Corrected Total	30.909	10			

Dependent Variable: Scrap/rework

Source	SS	df	MS	F	p
Corrected Model	.109	6	1.818E-02	.091	.994
Intercept	7.793	1	7.793	38.963	.003
Unacceptable product quality	3.333E-02	1	3.333E-02	.167	.704
Error	.800	4	.200		
Total	14.000	11			
Corrected Total	.909	10			

Dependent Variable: Finished product completed-not delivered

Source	SS	df	MS	F	p
Corrected Model	18.136	4	4.534	.989	.480
Intercept	24.801	1	24.801	5.411	.059
Awaiting despatch	.429	1	.429	.094	.770
Error	27.500	6	4.583		
Total	82.000	11			
Corrected Total	45.636	10			

Dependent Variable: Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items

Source	SS	df	MS	F	p
Corrected Model	55.545	8	6.943	2.777	.292
Intercept	315.809	1	315.809	126.324	.008
Rejected by quality	.500	2	.250	.100	.909
Late delivery	33.750	3	11.250	4.500	.187*
Error	5.000	2	2.500		
Total	410 000	11			
Corrected Total	60.545	10			

Dependent Variable: Stock-out due to inaccuracies of stock records

Source	SS	df	MS	F	p
Corrected Model	.000	7	.000	.	.
Intercept	6.536	1	6.536	.	.
Insecure stores	.000	1	.000	.	.
Poor transaction recording	.000	2	.000	.	.
Error	.000	3	.000		
Total	11.000	11			
Corrected Total	.000	10			

Dependent Variable: Stock-out caused by application of incorrect stock control rules

Source	SS	df	MS	F	p
Corrected Model	3 682	3	1.227	17.182	.001
Intercept	9.058	1	9.058	126.807	.000
Unexpected demand pattern changes	3.500	1	3.500	49.000	.000*
Error	.500	7	7.143E-02		
Total	22.000	11			
Corrected Total	4.182	10			

Dependent Variable: Stock-out caused by unexpected/urgent changes to production schedule

Source	SS	df	MS	F	p
Corrected Model	25.727	7	3.675	.848	.616
Intercept	48.227	1	48.227	11.129	.045
Inaccurate forecast	14.714	3	4.905	1.132	.461
Error	13.000	3	4.333		
Total	105.000	11			
Corrected Total	38.727	10			

Dependent Variable: Absenteeism

Source	SS	df	MS	F	p
Corrected Model	96.909	7	13.844	.	.
Intercept	50.228	1	50.228	.	.
Maternity	.000	1	.000	.	.
Sickness	24.000	1	24.000	.	.
Holiday	.500	1	.500	.	.
Error	.000	3	.000		
Total	190.000	11			
Corrected Total	96.909	10			

Dependent Variable: Schedule/work-to-list not followed

Source	SS	df	MS	F	p
Corrected Model	7.576	4	1.894	.213	.922
Intercept	20.626	1	20.626	2.320	.179
Schedule/work-to-list not produced	2.667	1	2.667	.300	.604
Schedule/work-to-list not controlled	2.381	1	2.381	.268	.623
Error	53.333	6	8 889		
Total	109.000	11			
Corrected Total	60 909	10			

Dependent Variable: Lack of skill availability

Source	SS	df	MS	F	p
Corrected Model	20.409	5	4 082	.833	.577
Intercept	28.481	1	28.481	5.813	.061
Inherent shortage of skill labour	17.500	1	17.500	3.571	.117*
Unexpected demand for particular skill	3.333	1	3.333	.680	.447
Error	24.500	5	4.900		
Total	85.000	11			
Corrected Total	44.909	10			

Dependent Variable: Labour overload

Source	SS	df	MS	F	p
Corrected Model	36.136	3	12.045	2.677	.128
Intercept	110.577	1	110.577	24.573	.002
MRP plan overload (Infinite scheduling of labour)	9.389	1	9.389	2.086	.192*
Error	31.500	7	4.500		
Total	155.000	11			
Corrected Total	67.636	10			

Dependent Variable: Unplanned machine downtime

Source	SS	df	MS	F	p
Corrected Model	96 000	8	12.000	.	.
Intercept	224.959	1	224.959	.	.
Planned set-up/change-over time exceeded	27.000	1	27.000	.	.
Breakdown	36.750	1	36.750	.	.
Error	.000	2	.000		
Total	272.000	11			
Corrected Total	96.000	10			

Dependent Variable: Machine overload

Source	SS	df	MS	F	p
Corrected Model	14.227	4	3.557	42.682	.000
Intercept	25.663	1	25.663	307.960	.000
Unexpected/urgent changes to schedule (Machine assignment)	.000	1	.000	.000	1.000
Error	.500	6	8.333E-02		
Total	38.000	11			
Corrected Total	14.727	10			

Dependent Variable: Idle machine waiting for resources (Labour/machine/tooling not available)

Source	SS	df	MS	F	p
Corrected Model	74 000	7	10.571	3.964	.143
Intercept	87.932	1	87.932	32.974	.010
Waiting for labour	.750	1	.750	.281	.633
Waiting for material internally supplied	.750	1	.750	.281	.633
Waiting for material externally supplied	30.000	1	30.000	11.250	.044*
Error	8.000	3	2.667		
Total	181.000	11			
Corrected Total	82.000	10			

Dependent Variable: Unacceptable product quality

Source	SS	df	MS	F	p
Corrected Model	98.727	10	9.873	.	.
Intercept	504.741	1	504.741	.	.
Labour error	34.667	2	17.333	.	.
Defective raw material	18.000	1	18.000	.	.
Machine error	24.500	1	24.500	.	.
Total	557.000	11			
Corrected Total	98.727	10			

Dependent Variable: Engineering design changes during/after production

Source	SS	df	MS	F	p
Corrected Model	37.136	5	7.427	1.143	.444
Intercept	77.356	1	77.356	11.901	.018
Customer design changes during/after production	6.000	1	6.000	.923	.381
Internal design changes during/after production	14.700	1	14.700	2.262	.193*
Error	32.500	5	6.500		
Total	157.000	11			
Corrected Total	69.636	10			

Dependent Variable: Awaiting quality clearance

Source	SS	df	MS	F	p
Corrected Model	42.545	3	14.182	7.091	.016
Intercept	60.521	1	60.521	30.260	.001
Waiting for inspection labour	18.000	1	18.000	9.000	.020*
Error	14.000	7	2.000		
Total	118.000	11			
Corrected Total	56.545	10			

Dependent Variable: Awaiting despatch

Source	SS	df	MS	F	p
Corrected Model	103.727	7	14.818	1.646	.369
Intercept	319.386	1	319.386	35.487	.009
Items on-hold (Financial)	33.800	1	33.800	3.756	.148*
Unavailability of transport	34.333	2	17.167	1.907	.292
Error	27.000	3	9.000		
Total	458.000	11			
Corrected Total	130.727	10			

3.2 MM operating environments

Dependent Variable: Late delivery to customer

Source	SS	df	MS	F	p
Corrected Model	57.750	40	1.444	8.662	.049
Intercept	46.610	1	46.610	279.661	.000
Material shortages	26.683	8	3.335	20.012	.016*
Labour shortages	2.167	4	.542	3.250	.180*
Machine capacity shortages	5.250	3	1.750	10.500	.042*
Scrap/rework	2.006	2	1.003	6.019	.089*
Finished product completed – not delivered	4.500	2	2.250	13.500	.032*
Material shortages * Machine capacity shortages	.250	1	.250	1.500	.308
Material shortages * Scrap/rework	.000	1	.000	.000	1.000
Error	.500	3	.167		
Total	193.000	44			
Corrected Total	58.250	43			

Dependent Variable: Material shortages

Source	SS	df	MS	F	p
Corrected Model	219.520	31	7.081	2.215	.072
Intercept	299.279	1	299.279	93.606	.000
Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items	84.349	8	10.544	3.298	.031*
Stock-out due to inaccuracies of stock records	40.759	4	10.190	3.187	.053*
Stock-out caused by application of incorrect stock control rules	2.000	1	2.000	.626	.444
Stock-out caused by unexpected/urgent changes to production schedule	29.684	4	7.421	2.321	.116*
Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items * Stock-out due to inaccuracies of stock records	16.000	1	16.000	5.004	.045*
Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items * Stock-out caused by unexpected/urgent changes to production schedule	7.217	2	3.608	1.129	.356
Stock-out due to inaccuracies of stock records * Stock-out caused by unexpected/urgent changes to production schedule	2.571	1	2.571	.804	.387
Error	38.367	12	3.197		
Total	907.000	44			
Corrected Total	257.886	43			

Dependent Variable: Labour shortages

Source	SS	df	MS	F	p
Corrected Model	101.886	30	3.396	1.698	.156
Intercept	160.197	1	160.197	80.099	.000
Absenteeism	4.080	5	.816	.408	.835
Schedule/work-to-list not followed	.000	2	.000	.000	1.000
Lack of skill availability	1.273	1	1.273	.636	.439
Labour overload	4.889	4	1.222	.611	.662
Error	26.000	13	2.000		
Total	333.000	44			
Corrected Total	127.886	43			

Dependent Variable: Machine capacity shortages

Source	SS	df	MS	F	p
Corrected Model	48.686	23	2.117	.860	.638
Intercept	107.995	1	107.995	43.901	.000
Unexpected machine downtime	11.667	4	2.917	1.186	.347
Machine overload	19.438	4	4.859	1.975	.137*
Idle machine waiting for resources	8.182	2	4.091	1.663	.215
Error	49 200	20	2.460		
Total	247.000	44			
Corrected Total	97.886	43			

Dependent Variable: Scrap/rework

Source	SS	df	MS	F	p
Corrected Model	8.187	10	.819	.824	.609
Intercept	38.308	1	38.308	38.553	.000
Unacceptable product quality	3.751	2	1.876	1.888	.167*
Engineering design changes during/after production	.667	3	.222	.224	.879
Error	32.790	33	.994		
Total	143.000	44			
Corrected Total	40.977	43			

Dependent Variable: Finished product completed-not delivered

Source	SS	df	MS	F	p
Corrected Model	9.258	7	1.323	.558	.785
Intercept	24.729	1	24.729	10.427	.003
Awaiting quality clearance	5.602E-03	1	5.602E-03	.002	.962
Awaiting despatch	6.072	1	6.072	2.560	.118*
Error	85.378	36	2.372		
Total	206.000	44			
Corrected Total	94.636	43			

Dependent Variable: Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items

Source	SS	df	MS	F	p
Corrected Model	129.436	22	5.883	.971	.528
Intercept	433.407	1	433.407	71.553	.000
Rejected by quality	21.242	3	7.081	1.169	.345
Delivered with shortages	.795	2	.397	.066	.937
Late delivery	69.262	7	9.895	1.634	.181*
Incorrect items supplied	4.500	1	4.500	.743	.398
Error	127.200	21	6.057		
Total	1184.000	44			
Corrected Total	256.636	43			

Dependent Variable: Stock-out due to inaccuracies of stock records

Source	SS	df	MS	F	p
Corrected Model	53.891	21	2.566	1.154	.370
Intercept	101.328	1	101.328	45.583	.000
Items missing in BOM	6.500	2	3.250	1.462	.253
Insecure stores	21.810	3	7.270	3.270	.040*
Poor transaction recording	14.429	4	3.607	1.623	.204
Error	48.905	22	2.223		
Total	267.000	44			
Corrected Total	102.795	43			

Dependent Variable: Stock-out caused by application of incorrect stock control rules

Source	SS	df	MS	F	p
Corrected Model	18 059	9	2.007	3.827	.002
Intercept	52.102	1	52.102	99.366	.000
Unexpected demand pattern changes	5.602E-03	1	5.602E-03	.011	.918
Demand/usage analysis not used to drive stock control rules	7.941E-02	1	7.941E-02	.151	.700
Error	17.828	34	.524		
Total	115.000	44			
Corrected Total	35.886	43			

Dependent Variable: Stock-out caused by unexpected/urgent changes to production schedule

Source	SS	df	MS	F	p
Corrected Model	90.561	33	2.744	.941	.583
Intercept	138.628	1	138.628	47.530	.000
Inaccurate forecast	26.666	7	3.809	1.306	.339
Customer changes delivery lead-time	.720	2	.360	.123	.885
Customer changes product ordered	1.600	2	.800	.274	.766
Internal design changes during/after production	9.100	4	2.275	.780	.563
Inaccurate forecast * Customer changes delivery lead-time	5.469	1	5.469	1.875	.201
Error	29.167	10	2.917		
Total	338.000	44			
Corrected Total	119.727	43			

Dependent Variable: Absenteeism

Source	SS	df	MS	F	p
Corrected Model	85.265	21	4.060	.547	.914
Intercept	105.441	1	105.441	14.217	.001
Maternity	2.769	1	2.769	.373	.547
Sickness	35.999	8	4.500	.607	.762
Holiday	7.556	6	1.259	.170	.982
Sickness * Holiday	7.413	2	3.707	.500	.613
Error	163.167	22	7.417		
Total	549.000	44			
Corrected Total	248.432	43			

Dependent Variable: Schedule/work-to-list not followed

Source	SS	df	MS	F	p
Corrected Model	90.066	18	5.004	1.607	.134
Intercept	73.815	1	73.815	23.713	.000
Schedule/work-to-list not produced	13.379	2	6.689	2.149	.138*
Schedule/work-to-list not controlled	43.132	6	7.189	2.309	.065*
Schedule/work-to-list produced but not available to workforce	.785	3	.262	.084	.968
Schedule/work-to-list not controlled * Schedule/work-to-list produced but not available to workforce	5.786	1	5.786	1.859	.185*
Error	77.820	25	3.113		
Total	373.000	44			
Corrected Total	167.886	43			

Dependent Variable: Lack of skill availability

Source	SS	df	MS	F	p
Corrected Model	43.576	8	5.447	3.944	.002
Intercept	154.719	1	154.719	112.038	.000
Inherent shortage of skill labour	.800	1	.800	.579	.452
Unexpected demand for particular skill	3.030	1	3.030	2.194	.147*
Error	48.333	35	1.381		
Total	260.000	44			
Corrected Total	91.909	43			

Dependent Variable: Labour overload

Source	SS	df	MS	F	p
Corrected Model	103.076	9	11.453	3.040	.009
Intercept	360.472	1	360.472	95.688	.000
MRP plan overload (Infinite scheduling of labour)	42.949	1	42.949	11.401	.002*
Unexpected/urgent changes to schedule (Labour assignment)	42.949	1	42.949	11.401	.002*
Error	128.083	34	3.767		
Total	575.000	44			
Corrected Total	231.159	43			

Dependent Variable: Unplanned machine downtime

Source	SS	df	MS	F	p
Corrected Model	190.898	19	10.047	4.342	.000
Intercept	226.620	1	226.620	97.939	.000
Planned maintenance/repair time exceeded	2.700	1	2.700	1.167	.291
Planned set-up/change-over time exceeded	40.679	4	10.170	4.395	.008*
Breakdown	81.474	5	16.295	7.042	.000*
Error	55.533	24	2.314		
Total	673.000	44			
Corrected Total	246.432	43			

Dependent Variable: Machine overload

Source	SS	df	MS	F	p
Corrected Model	191.227	12	15.936	3.867	.001
Intercept	503.840	1	503.840	122.262	.000
MRP plan overload (Infinite scheduling of machine)	109.825	4	27.456	6.663	.001*
Unexpected/urgent changes to schedule (Machine assignment)	75.194	4	18.799	4.562	.005*
Error	127.750	31	4.121		
Total	851.000	44			
Corrected Total	318.977	43			

Dependent Variable: Idle machine waiting for resources (Labour/machine/tooling not available)

Source	SS	df	MS	F	p
Corrected Model	170.727	21	8.130	89.429	.000
Intercept	270.403	1	270.403	2974.434	.000
Waiting for labour	43.101	4	10.775	118.529	.000*
Waiting for tooling	61.217	1	61.217	673.391	.000*
Waiting for material internally supplied	.500	1	.500	5.500	.028*
Error	2.000	22	9.091E-02		
Total	400.000	44			
Corrected Total	172.727	43			

Dependent Variable: Unacceptable product quality

Source	SS	df	MS	F	p
Corrected Model	399.561	28	14.270	2.348	.043
Intercept	1322.843	1	1322.843	217.652	.000
Labour error	100.795	7	14.399	2.369	.076*
Defective raw material	85.214	4	21.304	3.505	.033*
Machine error	70.000	3	23.333	3.839	.032*
Error	91.167	15	6.078		
Total	1934.000	44			
Corrected Total	490.727	43			

Dependent Variable: Engineering design changes during/after production

Source	SS	df	MS	F	p
Corrected Model	95.636	8	11.954	1.980	.079
Intercept	216.483	1	216.483	35.851	.000
Customer design changes during/after production	11.733	1	11.733	1.943	.172*
Internal design changes during/after production	3.438	1	3.438	.569	.456
Error	211.342	35	6.038		
Total	697.000	44			
Corrected Total	306.977	43			

Dependent Variable: Awaiting quality clearance

Source	SS	df	MS	F	p
Corrected Model	201.244	4	50.311	11.027	.000
Intercept	153.988	1	153.988	33.751	.000
Waiting for inspection labour	109.457	1	109.457	23.991	.000*
Error	177.938	39	4.563		
Total	740.000	44			
Corrected Total	379.182	43			

Dependent Variable: Awaiting despatch

Source	SS	*df*	MS	F	p
Corrected Model	550.636	27	20.394	14.832	.000
Intercept	560.587	1	560.587	407.700	.000
Items on-hold (Financial)	145 385	5	29.077	21.147	.000*
Unavailability of transport	120.000	5	24.000	17.455	.000*
Awaiting balance of order	59.417	6	9.903	7.202	.001*
Seeking concession	57.167	2	28.583	20.788	.000*
Error	22.000	16	1.375		
Total	1500.000	44			
Corrected Total	572.636	43			

3.3 MTS operating environments

Dependent Variable: Late delivery to customer

Source	SS	*df*	MS	F	p
Corrected Model	8.400	9	.933	.	.
Intercept	25.183	1	25.183	.	.
Scrap/rework	.500	1	.500	.	.
Error	.000	0	.		
Total	34 000	10			
Corrected Total	8.400	9			

Dependent Variable: Material shortages

Source	SS	*df*	MS	F	p
Corrected Model	66.400	9	7.378	.	.
Intercept	107.866	1	107.866	.	.
Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items	4.500	1	4.500	.	.
Stock-out caused by unexpected/urgent changes to production schedule	.000	1	.000	.	.
Error	.000	0	.		
Total	182.000	10			
Corrected Total	66.400	9			

Dependent Variable: Labour shortages

Source	SS	*df*	MS	F	p
Corrected Model	18.000	6	3.000	.	.
Intercept	45.684	1	45.684	.	.
Absenteeism	.800	1	.800	.	.
Lack of skill availability	8.000	1	8.000	.	.
Error	.000	3	.000		
Total	58.000	10			
Corrected Total	18.000	9			

Dependent Variable: Machine capacity shortages

Source	SS	*df*	MS	F	p
Corrected Model	9.100	6	1.517	9.100	.049
Intercept	29.420	1	29.420	176.522	.001
Unexpected machine downtime	2.700	1	2.700	16.200	.028*
Machine overload	.000	1	.000	.000	1.000
Idle machine waiting for resources	.750	1	.750	4.500	.124*
Error	.500	3	.167		
Total	42.000	10			
Corrected Total	9.600	9			

Dependent Variable: Scrap/rework

Source	SS	*df*	MS	F	p
Corrected Model	4 850	4	1.213	.564	.701
Intercept	21.098	1	21 098	9 813	.026
Unacceptable product quality	2.679	1	2.679	1.246	.315
Engineering design changes during/after production	3.000	1	3.000	1.395	.291
Error	10.750	5	2.150		
Total	48.000	10			
Corrected Total	15.600	9			

Dependent Variable: Finished product completed-not delivered

Source	SS	*df*	MS	F	p
Corrected Model	51.600	3	17.200	4.300	.061
Intercept	53.937	1	53 937	13.484	.010
Awaiting quality clearance	.000	1	.000	.000	1.000
Awaiting despatch	46.875	1	46.875	11.719	.014*
Error	24.000	6	4.000		
Total	154 000	10			
Corrected Total	75.600	9			

Dependent Variable: Supplier not achieving promise date/supplying faulty items/delivery shortages/incorrect items

Source	SS	*df*	MS	F	p
Corrected Model	16.100	8	2.012	.	.
Intercept	72.753	1	72.753	.	.
Rejected by quality	.500	1	.500	.	.
Delivered with shortages	.500	1	.500	.	.
Late delivery	1.167	2	.583	.	.
Error	.000	1	.000		
Total	89.000	10			
Corrected Total	16.100	9			

Dependent Variable: Stock-out due to inaccuracies of stock records

Source	SS	*df*	MS	F	p
Corrected Model	14.900	6	2.483	1.242	.465
Intercept	34.702	1	34.702	17.351	.025
Items missing in BOM	.000	1	.000	.000	1.000
Poor transaction recording	.750	1	.750	.375	.584
Error	6.000	3	2.000		
Total	57.000	10			
Corrected Total	20.900	9			

Dependent Variable: Stock-out caused by unexpected/urgent changes to production schedule

Source	SS	*df*	MS	F	p
Corrected Model	26 600	4	6.650	3.500	.101
Intercept	91.345	1	91.345	48.076	.001
Inaccurate forecast	6 000	2	3.000	1.579	.294
Error	9.500	5	1.900		
Total	173 000	10			
Corrected Total	36.100	9			

Dependent Variable: Absenteeism

Source	SS	*df*	MS	F	p
Corrected Model	60.400	5	12.080	24.160	.004
Intercept	96.433	1	96.433	192.866	.000
Sickness	1.333	1	1.333	2.667	.178*
Holiday	.000	1	.000	.000	1.000
Error	2.000	4	.500		
Total	130.000	10			
Corrected Total	62.400	9			

Dependent Variable: Schedule/work-to-list not followed

Source	SS	*df*	MS	F	p
Corrected Model	17.600	3	5.867	.	.
Intercept	45.784	1	45.784	.	.
Schedule/work-to-list not controlled	3.500	1	3.500	.	.
Error	.000	6	.000		
Total	50.000	10			
Corrected Total	17.600	9			

Dependent Variable: Lack of skill availability

Source	SS	*df*	MS	F	p
Corrected Model	20.900	3	6.967	5.225	.041
Intercept	61.333	1	61.333	46.000	.001
Unexpected demand for particular skill	13.714	1	13.714	10.286	.018*
Error	8.000	6	1.333		
Total	73.000	10			
Corrected Total	28.900	9			

Dependent Variable: Unplanned machine downtime

Source	SS	*df*	MS	F	p
Corrected Model	88.500	4	22.125	6.146	.036
Intercept	146.003	1	146.003	40.556	.001
Breakdown	35.714	1	35.714	9.921	.025*
Error	18 000	5	3.600		
Total	229.000	10			
Corrected Total	106.500	9			

Dependent Variable: Machine overload

Source	SS	*df*	MS	F	p
Corrected Model	76.100	5	15.220	.	.
Intercept	97.867	1	97.867	.	.
MRP plan overload (Infinite scheduling of machine)	53.333	1	53.333	.	.
Unexpected/urgent changes to schedule (Machine assignment)	.000	1	.000	.	.
Error	.000	4	.000		
Total	149.000	10			
Corrected Total	76.100	9			

Dependent Variable: Idle machine waiting for resources (Labour/machine/tooling not available)

Source	SS	*df*	MS	F	p
Corrected Model	56.100	6	9.350	.	.
Intercept	61.636	1	61.636	.	.
Waiting for labour	3.200	1	3.200	.	.
Waiting for material externally supplied	.800	1	.800	.	.
Error	.000	3	.000		
Total	109.000	10			
Corrected Total	56.100	9			

Dependent Variable: Unacceptable product quality

Source	SS	*df*	MS	F	p
Corrected Model	83.600	6	13.933	.871	.597
Intercept	229.706	1	229.706	14.357	.032
Defective raw material	3.200	1	3.200	.200	.685
Error	48.000	3	16.000		
Total	362.000	10			
Corrected Total	131.600	9			

Dependent Variable: Engineering design changes during/after production

Source	SS	*df*	MS	F	p
Corrected Model	51.600	3	17.200	3.225	.103
Intercept	114.632	1	114.632	21.493	.004
Internal design changes during/after production	24.000	1	24.000	4.500	.078*
Error	32.000	6	5.333		
Total	162.000	10			
Corrected Total	83.600	9			

Dependent Variable: Awaiting quality clearance

Source	SS	*df*	MS	F	p
Corrected Model	33.611	1	33.611	4.727	.061
Intercept	88.011	1	88.011	12.377	.008
Waiting for inspection labour	33.611	1	33.611	4.727	.061*
Error	56.889	8	7.111		
Total	153.000	10			
Corrected Total	90.500	9			

Dependent Variable: Awaiting despatch

Source	SS	*df*	MS	F	p
Corrected Model	34.500	2	17.250	1.258	.341
Intercept	76.923	1	76.923	5.609	.050
Unavailability of transport	32.000	1	32.000	2.333	.170*
Seeking concession	.889	1	.889	.065	.806
Error	96.000	7	13.714		
Total	253.000	10			
Corrected Total	130.500	9			

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	11	Ballast transformer 950V 50mA	1	M	2
.1	11001	Terminal block	2	B	30
.1	11002	Cable	1	B	4
.1	11013	Sleeve	2	B	20
.1	11017	Rivet	2	B	15
.1	11003	Screw	1	B	4
.1	11004	Filling material subassembly	1	M	1
..2	11007	Resin	1	B	10
..2	11008	Activator	1	B	10
.1	11006	Packing subassembly	1	M	1
..2	11014	Carton	1	B	10
..2	11015	Tape	1	B	5
.1	11005	Case subassembly	1	M	1
..2	11009	Rivet	1	B	20
..2	11010	Enclosure	1	M	2
...3	11022	Sheet metal	1	B	4
...3	11023	Paint	1	B	4
..2	11011	Lid	1	M	1
...3	11024	Sheet metal	1	B	4
...3	11025	Paint	1	B	4
..2	11012	Terminal cover	1	M	2
...3	11026	Sheet metal	1	B	4
...3	11027	Paint	1	B	4
.1	11016	Ballast subassembly	1	M	1
..2	11033	Press/Melx	2	B	20
..2	11018	Lamination	2	M	1
...3	11031	Presspahn/Melinex	1	B	4
..2	11019	Bakelite	2	M	1
...3	11032	Bakelite sheet	1	B	10
..2	11020	Shunt strip	2	M	1
...3	11034	Sheet metal	1	B	4
..2	11021	Shunt ballast	3	M	1
...3	11035	Sheet metal	1	B	4
..2	11028	Primary coil	1	M	1
...3	11045	Tape kit	1	B	4
...3	11046	Wire kit	1	B	10
..2	11030	Secondary coil	1	M	1
...3	11050	Wire kit	1	B	20
...3	11051	Half shroud kit	1	B	4
..2	11029	Thermal fuse subassembly	1	M	1
...3	11047	Thermal fuse	1	B	10
...3	11048	Tape	1	B	10

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	12	Ballast transformer 950V 90mA	1	M	1
.1	12001	Terminal block	2	B	30
.1	12002	Cable	1	B	4
.1	12013	Sleeve	2	B	20
.1	12017	Rivet	2	B	15
.1	12003	Screw	1	B	4
.1	12004	Filling material subassembly	1	M	1
..2	12007	Resin	1	B	10
..2	12008	Activator	1	B	10
.1	12006	Packing subassembly	1	M	1
..2	12014	Carton	1	B	10
..2	12015	Tape	1	B	5
.1	12005	Case subassembly	1	M	1
..2	12009	Rivet	1	B	20
..2	12010	Enclosure	1	M	1
...3	12022	Sheet metal	1	B	4
...3	12023	Paint	1	B	4
..2	12011	Lid	1	M	1
...3	12024	Sheet metal	1	B	4
...3	12025	Paint	1	B	4
..2	12012	Terminal cover	1	M	1
...3	12026	Sheet metal	1	B	4
...3	12027	Paint	1	B	4
.1	12016	Ballast subassembly	1	M	1
..2	12032	Press/Melx	1	B	20
..2	12020	Lamination	2	M	1
...3	12033	Presspahn/Melinex	1	B	4
..2	12018	Bakelite	2	M	1
...3	12030	Bakelite sheet	1	B	4
..2	12019	Shunt strip	2	M	1
...3	12031	Sheet metal	1	B	10
..2	12021	Shunt ballast	2	M	1
...3	12034	Sheet metal	1	B	4
..2	12028	Primary coil	1	M	1
...3	12044	Wire kit	1	B	10
...3	12045	Tape kit	1	B	10
..2	12029	Thermal fuse subassembly	1	M	1
...3	12047	Tape	1	B	20
...3	12048	Thermal fuse	1	B	4

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	13	Eurosafe transformer 5kV 50mA	1	M	1
.1	13004	Rivet	1	B	15
.1	13005	LAM stack	2	M	1
..2	13013	Lamination	1	B	15
.1	13003	Filling material subassembly	3	M	2
..2	13011	Resin	1	B	10
..2	13012	Activator	1	B	10
.1	13006	Packing subassembly	1	M	1
..2	13017	Carton	6	B	45
..2	13018	Tape	3	B	45
.1	13001	Primary coil	1	M	1
..2	13008	Wire kit	1	B	30
..2	13009	Tape kit	1	B	20
.1	13002	Secondary coil	2	M	2
..2	13014	Strip	1	B	4
..2	13015	Tape kit	1	B	25
..2	13016	Wire kit	1	B	30
..2	13010	Former	2	M	1
...3	13026	Presspahn	1	B	14
.1	13007	Eurosafe control subassembly	1	M	1
..2	13022	Eurosafe open circuit PCB	1	B	14
..2	13019	Spacer	1	B	4
..2	13020	Bracket left	1	M	1
...3	13027	Sheet metal	1	B	4
..2	13021	Bracket right	1	M	1
...3	13028	Sheet metal	1	B	4
..2	13024	Melinex	2	M	1
...3	13031	Melinex roll	1	B	15
..2	13025	Carton subassembly	1	M	1
...3	13032	Tape	1	B	20
...3	13033	Carton	1	B	30
..2	13023	Case subassembly	1	M	1
...3	13029	Lid subassembly	1	M	1
....4	13036	Bolt	2	B	20
....4	13034	Gasket	1	B	30
....4	13035	Lid	1	M	1
.....5	13040	Sheet metal	1	B	4
.....5	13041	Paint	1	B	4
...3	13030	Enclosure subassembly	1	M	1
....4	13039	Tape	4	B	15
....4	13037	Enclosure	1	M	1
.....5	13042	Paint	1	B	4
.....5	13043	Sheet metal	2	B	30
....4	13038	Earth subassembly	1	M	2
.....5	13044	Bolt/nut	1	B	4
.....5	13045	Washer	1	B	4

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	14	Eurosafe transformer 6kV 50mA	1	M	2
.1	14004	Rivet	1	B	15
.1	14005	LAM stack	2	M	1
..2	14013	Lamination	1	B	15
.1	14003	Filling material subassembly	2	M	2
..2	14011	Resin	1	B	10
..2	14012	Activator	1	B	10
.1	14006	Packing subassembly	1	M	1
..2	14015	Carton	6	B	45
..2	14016	Tape	3	B	45
.1	14001	Primary coil	1	M	1
..2	14009	Wire kit	1	B	30
..2	14010	Tape kit	1	B	20
.1	14002	Secondary coil	2	M	2
..2	14014	Wire kit	1	B	25
..2	14017	Tape kit	1	B	10
..2	14008	Former	1	M	1
...3	14025	Presspahn	1	B	14
.1	14007	Eurosafe control subassembly	1	M	1
..2	14018	Spacer	1	B	4
..2	14021	Eurosafe open circuit PCB	1	B	14
..2	14020	Bracket left	1	M	1
...3	14027	Sheet metal	1	B	4
..2	14019	Bracket right	1	M	1
...3	14026	Sheet metal	1	B	4
..2	14023	Melinex	2	M	1
...3	14030	Melinex roll	1	B	15
..2	14024	Carton subassembly	1	M	1
...3	14031	Tape	1	B	20
...3	14032	Carton	1	B	30
..2	14022	Case subassembly	1	M	1
...3	14028	Lid subassembly	1	M	1
....4	14035	Bolt	2	B	20
....4	14033	Gasket	1	B	30
....4	14034	Lid	1	M	1
.....5	14039	Sheet metal	1	B	4
.....5	14040	Paint	1	B	4
...3	14029	Enclosure subassembly	1	M	1
....4	14038	Tape	4	B	15
....4	14036	Enclosure	1	M	1
.....5	14041	Paint	1	B	4
.....5	14042	Sheet metal	2	B	30
....4	14037	Earth subassembly	1	M	2
.....5	14043	Bolt/nut	1	B	4
.....5	14044	Washer	1	B	4

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	15	Eurosafe transformer 4kV 60mA	1	M	2
.1	15004	Rivet	1	B	15
.1	15005	LAM stack	2	M	1
..2	15016	Lamination	1	B	15
.1	15003	Filling material subassembly	2	M	3
..2	15011	Resin	1	B	10
..2	15012	Activator	1	B	10
.1	15006	Packing subassembly	1	M	1
..2	15017	Carton	6	B	45
..2	15018	Tape	3	B	45
.1	15001	Primary coil	1	M	2
..2	15008	Wire kit	1	B	30
..2	15009	Tape kit	1	B	20
.1	15002	Secondary coil	2	M	3
..2	15013	Strip	1	B	4
..2	15014	Tape kit	1	B	25
..2	15015	Wire kit	1	B	30
..2	15010	Former	1	M	1
...3	15026	Presspahn	1	B	14
.1	15007	Eurosafe control subassembly	1	M	2
..2	15022	Eurosafe open circuit PCB	1	B	14
..2	15019	Spacer	1	B	4
..2	15020	Bracket left	1	M	1
...3	15027	Sheet metal	1	B	4
..2	15021	Bracket right	1	M	1
...3	15028	Sheet metal	1	B	4
..2	15024	Melinex	2	M	1
...3	15031	Melinex roll	1	B	15
..2	15025	Carton subassembly	1	M	1
...3	15032	Tape	1	B	20
...3	15033	Carton	1	B	30
..2	15023	Case subassembly	1	M	1
...3	15029	Lid subassembly	1	M	1
....4	15036	Bolt	2	B	20
....4	15034	Gasket	1	B	30
....4	15035	Lid	1	M	2
.....5	15040	Sheet metal	1	B	4
.....5	15041	Paint	1	B	4
...3	15030	Enclosure subassembly	1	M	2
....4	15039	Tape	4	B	15
....4	15037	Enclosure	1	M	2
.....5	15042	Paint	1	B	4
.....5	15043	Sheet metal	2	B	30
....4	15038	Earth subassembly	1	M	4
.....5	15044	Bolt/nut	1	B	4
.....5	15045	Washer	1	B	4

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	16	Eurosafe transformer 6kV 60mA	1	M	1
.1	16004	Rivet	1	B	15
.1	16005	LAM stack	2	M	1
..2	16013	Lamination	1	B	15
.1	16003	Filling material subassembly	3	M	2
..2	16011	Resin	1	B	10
..2	16012	Activator	1	B	10
.1	16006	Packing subassembly	1	M	1
..2	16017	Carton	6	B	45
..2	16018	Tape	5	B	45
.1	16001	Primary coil	1	M	1
..2	16009	Wire kit	1	B	30
..2	16010	Tape kit	1	B	20
.1	16002	Secondary coil	2	M	1
..2	16014	Strip	1	B	25
..2	16015	Wire kit	1	B	30
..2	16016	Tape kit	1	B	20
..2	16008	Former	2	M	1
...3	16026	Presspahn	1	B	14
.1	16007	Eurosafe control subassembly	1	M	1
..2	16022	Eurosafe open circuit PCB	1	B	14
..2	16019	Spacer	1	B	4
..2	16020	Bracket left	1	M	1
...3	16027	Sheet metal	1	B	4
..2	16021	Bracket right	1	M	1
...3	16028	Sheet metal	1	B	4
..2	16024	Melinex	2	M	1
...3	16031	Melinex roll	1	B	15
..2	16025	Carton subassembly	1	M	1
...3	16032	Tape	1	B	20
...3	16033	Carton	1	B	30
..2	16023	Case subassembly	1	M	1
...3	16029	Lid subassembly	1	M	1
....4	16041	Bolt	2	B	20
....4	16039	Gasket	1	B	30
....4	16040	Lid	1	M	1
.....5	16046	Sheet metal	1	B	4
.....5	16047	Paint	1	B	4
...3	16030	Enclosure subassembly	1	M	1
....4	16036	Tape	3	B	20
....4	16037	Grommet	1	B	20
....4	16038	Thermal transfer label	4	B	15
....4	16034	Enclosure	1	M	1
.....5	16042	Paint	1	B	4
.....5	16043	Sheet metal	2	B	30
....4	16035	Earth subassembly	1	M	1
.....5	16044	Bolt/nut	1	B	4
.....5	16045	Washer	1	B	4

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	17	Eurosafe transformer 10kV 100mA	1	M	2
.1	17004	LAM stack	2	M	1
..2	17015	Lamination	1	B	15
.1	17005	Filling material subassembly	2	M	1
..2	17016	Resin	6	B	45
..2	17017	Activator	6	B	45
.1	17003	Packing subassembly	4	M	2
..2	17010	Carton	1	B	10
..2	17011	Tape	1	B	10
.1	17001	Primary coil	1	M	1
..2	17007	Wire kit	1	B	30
..2	17008	Tape kit	1	B	20
.1	17002	Secondary coil	2	M	1
.2	17012	Strip	1	B	18
..2	17013	Wire kit	1	B	30
..2	17014	Tape kit	1	B	20
..2	17009	Former	2	M	1
...3	17019	Presspahn	1	B	14
.1	17006	Eurosafe control subassembly	1	M	1
..2	17027	Eurosafe open circuit PCB	1	B	14
..2	17025	Spacer	1	B	4
..2	17026	Bracket	2	M	1
...3	17031	Sheet metal	1	B	4
..2	17018	Melinex	2	M	1
...3	17021	Melinex roll	1	B	15
..2	17028	Case subassembly	1	M	1
...3	17020	Enclosure	1	M	1
....4	17022	Paint	1	B	4
....4	17023	Sheet metal	2	B	30
...3	17033	Earth subassembly	1	M	1
....4	17044	Bolt/nut	1	B	4
....4	17045	Washer	2	B	4
...3	17034	Lid	1	M	2
....4	17049	Paint	3	B	4
....4	17050	Sheet metal	1	B	10

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	18	Eurosafe transformer 4kV 120mA	1	M	2
.1	18004	Rivet	1	B	15
.1	18005	LAM stack	2	M	1
..2	18013	Lamination	1	B	15
.1	18006	Filling material subassembly	1	M	1
..2	18016	Resin	6	B	45
..2	18017	Activator	6	B	45
.1	18003	Packing subassembly	3	M	3
..2	18011	Carton	1	B	10
..2	18012	Tape	1	B	10
.1	18001	Primary coil	1	M	1
..2	18009	Wire kit	1	B	30
..2	18010	Tape kit	1	B	20
.1	18002	Secondary coil	2	M	2
..2	18014	Tape kit	1	B	25
..2	18015	Wire kit	1	B	30
..2	18007	Former	2	M	1
...3	18022	Presspahn	1	B	14
.1	18008	Eurosafe control subassembly	1	M	1
..2	18030	Eurosafe open circuit PCB	1	B	14
..2	18027	Spacer	1	B	4
..2	18018	Bracket left	1	M	1
...3	18023	Sheet metal	1	B	4
..2	18019	Bracket right	1	M	1
...3	18024	Sheet metal	1	B	4
..2	18020	Melinex	2	M	1
...3	18026	Melinex roll	1	B	15
..2	18021	Carton subassembly	1	M	1
...3	18028	Tape	1	B	20
...3	18029	Carton	1	B	30
..2	18031	Case subassembly	1	M	1
...3	18025	Lid subassembly	1	M	1
....4	18035	Bolt	2	B	20
....4	18033	Gasket	1	B	30
....4	18034	Lid	1	M	2
.....5	18039	Sheet metal	1	B	4
.....5	18040	Paint	1	B	4
...3	18037	Enclosure subassembly	1	M	1
....4	18032	Enclosure	1	M	1
.....5	18036	Paint	1	B	4
.....5	18038	Sheet metal	2	B	30
....4	18044	Earth subassembly	1	M	3
.....5	18055	Bolt/nut	1	B	4
.....5	18056	Washer	1	B	4

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	19	Eurosafe transformer 2kV 200mA	1	M	1
.1	19006	Rivet	1	B	15
.1	19004	LAM stack	2	M	1
..2	19021	Lamination	1	B	15
.1	19008	Primary coil	1	M	1
..2	19030	Wire kit	1	B	30
..2	19031	Tape kit	1	B	20
.1	19005	Packing subassembly	2	M	1
..2	19022	Carton	1	B	10
..2	19023	Tape	1	B	10
.1	19003	Filling material subassembly	1	M	1
..2	19019	Resin	6	B	45
..2	19020	Activator	5	B	45
.1	19001	Secondary coil	2	M	1
..2	19012	Wire kit	1	B	20
..2	19013	Tape kit	1	B	10
..2	19016	Strip	1	B	4
..2	19007	Former	2	M	1
...3	19024	Presspahn	1	B	14
.1	19002	Eurosafe control subassembly	1	M	1
..2	19014	Eurosafe open circuit PCB	1	B	14
..2	19009	Spacer	1	B	4
..2	19010	Bracket left	1	M	1
...3	19025	Sheet metal	1	B	4
..2	19011	Bracket right	1	M	1
...3	19026	Sheet metal	1	B	4
..2	19017	Melinex	2	M	1
...3	19029	Melinex roll	1	B	15
..2	19018	Carton subassembly	1	M	1
...3	19032	Tape	1	B	20
...3	19033	Carton	1	B	30
..2	19015	Case subassembly	1	M	1
...3	19027	Enclosure subassembly	1	M	1
....4	19036	Tape	3	B	20
....4	19037	Grommet	1	B	20
....4	19038	Thermal transfer label	4	B	15
....4	19034	Enclosure	1	M	1
.....5	19042	Paint	1	B	4
.....5	19043	Sheet metal	2	B	30
....4	19035	Earth subassembly	1	M	2
.....5	19044	Bolt/nut	1	B	4
.....5	19045	Washer	1	B	4
...3	19028	Lid subassembly	1	M	1
....4	19041	Bolt	2	B	20
....4	19039	Gasket	1	B	30
....4	19040	Lid	1	M	1
.....5	19046	Sheet metal	1	B	4
.....5	19047	Paint	1	B	4

Level	PartNo	Description	Quantity/unit	Make(M)/Buy(B)	Lead-time(Days)
0	20	Eurosafe transformer 3kV 25mA	1	M	2
.1	20004	Rivet	1	B	15
.1	20005	LAM stack	1	M	1
..2	20013	Lamination	1	B	15
.1	20001	Primary coil	1	M	1
..2	20010	Wire kit	1	B	20
..2	20012	Tape kit	1	B	4
.1	20003	Packing subassembly	2	M	2
..2	20009	Carton	1	B	10
..2	20011	Tape	1	B	10
.1	20007	Filling material subassembly	1	M	1
..2	20025	Resin	6	B	45
..2	20026	Activator	3	B	45
.1	20002	Secondary coil	1	M	1
..2	20019	Tape kit	1	B	10
..2	20020	Wire kit	1	B	20
..2	20006	Former	2	M	1
...3	20016	Presspahn	1	B	14
.1	20008	Eurosafe control subassembly	1	M	1
..2	20027	Push sprung connector red	1	B	30
..2	20028	Push sprung connector black	1	B	30
..2	20029	Eurosafe open circuit PCB	1	B	14
..2	20014	Melinex	1	M	1
...3	20017	Melinex roll	1	B	15
..2	20015	Carton subassembly	1	M	1
...3	20018	Tape	1	B	20
...3	20022	Carton	1	B	30
..2	20030	Case subassembly	1	M	1
...3	20034	Enclosure subassembly	1	M	1
....4	20042	Tape	1	B	20
....4	20043	Grommet	1	B	20
....4	20044	Thermal transfer label	4	B	15
....4	20023	Earth subassembly	1	M	2
.....5	20032	Bolt/nut	1	B	4
.....5	20033	Washer	1	B	4
....4	20024	Enclosure	1	M	1
.....5	20036	Paint	1	B	4
.....5	20037	Sheet metal	2	B	30
...3	20035	Lid subassembly	1	M	1
....4	20045	Gasket	1	B	30
....4	20047	Bolt	2	B	20
....4	20031	Lid	1	M	2
.....5	20038	Sheet metal	1	B	4
.....5	20039	Paint	1	B	4

MRP spreadsheet

Part No.	19		19001		19002		19003		19004		19005		19006		19008		19012		19013		19016		19007		19009		19010		19011	
Level	0		1		1		1		1		1		1		1		2		2		2		2		2		2		2	
Lead Time	1		1		1		1		1		1		15		1		20		10		4		1		4		1		1	
Qty/Unit	1		2		1		1		2		2		1		1		1		1		1		2		1		1		1	
Days	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR	DD	POR
524		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	0	0	0	0	0	0	0	0	0	0	0	0
525		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
526		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
527		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
528		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
529		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
530		0	0	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
531		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
532		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
533		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
534		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	0	0	0	0	0	0	0	0	0	0
535		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
536		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
537		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
538		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
539		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
540		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	0	0	0	32	0	0	0	0
541		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
542		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
543		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	128	0	0	0	32	0	32
544		0	[illegible]	64	0	32	0	32	0	64	0	64	0	0	0	32	64	0	64	0	64	0	128	0	32	0	32	0	32	0
545		32	64	0	32	0	32	0	64	0	64	0	32	0	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
546	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Part No.	Parent Tag	Order No.	Part Type	Batch Size	Rel Date (mins)	DD (mins)	Part Tag	Child	HoldSeq
19	195460	19546	11901	32	261600	262080	1954619	7	9
19001	1954619	19546	11902	64	261120	261600	1954619001	4	9
19002	1954619	19546	11903	32	261120	261600	1954619002	7	9
19003	1954619	19546	11904	32	261120	261600	1954619003	2	9
19004	1954619	19546	11905	64	261120	261600	1954619004	1	9
19005	1954619	19546	11906	64	261120	261600	1954619005	2	9
19006	1954619	19546	1901	32	254400	261600	1954619006	0	9
19008	1954619	19546	11908	32	261120	261600	1954619008	2	9
19012	1954619001	19546	1903	64	251520	261120	1954619012	0	9
19013	1954619001	19546	1904	64	256320	261120	1954619013	0	9
19016	1954619001	19546	1906	64	259200	261120	1954619016	0	9
19007	1954619001	19546	11907	128	260640	261120	1954619007	1	9
19009	1954619002	19546	1902	32	259200	261120	1954619009	0	9
19010	1954619002	19546	11909	32	260640	261120	1954619010	1	9
19011	1954619002	19546	11910	32	260640	261120	1954619011	1	9

POR input file

Keys:
Parent Tag = Order No. + parent Part No.
Part Tag = Order No. + Part No.
Part Type = Sequence No.
Child = No. of child parts
HoldSeq = Parent holding stations

```
; -------------------- DETERMINISTIC MODEL FILE --------------------
BEGIN;
          CREATE;
          ASSIGN:          PDL = 0; !Assign attribute for calculations
          ASSIGN:          TOTParts = 49659;
ReadNext  READ, MRPFile:
                     PartNo, ParentTag, OrderNo, PartType, BatchSize,
                     ReleaseDate, DueDate, PartTag, Child, HoldSeq;
                     !Read POR from MRP run and additional data

          IF:              (Child == 0);
            ASSIGN:        Category = 0;
                           !Category 0 is assigned to bought-out parts
          ELSEIF:          (Child > 0);
            ASSIGN:        Category = 1;
                           !Category 1 is assigned to made-in parts
          ENDIF;
          IF:              ((PartNo >= 11).AND.(PartNo <= 20));
            ASSIGN:        Category = 2;
                           !Category 2 is assigned to finished products
          ENDIF;

; ---------- PARENT-CHILD RELEASE CONTROL ----------

          IF:              (Child <> 0);
            COUNT:         ParentParts;
            ASSIGN:        NS = HoldSeq;
            DUPLICATE:     1,ReadNext;
            ROUTE;         !Route parent to SDependent stations
          ELSE;
            ASSIGN:        NS = PartType;
            DUPLICATE:     1, ReadNext;
            DELAY:         ReleaseDate - TNOW;
            ROUTE;         !Route child for operations
          ENDIF;

; ========== OPERATIONS SUBMODEL ==========

          STATION,         StationSet;
          ASSIGN:          SetIndex = MemIdx(StationSet,M);
          ASSIGN:          TimeIn = TNOW;
          QUEUE,           QueueSet(SetIndex);
          SEIZE:           MachineSet(SetIndex);

; ---------- RELEASE TIMELINESS ----------

          IF:              (IS == 1);
            ASSIGN:        TARDYREL = TNOW-ReleaseDate;
            IF:            (TARDYREL <= 480);
              ASSIGN:      ReleaseCat = 1;
              COUNT:       OnTimeRel;
            ELSEIF:        (TARDYREL > 480);
              ASSIGN:      ReleaseCat = 2;
              COUNT:       LateRel;
            ENDIF;
          ENDIF;

          DELAY:           SetupTime + (BatchSize * OpTime);
          RELEASE:         MachineSet(SetIndex);
          ROUTE;

; ========== END OF OPERATIONS SUBMODEL ==========

; ---------- PARENT RELEASE CONTROL ----------

          STATION,         SDependentSet;
          ASSIGN:          DsetIndex = MemIdx(SDependentSet,M);
          QUEUE,           DependentQSet(DSetIndex);
          WAIT:            DSetIndex;

CSOP      ASSIGN:          IS = 0;
          ASSIGN:          Child = Child - 1;
          IF:              (Child == 0);
            ASSIGN:        NS = PartType;
            IF:            (ReleaseDate > TNOW);
              DELAY:       ReleaseDate - TNOW;
            ENDIF;
            ROUTE;         !Route parent for operations
          ELSE;
            ROUTE;         !Reroute to SDependent stations
          ENDIF;

; ---------- EXITSYSTEM ----------

Finish    STATION,         ExitSystem;
          TALLY:           FlowTime,Int(ReleaseDate);
          TALLY:           OverallThruTime,Int(TimeIn);

; ---------- RELEASE TIMELINESS AND DELAY COLLECTIONS ----------

          ASSIGN:          TARDYDUE = TNOW-DueDate;

          IF:              (TARDYDUE > 480);
            COUNT:         PartDueLate;
            IF:            (ReleaseCat == 2);
              IF:          (Category == 0);
                ASSIGN:    PDLRLBO = PDLRLBO + 1;
              ELSEIF:      (Category == 1);
                ASSIGN:    PDLRLMI = PDLRLMI + 1;
              ELSEIF:      (Category == 2);
                ASSIGN:    PDLRLFP = PDLRLFP + 1;
              ENDIF;
              COUNT:       PDLRL;
            ELSEIF:        (ReleaseCat == 1);
              IF:          (Category == 0);
                ASSIGN:    PDLROBO = PDLROBO + 1;
              ELSEIF:      (Category == 1);
                ASSIGN:    PDLROMI = PDLROMI + 1;
              ELSEIF:      (Category == 2);
                ASSIGN:    PDLROFP = PDLROFP + 1;
              ENDIF;
              COUNT:       PDLRO;
            ENDIF;
          ELSEIF:          (TARDYDUE < -480);
            COUNT:         PartDueEarly;
            IF:            (ReleaseCat == 2);
              IF:          (Category == 0);
                ASSIGN:    PDERLBO = PDERLBO + 1;
              ELSEIF:      (Category == 1);
                ASSIGN:    PDERLMI = PDERLMI + 1;
              ELSEIF:      (Category == 2);
                ASSIGN:    PDERLFP = PDERLFP + 1;
              ENDIF;
```

```
          COUNT:          PDERL;
        ELSEIF:           (ReleaseCat == 1);
          IF:             (Category == 0);
            ASSIGN:       PDEROBO = PDEROBO + 1;
          ELSEIF:         (Category == 1);
            ASSIGN:       PDEROMI = PDEROMI + 1;
          ELSEIF:         (Category == 2);
            ASSIGN:       PDEROFP = PDEROFP + 1;
          ENDIF;
          COUNT:          PDERO;
        ENDIF;
      ELSEIF:             (TARDYDUE <= 480).AND.(TARDYDUE >= -480);
        COUNT:            PartDueOnTime;
        IF:               (ReleaseCat == 2);
          IF:             (Category == 0);
            ASSIGN:       POTRLBO = POTRLBO + 1;
          ELSEIF:         (Category == 1);
            ASSIGN:       POTRLMI = POTRLMI + 1;
          ELSEIF:         (Category == 2);
            ASSIGN:       POTRLFP = POTRLFP + 1;
          ENDIF;
          COUNT:          POTRL;
        ELSEIF:           (ReleaseCat == 1);
          IF:             (Category == 0);
            ASSIGN:       POTROBO = POTROBO + 1;
          ELSEIF:         (Category == 1);
            ASSIGN:       POTROMI = POTROMI + 1;
          ELSEIF:         (Category == 2);
            ASSIGN:       POTROFP = POTROFP + 1;
          ENDIF;
          COUNT:          POTRO;
        ENDIF;
      ENDIF;

; ---------- SIGNALING PARENT FOR A COMPLETED CHILD ----------

      ASSIGN:             CompletedTag = ParentTag;
      SEARCH,             DependentQSet(HoldSeq):
                          (CompletedTag == PartTag);
      REMOVE:             J, DependentQSet(HoldSeq), CSOP;

; ---------- SIMULATION OUTPUT CALCULATIONS ----------

      COUNT:              TotalParts;
      IF:                 ((NC(TotalParts) == TOTParts));
        ASSIGN:           PDL = (NC(PartDueLate) / TOTParts) * 100;
        ASSIGN:           PDE = (NC(PartDueEarly) / TOTParts) * 100;
        ASSIGN:           POT = (NC(PartDueOnTime) / TOTParts) * 100;

; Formula for Late Release
        ASSIGN:           LTR = (NC(LateRel) / TOTParts) * 100;
        ASSIGN:           OTR = (NC(OnTimeRel) / TOTParts) * 100;
        ASSIGN:           PDLMIO = (PDLRLMI / TOTParts) * 100;
        ASSIGN:           PDLBOO = (PDLRLBO / TOTParts) * 100;
        ASSIGN:           PDLFPO = (PDLRLFP / TOTParts) * 100;
        ASSIGN:           PDEMIO = (PDERLMI / TOTParts) * 100;
        ASSIGN:           PDEBOO = (PDERLBO / TOTParts) * 100;
        ASSIGN:           PDEFPO = (PDERLFP / TOTParts) * 100;
        ASSIGN:           POTMIO = (POTRLMI / TOTParts) * 100;
        ASSIGN:           POTBOO = (POTRLBO / TOTParts) * 100;
        ASSIGN:           POTFPO = (POTRLFP / TOTParts) * 100;

; Formula for Ontime Release
        ASSIGN:           PDLROMIO = (PDLROMI / TOTParts) * 100;
        ASSIGN:           PDLROBOO = (PDLROBO / TOTParts) * 100;
        ASSIGN:           PDLROFPO = (PDLROFP / TOTParts) * 100;
        ASSIGN:           PDEROMIO = (PDEROMI / TOTParts) * 100;
        ASSIGN:           PDEROBOO = (PDEROBO / TOTParts) * 100;
        ASSIGN:           PDEROFPO = (PDEROFP / TOTParts) * 100;
        ASSIGN:           POTROMIO = (POTROMI / TOTParts) * 100;
        ASSIGN:           POTROBOO = (POTROBO / TOTParts) * 100;
        ASSIGN:           POTROFPO = (POTROFP / TOTParts) * 100;

; ---------- WRITE SECTION ----------

        WRITE,            OutOut,"\n\nREP No: %3.0f\n":NREP;
        WRITE,            OutOut,"%%PDL: %5.2f %%PDE: %5.2f %%PDOT: %5.2f
                          %%PRL: %5.2f %%PROT: %5.2f\n\n":
                          PDL, PDE, POT, LTR, OTR;

; PDL and POT and PDE due to PRL
        WRITE,            OutOut,"\n--- PDL     POT     PDE due to RL\n";
        WRITE,            OutOut,"%7.0f %7.0f %7.0f\n":
                          NC(PDLRL), NC(POTRL), NC(PDERL);
        WRITE,            OutOut,"\t   MadeIn   BoughtOut   FinishProduct\n";
        WRITE,            OutOut,"PDL\t%9.0f %11.0f %15.0f\n":
                          PDLRLMI, PDLRLBO, PDLRLFP;
        WRITE,            OutOut,"%%PDLO\t%9.2f %11.2f %15.2f\n":
                          PDLMIO, PDLBOO, PDLFPO;
        WRITE,            OutOut,"POT\t%9.0f %11.0f %15.0f\n":
                          POTRLMI, POTRLBO, POTRLFP;
        WRITE,            OutOut,"%%POTO\t%9.2f %11.2f %15.2f\n":
                          POTMIO, POTBOO, POTFPO;
        WRITE,            OutOut,"PDE\t%9.0f %11.0f %15.0f\n":
                          PDERLMI, PDERLBO, PDERLFP;
        WRITE,            OutOut,"%%PDEO\t%9.2f %11.2f %15.2f\n":
                          PDEMIO, PDEBOO, PDEFPO;

; PDL and POT and PDE due to PRO
        WRITE,            OutOut,"\n--- PDL     POT     PDE due to RO\n";
        WRITE,            OutOut,"%7.0f %7.0f %7.0f\n":
                          NC(PDLRO), NC(POTRO), NC(PDERO);
        WRITE,            OutOut,"\t   MadeIn   BoughtOut   FinishProduct\n";
        WRITE,            OutOut,"PDL\t%9.0f %11.0f %15.0f\n":
                          PDLROMI, PDLROBO, PDLROFP;
        WRITE,            OutOut,"%%PDLO\t%9.2f %11.2f %15.2f\n":
                          PDLROMIO, PDLROBOO, PDLROFPO;
        WRITE,            OutOut,"POT\t%9.0f %11.0f %15.0f\n":
                          POTROMI, POTROBO, POTROFP;
        WRITE,            OutOut,"%%POTO\t%9.2f %11.2f %15.2f\n":
                          POTROMIO, POTROBOO, POTROFPO;
        WRITE,            OutOut,"PDE\t%9.0f %11.0f %15.0f\n":
                          PDEROMI, PDEROBO, PDEROFP;
        WRITE,            OutOut,"%%PDEO\t%9.2f %11.2f %15.2f\n":
                          PDEROMIO, PDEROBOO, PDEROFPO;
      ENDIF;

      DISPOSE;
END;
```

```
BEGIN;

PROJECT,      DETERMINISTIC DOMAIN, SIAU CHING LENNY KOH;

ATTRIBUTES:          PartNo:
                     ParentTag:
                     OrderNo:
                     PartType:
                     BatchSize:
                     ReleaseDate:
                     DueDate:
                     PartTag:
                     Child:
                     HoldSeq:
                     SetIndex:
                     DSetIndex:
                     SetupTime:
                     OpTime:
                     TimeIn:
                     TARDYREL:
                     TARDYDUE:
                     ReleaseCat:
                     Category;

VARIABLES:           CompletedTag:
                     TOTParts:
                     LTR: OTR: PDL: PDE: POT:
                     PDLRLMI: PDLRLBO: PDLRLFP: PDERLMI: PDERLBO: PDERLFP: POTRLMI:
                     POTRLBO: POTRLFP: PDLMIO: PDLBOO: PDLFPO: PDEMIO: PDEBOO: PDEFPO:
                     POTMIO: POTBOO: POTFPO:
                     PDLROMI: PDLROBO: PDLROFP: PDEROMI: PDEROBO: PDEROFP: POTROMI:
                     POTROBO: POTROFP: PDLROMIO: PDLROBOO: PDLROFPO: PDEROMIO: PDEROBOO:
                     PDEROFPO: POTROMIO: POTROBOO: POTROFPO;

QUEUES:        GUILQ:
               BRKPRSQ:
               DRLQ:
               CLRQ:
               ASS1Q:
               ASS2Q:
               ASS3Q:
               ASS4Q:
               FCLRQ:
               TPCHQ:
               WELDQ:
               DBRRQ:
               SCLRQ:
               MIXQ:
               SETTGQ:
               INSQ:
               FIXAQ:
               FIXBQ:
               FIXCQ:
               FIXDQ:
               C11001Q:     }
               C11002Q:     }
               .            }
               .            }  Part number queues
               .            }
               C20045Q:     }
               C20047Q:     }
               DependentQ11:
               DependentQ12:
               DependentQ13:
               DependentQ14:
               DependentQ15:
               DependentQ16:
               DependentQ17:
               DependentQ18:
               DependentQ19:
               DependentQ20;

STATESETS:     GUILState, Working(Busy):
               BRKPRSState, Working(Busy):
               DRLState, Working(Busy):
               CLRState, Working(Busy):
               ASS1State, Working(Busy):
               ASS2State, Working(Busy):
               ASS3State, Working(Busy):
               ASS4State, Working(Busy):
               FCLRState, Working(Busy):
               TPCHState, Working(Busy):
               WELDState, Working(Busy):
               DBRRState, Working(Busy):
               SCLRState, Working(Busy):
               MIXState, Working(Busy):
               SETTGState, Working(Busy):
               INSState, Working(Busy):
               FIXAState, Working(Busy):
               FIXBState, Working(Busy):
               FIXCState, Working(Busy):
               FIXDState, Working(Busy):
               C11001State, Working(Busy):   }
               C11002State, Working(Busy):   }
               .                             }
               .                             }  Part number statesets
               .                             }
               C20045State, Working(Busy):   }
               C20047State, Working(Busy);   }

RESOURCES:     GUIL,1,GUILState:
               BRKPRS,1,BRKPRSState:
               DRL,1,DRLState:
               CLR,4,CLRState:
               ASS1,12,ASS1State:
               ASS2,1,ASS2State:
               ASS3,1,ASS3State:
               ASS4,2,ASS4State:
               FCLR,1,FCLRState:
               TPCH,2,TPCHState:
               WELD,3,WELDState:
               DBRR,1,DBRRState:
               SCLR,1,SCLRState:
               MIX,5,MIXState:
               SETTG,1,SETTGState:
               INS,1,INSState:
               FIXA,1,FIXAState:
               FIXB,1,FIXBState:
               FIXC,2,FIXCState:
               FIXD,2,FIXDState:
               C11001,200,C11001State:   }
               C11002,200,C11002State:   }
               .                         }
               .                         }  Part number resources
               .                         }
               C20045,200,C20045State:   }
               C20047,200,C20047State;   }
```

```
FREQUENCIES: STATE(GUIL), GUIL Statistics,,,Working & Idle,,Exclude:
             STATE(BRKPRS), BRKPRS Statistics,,,Working & Idle,,Exclude:
             STATE(DRL), DRL Statistics,,,Working & Idle,,Exclude:
             STATE(CLR), CLR Statistics,,,Working & Idle,,Exclude:
             STATE(ASS1), ASS1 Statistics,,,Working & Idle,,Exclude:
             STATE(ASS2), ASS2 Statistics,,,Working & Idle,,Exclude:
             STATE(ASS3), ASS3 Statistics,,,Working & Idle,,Exclude:
             STATE(ASS4), ASS4 Statistics,,,Working & Idle,,Exclude:
             STATE(FCLR), FCLR Statistics,,,Working & Idle,,Exclude:
             STATE(TPCH), TPCH Statistics,,,Working & Idle,,Exclude:
             STATE(WELD), WELD Statistics,,,Working & Idle,,Exclude:
             STATE(DBRR), DBRR Statistics,,,Working & Idle,,Exclude:
             STATE(SCLR), SCLR Statistics,,,Working & Idle,,Exclude:
             STATE(MIX), MIX Statistics,,,Working & Idle,,Exclude:
             STATE(SETTG), SETTG Statistics,,,Working & Idle,,Exclude:
             STATE(INS), INS Statistics,,,Working & Idle,,Exclude:
             STATE(FIXA), FIXA Statistics,,,Working & Idle,,Exclude:
             STATE(FIXB), FIXB Statistics,,,Working & Idle,,Exclude:
             STATE(FIXC), FIXC Statistics,,,Working & Idle,,Exclude:
             STATE(FIXD), FIXD Statistics,,,Working & Idle,,Exclude;

STATIONS:    StationGUIL:
             StationBRKPRS:
             StationDRL:
             StationCLR:
             StationASS1:
             StationASS2:
             StationASS3:
             StationASS4:
             StationFCLR:
             StationTPCH:
             StationWELD:
             StationDBRR:
             StationSCLR:
             StationMIX:
             StationSETTG:
             StationINS:
             StationFIXA:
             StationFIXB:
             StationFIXC:
             StationFIXD:
             ExitSystem:
             StationC11001:  }
             StationC11002:  }
             .               }
             .               }  Part number stations
             .               }
             StationC20045:  }
             StationC20047:  }
             SDependent11:
             SDependent12:
             SDependent13:
             SDependent14:
             SDependent15:
             SDependent16:
             SDependent17:
             SDependent18:
             SDependent19:
             SDependent20;

SETS:        StationSet,
                    StationGUIL,
                    StationBRKPRS,
                    StationDRL,
                    StationCLR,
                    StationASS1,
                    StationASS2,
                    StationASS3,
                    StationASS4,
                    StationFCLR,
                    StationTPCH,
                    StationWELD,
                    StationDBRR,
                    StationSCLR,
                    StationMIX,
                    StationSETTG,
                    StationINS,
                    StationFIXA,
                    StationFIXB,
                    StationFIXC,
                    StationFIXD,
                    StationC11001,  }
                    StationC11002,  }
                    .               }
                    .               }  Part number stationsets
                    .               }
                    StationC20045,  }
                    StationC20047:  }
             QueueSet,
                    GUILQ,
                    BRKPRSQ,
                    DRLQ,
                    CLRQ,
                    ASS1Q,
                    ASS2Q,
                    ASS3Q,
                    ASS4Q,
                    FCLRQ,
                    TPCHQ,
                    WELDQ,
                    DBRRQ,
                    SCLRQ,
                    MIXQ,
                    SETTGQ,
                    INSQ,
                    FIXAQ,
                    FIXBQ,
                    FIXCQ,
                    FIXDQ,
                    C11001Q,  }
                    C11002Q,  }
                    .         }
                    .         }  Part number queuesets
                    .         }
                    C20045Q,  }
                    C20047Q:  }
             MachineSet,
                    GUIL,
                    BRKPRS,
                    DRL,
                    CLR,
                    ASS1,
                    ASS2,
                    ASS3,
                    ASS4,
                    FCLR,
                    TPCH,
                    WELD,
```

```
          DBRR,
          SCLR,
          MIX,
          SETTG,
          INS,
          FIXA,
          FIXB,
          FIXC,
          FIXD,
          C11001,  }
          C11002,  }
          .        }
          .        }  Part number machinesets
          .        }
          C20045,  }
          C20047:  }
        SDependentSet,
          SDependent11,
          SDependent12,
          SDependent13,
          SDependent14,
          SDependent15,
          SDependent16,
          SDependent17,
          SDependent18,
          SDependent19,
          SDependent20:
        DependentQSet,
          DependentQ11,
          DependentQ12,
          DependentQ13,
          DependentQ14,
          DependentQ15,
          DependentQ16,
          DependentQ17,
          DependentQ18,
          DependentQ19,
          DependentQ20;

TALLIES:    FlowTime:
            OverallThruTime;

DSTATS:     (NR(GUIL)/1)*100, GUIL Utilisation,"GUILUtil.dat":
            (NR(BRKPRS)/1)*100, BRKPRS Utilisation,"BRKPRSUtil.dat":
            (NR(DRL)/1)*100, DRL Utilisation,"DRLUtil.dat":
            (NR(CLR)/4)*100, CLR Utilisation,"CLRUtil.dat":
            (NR(ASS1)/12)*100, ASS1 Utilisation,"ASS1Util.dat":
            (NR(ASS2)/1)*100, ASS2 Utilisation,"ASS2Util.dat":
            (NR(ASS3)/1)*100, ASS3 Utilisation,"ASS3Util.dat":
            (NR(ASS4)/2)*100, ASS4 Utilisation,"ASS4Util.dat":
            (NR(FCLR)/1)*100, FCLR Utilisation,"FCLRUtil.dat":
            (NR(TPCH)/2)*100, TPCH Utilisation,"TPCHUtil.dat":
            (NR(WELD)/3)*100, WELD Utilisation,"WELDUtil.dat":
            (NR(DBRR)/1)*100, DBRR Utilisation,"DBRRUtil.dat":
            (NR(SCLR)/1)*100, SCLR Utilisation,"SCLRUtil.dat":
            (NR(MIX)/5)*100, MIX Utilisation,"MIXUtil.dat":
            (NR(SETTG)/1)*100, SETTG Utilisation,"SETTGUtil.dat":
            (NR(INS)/1)*100, INS Utilisation,"INSUtil.dat":
            (NR(FIXA)/1)*100, FIXA Utilisation,"FIXAUtil.dat":
            (NR(FIXB)/1)*100, FIXB Utilisation,"FIXBUtil.dat":
            (NR(FIXC)/2)*100, FIXC Utilisation,"FIXCUtil.dat":
            (NR(FIXD)/2)*100, FIXD Utilisation,"FIXDUtil.dat":
            NQ(GUILQ), Buffer GUIL,"GUILQueue.dat":
            NQ(BRKPRSQ), Buffer BRKPRS,"BRKPRSQueue.dat":
            NQ(DRLQ), Buffer DRL,"DRLQueue.dat":
            NQ(CLRQ), Buffer CLR,"CLRQueue.dat":
            NQ(ASS1Q), Buffer ASS1,"ASS1Queue.dat":
            NQ(ASS2Q), Buffer ASS2,"ASS2Queue.dat":
            NQ(ASS3Q), Buffer ASS3,"ASS3Queue.dat":
            NQ(ASS4Q), Buffer ASS4,"ASS4Queue.dat":
            NQ(FCLRQ), Buffer FCLR,"FCLRQueue.dat":
            NQ(TPCHQ), Buffer TPCH,"TPCHQueue.dat":
            NQ(WELDQ), Buffer WELD,"WELDQueue.dat":
            NQ(DBRRQ), Buffer DBRR,"DBRRQueue.dat":
            NQ(SCLRQ), Buffer SCLR,"SCLRQueue.dat":
            NQ(MIXQ), Buffer MIX,"MIXQueue.dat":
            NQ(SETTGQ), Buffer SETTG,"SETTGQueue.dat":
            NQ(INSQ), Buffer INS,"INSQueue.dat":
            NQ(FIXAQ), Buffer FIXA,"FIXAQueue.dat":
            NQ(FIXBQ), Buffer FIXB,"FIXBQueue.dat":
            NQ(FIXCQ), Buffer FIXC,"FIXCQueue.dat":
            NQ(FIXDQ), Buffer FIXD,"FIXDQueue.dat":
            NQ(DependentQ11), Buffer DependentQ11:
            NQ(DependentQ12), Buffer DependentQ12:
            NQ(DependentQ13), Buffer DependentQ13:
            NQ(DependentQ14), Buffer DependentQ14:
            NQ(DependentQ15), Buffer DependentQ15:
            NQ(DependentQ16), Buffer DependentQ16:
            NQ(DependentQ17), Buffer DependentQ17:
            NQ(DependentQ18), Buffer DependentQ18:
            NQ(DependentQ19), Buffer DependentQ19:
            NQ(DependentQ20), Buffer DependentQ20;

COUNTERS:   ParentParts:
            TotalParts:
            PartDueLate:
            PartDueEarly:
            PartDueOnTime:
            OnTimeRel:
            LateRel:
            PDLRL:
            PDERL:
            POTRL:
            PDLRO:
            PDERO:
            POTRO;

SEQUENCES:
; holdseq for madein parts
            1,Hold11, SDependent11:
            2,Hold12, SDependent12:
            3,Hold13, SDependent13:
            4,Hold14, SDependent14:
            5,Hold15, SDependent15:
            6,Hold16, SDependent16:
            7,Hold17, SDependent17:
            8,Hold18, SDependent18:
            9,Hold19, SDependent19:
            10,Hold20, SDependent20:

; boughtout for 11
            1101,Part11001, StationC11001, SetupTime=(14400),OpTime=(0) & ExitSystem:
            1102,Part11002, StationC11002, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1103,Part11003, StationC11003, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1104,Part11007, StationC11007, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1105,Part11008, StationC11008, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1106,Part11009, StationC11009, SetupTime=(9600),OpTime=(0) & ExitSystem:
```

```
        1107,Part11013, StationC11013, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1108,Part11014, StationC11014, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1109,Part11015, StationC11015, SetupTime=(2400),OpTime=(0) & ExitSystem:
        1110,Part11017, StationC11017, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1111,Part11022, StationC11022, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1112,Part11023, StationC11023, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1113,Part11024, StationC11024, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1114,Part11025, StationC11025, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1115,Part11026, StationC11026, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1116,Part11027, StationC11027, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1117,Part11031, StationC11031, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1118,Part11032, StationC11032, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1119,Part11033, StationC11033, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1120,Part11034, StationC11034, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1121,Part11035, StationC11035, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1122,Part11045, StationC11045, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1123,Part11046, StationC11046, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1124,Part11047, StationC11047, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1125,Part11048, StationC11048, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1126,Part11050, StationC11050, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1127,Part11051, StationC11051, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 12
        1201,Part12001, StationC12001, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1202,Part12002, StationC12002, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1203,Part12003, StationC12003, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1204,Part12007, StationC12007, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1205,Part12008, StationC12008, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1206,Part12009, StationC12009, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1207,Part12013, StationC12013, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1208,Part12014, StationC12014, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1209,Part12015, StationC12015, SetupTime=(2400),OpTime=(0) & ExitSystem:
        1210,Part12017, StationC12017, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1211,Part12022, StationC12022, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1212,Part12023, StationC12023, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1213,Part12024, StationC12024, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1214,Part12025, StationC12025, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1215,Part12026, StationC12026, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1216,Part12027, StationC12027, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1217,Part12030, StationC12030, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1218,Part12031, StationC12031, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1219,Part12032, StationC12032, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1220,Part12033, StationC12033, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1221,Part12034, StationC12034, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1222,Part12044, StationC12044, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1223,Part12045, StationC12045, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1224,Part12047, StationC12047, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1225,Part12048, StationC12048, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 13
        1301,Part13004, StationC13004, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1302,Part13008, StationC13008, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1303,Part13009, StationC13009, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1304,Part13011, StationC13011, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1305,Part13012, StationC13012, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1306,Part13013, StationC13013, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1307,Part13014, StationC13014, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1308,Part13015, StationC13015, SetupTime=(12000),OpTime=(0) & ExitSystem:
        1309,Part13016, StationC13016, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1310,Part13017, StationC13017, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1311,Part13018, StationC13018, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1312,Part13019, StationC13019, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1313,Part13022, StationC13022, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1314,Part13026, StationC13026, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1315,Part13027, StationC13027, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1316,Part13028, StationC13028, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1317,Part13031, StationC13031, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1318,Part13032, StationC13032, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1319,Part13033, StationC13033, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1320,Part13034, StationC13034, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1321,Part13036, StationC13036, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1322,Part13039, StationC13039, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1323,Part13040, StationC13040, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1324,Part13041, StationC13041, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1325,Part13042, StationC13042, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1326,Part13043, StationC13043, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1327,Part13044, StationC13044, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1328,Part13045, StationC13045, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 14
        1401,Part14004, StationC14004, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1402,Part14009, StationC14009, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1403,Part14010, StationC14010, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1404,Part14011, StationC14011, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1405,Part14012, StationC14012, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1406,Part14013, StationC14013, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1407,Part14014, StationC14014, SetupTime=(12000),OpTime=(0) & ExitSystem:
        1408,Part14015, StationC14015, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1409,Part14016, StationC14016, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1410,Part14017, StationC14017, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1411,Part14018, StationC14018, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1412,Part14021, StationC14021, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1413,Part14025, StationC14025, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1414,Part14026, StationC14026, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1415,Part14027, StationC14027, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1416,Part14030, StationC14030, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1417,Part14031, StationC14031, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1418,Part14032, StationC14032, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1419,Part14033, StationC14033, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1420,Part14035, StationC14035, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1421,Part14038, StationC14038, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1422,Part14039, StationC14039, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1423,Part14040, StationC14040, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1424,Part14041, StationC14041, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1425,Part14042, StationC14042, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1426,Part14043, StationC14043, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1427,Part14044, StationC14044, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 15
        1501,Part15004, StationC15004, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1502,Part15008, StationC15008, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1503,Part15009, StationC15009, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1504,Part15011, StationC15011, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1505,Part15012, StationC15012, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1506,Part15013, StationC15013, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1507,Part15014, StationC15014, SetupTime=(12000),OpTime=(0) & ExitSystem:
        1508,Part15015, StationC15015, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1509,Part15016, StationC15016, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1510,Part15017, StationC15017, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1511,Part15018, StationC15018, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1512,Part15019, StationC15019, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1513,Part15022, StationC15022, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1514,Part15026, StationC15026, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1515,Part15027, StationC15027, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1516,Part15028, StationC15028, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1517,Part15031, StationC15031, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1518,Part15032, StationC15032, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1519,Part15033, StationC15033, SetupTime=(14400),OpTime=(0) & ExitSystem:
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1520,Part15034, StationC15034, SetupTime=(14400),OpTime=(0) & ExitSystem:
1521,Part15036, StationC15036, SetupTime=(9600),OpTime=(0) & ExitSystem:
1522,Part15039, StationC15039, SetupTime=(7200),OpTime=(0) & ExitSystem:
1523,Part15040, StationC15040, SetupTime=(1920),OpTime=(0) & ExitSystem:
1524,Part15041, StationC15041, SetupTime=(1920),OpTime=(0) & ExitSystem:
1525,Part15042, StationC15042, SetupTime=(1920),OpTime=(0) & ExitSystem:
1526,Part15043, StationC15043, SetupTime=(14400),OpTime=(0) & ExitSystem:
1527,Part15044, StationC15044, SetupTime=(1920),OpTime=(0) & ExitSystem:
1528,Part15045, StationC15045, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 16
1601,Part16004, StationC16004, SetupTime=(7200),OpTime=(0) & ExitSystem:
1602,Part16009, StationC16009, SetupTime=(14400),OpTime=(0) & ExitSystem:
1603,Part16010, StationC16010, SetupTime=(9600),OpTime=(0) & ExitSystem:
1604,Part16011, StationC16011, SetupTime=(4800),OpTime=(0) & ExitSystem:
1605,Part16012, StationC16012, SetupTime=(4800),OpTime=(0) & ExitSystem:
1606,Part16013, StationC16013, SetupTime=(7200),OpTime=(0) & ExitSystem:
1607,Part16014, StationC16014, SetupTime=(12000),OpTime=(0) & ExitSystem:
1608,Part16015, StationC16015, SetupTime=(14400),OpTime=(0) & ExitSystem:
1609,Part16016, StationC16016, SetupTime=(9600),OpTime=(0) & ExitSystem:
1610,Part16017, StationC16017, SetupTime=(21600),OpTime=(0) & ExitSystem:
1611,Part16018, StationC16018, SetupTime=(21600),OpTime=(0) & ExitSystem:
1612,Part16019, StationC16019, SetupTime=(1920),OpTime=(0) & ExitSystem:
1613,Part16022, StationC16022, SetupTime=(6720),OpTime=(0) & ExitSystem:
1614,Part16026, StationC16026, SetupTime=(6720),OpTime=(0) & ExitSystem:
1615,Part16027, StationC16027, SetupTime=(1920),OpTime=(0) & ExitSystem:
1616,Part16028, StationC16028, SetupTime=(1920),OpTime=(0) & ExitSystem:
1617,Part16031, StationC16031, SetupTime=(7200),OpTime=(0) & ExitSystem:
1618,Part16032, StationC16032, SetupTime=(9600),OpTime=(0) & ExitSystem:
1619,Part16033, StationC16033, SetupTime=(14400),OpTime=(0) & ExitSystem:
1620,Part16036, StationC16036, SetupTime=(9600),OpTime=(0) & ExitSystem:
1621,Part16037, StationC16037, SetupTime=(9600),OpTime=(0) & ExitSystem:
1622,Part16038, StationC16038, SetupTime=(7200),OpTime=(0) & ExitSystem:
1623,Part16039, StationC16039, SetupTime=(14400),OpTime=(0) & ExitSystem:
1624,Part16041, StationC16041, SetupTime=(9600),OpTime=(0) & ExitSystem:
1625,Part16042, StationC16042, SetupTime=(1920),OpTime=(0) & ExitSystem:
1626,Part16043, StationC16043, SetupTime=(14400),OpTime=(0) & ExitSystem:
1627,Part16044, StationC16044, SetupTime=(1920),OpTime=(0) & ExitSystem:
1628,Part16045, StationC16045, SetupTime=(4800),OpTime=(0) & ExitSystem:
1629,Part16046, StationC16046, SetupTime=(1920),OpTime=(0) & ExitSystem:
1630,Part16047, StationC16047, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 17
1701,Part17007, StationC17007, SetupTime=(14400),OpTime=(0) & ExitSystem:
1702,Part17008, StationC17008, SetupTime=(9600),OpTime=(0) & ExitSystem:
1703,Part17010, StationC17010, SetupTime=(4800),OpTime=(0) & ExitSystem:
1704,Part17011, StationC17011, SetupTime=(4800),OpTime=(0) & ExitSystem:
1705,Part17012, StationC17012, SetupTime=(8640),OpTime=(0) & ExitSystem:
1706,Part17013, StationC17013, SetupTime=(14400),OpTime=(0) & ExitSystem:
1707,Part17014, StationC17014, SetupTime=(9600),OpTime=(0) & ExitSystem:
1708,Part17015, StationC17015, SetupTime=(7200),OpTime=(0) & ExitSystem:
1709,Part17016, StationC17016, SetupTime=(21600),OpTime=(0) & ExitSystem:
1710,Part17017, StationC17017, SetupTime=(21600),OpTime=(0) & ExitSystem:
1711,Part17019, StationC17019, SetupTime=(6720),OpTime=(0) & ExitSystem:
1712,Part17021, StationC17021, SetupTime=(7200),OpTime=(0) & ExitSystem:
1713,Part17022, StationC17022, SetupTime=(1920),OpTime=(0) & ExitSystem:
1714,Part17023, StationC17023, SetupTime=(14400),OpTime=(0) & ExitSystem:
1715,Part17025, StationC17025, SetupTime=(1920),OpTime=(0) & ExitSystem:
1716,Part17027, StationC17027, SetupTime=(6720),OpTime=(0) & ExitSystem:
1717,Part17031, StationC17031, SetupTime=(1920),OpTime=(0) & ExitSystem:
1718,Part17044, StationC17044, SetupTime=(1920),OpTime=(0) & ExitSystem:
1719,Part17045, StationC17045, SetupTime=(1920),OpTime=(0) & ExitSystem:
1720,Part17049, StationC17049, SetupTime=(1920),OpTime=(0) & ExitSystem:
1721,Part17050, StationC17050, SetupTime=(4800),OpTime=(0) & ExitSystem:

; boughtout for 18
1801,Part18004, StationC18004, SetupTime=(7200),OpTime=(0) & ExitSystem:
1802,Part18009, StationC18009, SetupTime=(14400),OpTime=(0) & ExitSystem:
1803,Part18010, StationC18010, SetupTime=(9600),OpTime=(0) & ExitSystem:
1804,Part18011, StationC18011, SetupTime=(4800),OpTime=(0) & ExitSystem:
1805,Part18012, StationC18012, SetupTime=(4800),OpTime=(0) & ExitSystem:
1806,Part18013, StationC18013, SetupTime=(7200),OpTime=(0) & ExitSystem:
1807,Part18014, StationC18014, SetupTime=(12000),OpTime=(0) & ExitSystem:
1808,Part18015, StationC18015, SetupTime=(14400),OpTime=(0) & ExitSystem:
1809,Part18016, StationC18016, SetupTime=(21600),OpTime=(0) & ExitSystem:
1810,Part18017, StationC18017, SetupTime=(21600),OpTime=(0) & ExitSystem:
1811,Part18022, StationC18022, SetupTime=(6720),OpTime=(0) & ExitSystem:
1812,Part18023, StationC18023, SetupTime=(1920),OpTime=(0) & ExitSystem:
1813,Part18024, StationC18024, SetupTime=(1920),OpTime=(0) & ExitSystem:
1814,Part18026, StationC18026, SetupTime=(7200),OpTime=(0) & ExitSystem:
1815,Part18027, StationC18027, SetupTime=(1920),OpTime=(0) & ExitSystem:
1816,Part18028, StationC18028, SetupTime=(9600),OpTime=(0) & ExitSystem:
1817,Part18029, StationC18029, SetupTime=(14400),OpTime=(0) & ExitSystem:
1819,Part18030, StationC18030, SetupTime=(6720),OpTime=(0) & ExitSystem:
1820,Part18033, StationC18033, SetupTime=(14400),OpTime=(0) & ExitSystem:
1821,Part18035, StationC18035, SetupTime=(9600),OpTime=(0) & ExitSystem:
1822,Part18036, StationC18036, SetupTime=(1920),OpTime=(0) & ExitSystem:
1823,Part18038, StationC18038, SetupTime=(14400),OpTime=(0) & ExitSystem:
1824,Part18039, StationC18039, SetupTime=(1920),OpTime=(0) & ExitSystem:
1825,Part18040, StationC18040, SetupTime=(1920),OpTime=(0) & ExitSystem:
1826,Part18055, StationC18055, SetupTime=(1920),OpTime=(0) & ExitSystem:
1827,Part18056, StationC18056, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 19
1901,Part19006, StationC19006, SetupTime=(7200),OpTime=(0) & ExitSystem:
1902,Part19009, StationC19009, SetupTime=(1920),OpTime=(0) & ExitSystem:
1903,Part19012, StationC19012, SetupTime=(9600),OpTime=(0) & ExitSystem:
1904,Part19013, StationC19013, SetupTime=(4800),OpTime=(0) & ExitSystem:
1905,Part19014, StationC19014, SetupTime=(6720),OpTime=(0) & ExitSystem:
1906,Part19016, StationC19016, SetupTime=(1920),OpTime=(0) & ExitSystem:
1907,Part19019, StationC19019, SetupTime=(21600),OpTime=(0) & ExitSystem:
1908,Part19020, StationC19020, SetupTime=(21600),OpTime=(0) & ExitSystem:
1909,Part19021, StationC19021, SetupTime=(7200),OpTime=(0) & ExitSystem:
1910,Part19022, StationC19022, SetupTime=(4800),OpTime=(0) & ExitSystem:
1911,Part19023, StationC19023, SetupTime=(4800),OpTime=(0) & ExitSystem:
1912,Part19024, StationC19024, SetupTime=(6720),OpTime=(0) & ExitSystem:
1913,Part19025, StationC19025, SetupTime=(1920),OpTime=(0) & ExitSystem:
1914,Part19026, StationC19026, SetupTime=(1920),OpTime=(0) & ExitSystem:
1915,Part19029, StationC19029, SetupTime=(7200),OpTime=(0) & ExitSystem:
1916,Part19030, StationC19030, SetupTime=(14400),OpTime=(0) & ExitSystem:
1917,Part19031, StationC19031, SetupTime=(9600),OpTime=(0) & ExitSystem:
1918,Part19032, StationC19032, SetupTime=(9600),OpTime=(0) & ExitSystem:
1919,Part19033, StationC19033, SetupTime=(14400),OpTime=(0) & ExitSystem:
1920,Part19036, StationC19036, SetupTime=(9600),OpTime=(0) & ExitSystem:
1921,Part19037, StationC19037, SetupTime=(9600),OpTime=(0) & ExitSystem:
1922,Part19038, StationC19038, SetupTime=(7200),OpTime=(0) & ExitSystem:
1923,Part19039, StationC19039, SetupTime=(14400),OpTime=(0) & ExitSystem:
1924,Part19041, StationC19041, SetupTime=(9600),OpTime=(0) & ExitSystem:
1925,Part19042, StationC19042, SetupTime=(1920),OpTime=(0) & ExitSystem:
1926,Part19043, StationC19043, SetupTime=(14400),OpTime=(0) & ExitSystem:
1927,Part19044, StationC19044, SetupTime=(1920),OpTime=(0) & ExitSystem:
1928,Part19045, StationC19045, SetupTime=(4800),OpTime=(0) & ExitSystem:
1929,Part19046, StationC19046, SetupTime=(1920),OpTime=(0) & ExitSystem:
1930,Part19047, StationC19047, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 20
2001,Part20004, StationC20004, SetupTime=(7200),OpTime=(0) & ExitSystem:
2002,Part20009, StationC20009, SetupTime=(4800),OpTime=(0) & ExitSystem:
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2003,Part20010, StationC20010, SetupTime=(9600),OpTime=(0) & ExitSystem:
2004,Part20011, StationC20011, SetupTime=(4800),OpTime=(0) & ExitSystem:
2005,Part20012, StationC20012, SetupTime=(1920),OpTime=(0) & ExitSystem:
2006,Part20013, StationC20013, SetupTime=(7200),OpTime=(0) & ExitSystem:
2007,Part20016, StationC20016, SetupTime=(6720),OpTime=(0) & ExitSystem:
2008,Part20017, StationC20017, SetupTime=(7200),OpTime=(0) & ExitSystem:
2009,Part20018, StationC20018, SetupTime=(9600),OpTime=(0) & ExitSystem:
2010,Part20019, StationC20019, SetupTime=(4800),OpTime=(0) & ExitSystem:
2011,Part20020, StationC20020, SetupTime=(9600),OpTime=(0) & ExitSystem:
2012,Part20022, StationC20022, SetupTime=(14400),OpTime=(0) & ExitSystem:
2013,Part20025, StationC20025, SetupTime=(21600),OpTime=(0) & ExitSystem:
2014,Part20026, StationC20026, SetupTime=(21600),OpTime=(0) & ExitSystem:
2015,Part20027, StationC20027, SetupTime=(14400),OpTime=(0) & ExitSystem:
2016,Part20028, StationC20028, SetupTime=(14400),OpTime=(0) & ExitSystem:
2017,Part20029, StationC20029, SetupTime=(6720),OpTime=(0) & ExitSystem:
2018,Part20032, StationC20032, SetupTime=(1920),OpTime=(0) & ExitSystem:
2019,Part20033, StationC20033, SetupTime=(1920),OpTime=(0) & ExitSystem:
2020,Part20036, StationC20036, SetupTime=(1920),OpTime=(0) & ExitSystem:
2021,Part20037, StationC20037, SetupTime=(14400),OpTime=(0) & ExitSystem:
2022,Part20038, StationC20038, SetupTime=(1920),OpTime=(0) & ExitSystem:
2023,Part20039, StationC20039, SetupTime=(1920),OpTime=(0) & ExitSystem:
2024,Part20042, StationC20042, SetupTime=(9600),OpTime=(0) & ExitSystem:
2025,Part20043, StationC20043, SetupTime=(9600),OpTime=(0) & ExitSystem:
2026,Part20044, StationC20044, SetupTime=(7200),OpTime=(0) & ExitSystem:
2027,Part20045, StationC20045, SetupTime=(14400),OpTime=(0) & ExitSystem:
2028,Part20047, StationC20047, SetupTime=(9600),OpTime=(0) & ExitSystem:

; madein for 11
11101,Part11, StationASS4, SetupTime=(0),OpTime=(4) &
      StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
11102,Part11004, StationMIX, SetupTime=(5),OpTime=(3) &
      StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
11103,Part11005, StationASS1, SetupTime=(0),OpTime=(1.2) &
      StationASS2, SetupTime=(0),OpTime=(1.4) &
      StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11104,Part11006, StationASS1, SetupTime=(0),OpTime=(2) & ExitSystem:
11105,Part11010, StationFIXC, SetupTime=(0),OpTime=(0) &
      StationFIXD, SetupTime=(0),OpTime=(0) &
      StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
      StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
      StationWELD, SetupTime=(0),OpTime=(2.2) &
      StationWELD, SetupTime=(10),OpTime=(2) &
      StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:
11106,Part11011, StationFIXC, SetupTime=(0),OpTime=(0) &
      StationFIXD, SetupTime=(0),OpTime=(0) &
      StationTPCH, SetupTime=(6.5),OpTime=(0.7) &
      StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
      StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
11107,Part11012, StationFIXC, SetupTime=(0),OpTime=(0) &
      StationFIXD, SetupTime=(0),OpTime=(0) &
      StationTPCH, SetupTime=(6.5),OpTime=(0.7) &
      StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
      StationWELD, SetupTime=(0),OpTime=(0.8) &
      StationDBRR, SetupTime=(0),OpTime=(2.2) & ExitSystem:
11108,Part11016, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
11109,Part11018, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11110,Part11019, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11111,Part11020, StationASS1, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11112,Part11021, StationASS1, SetupTime=(0),OpTime=(0.1) & ExitSystem:
11113,Part11028, StationASS1, SetupTime=(0),OpTime=(2.2) & ExitSystem:
11114,Part11029, StationCLR, SetupTime=(5.5),OpTime=(1.5) &
      StationFCLR, SetupTime=(0),OpTime=(0.5) & ExitSystem:
11115,Part11030, StationSCLR, SetupTime=(5.5),OpTime=(1.2) &
      ExitSystem:

; madein for 12
11201,Part12,StationASS4, SetupTime=(0),OpTime=(12) &
      StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
11202,Part12004, StationMIX, SetupTime=(5),OpTime=(3) &
      StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
11203,Part12005, StationASS1, SetupTime=(0),OpTime=(1.2) &
      StationASS2, SetupTime=(0),OpTime=(1.4) &
      StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11204,Part12006, StationASS1, SetupTime=(0),OpTime=(2) & ExitSystem:
11205,Part12010, StationFIXC, SetupTime=(0),OpTime=(0) &
      StationFIXD, SetupTime=(0),OpTime=(0) &
      StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
      StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
      StationWELD, SetupTime=(0),OpTime=(2.2) &
      StationWELD, SetupTime=(10),OpTime=(2) &
      StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:
11206,Part12011, StationFIXC, SetupTime=(0),OpTime=(0) &
      StationFIXD, SetupTime=(0),OpTime=(0) &
      StationTPCH, SetupTime=(6.5),OpTime=(0.7) &
      StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
      StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
11207,Part12012, StationFIXC, SetupTime=(0),OpTime=(0) &
      StationFIXD, SetupTime=(0),OpTime=(0) &
      StationTPCH, SetupTime=(6.5),OpTime=(0.7) &
      StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
      StationWELD, SetupTime=(0),OpTime=(0.8) &
      StationDBRR, SetupTime=(0),OpTime=(2.2) & ExitSystem:
11208,Part12016, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
11209,Part12018, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11210,Part12019, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11211,Part12020, StationASS1, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11212,Part12021, StationASS1, SetupTime=(0),OpTime=(0.1) & ExitSystem:
11213,Part12028, StationCLR, SetupTime=(5.5),OpTime=(1.5) &
      StationFCLR, SetupTime=(0),OpTime=(0.5) & ExitSystem:
11214,Part12029, StationSCLR, SetupTime=(5.5),OpTime=(1.2) & ExitSystem:

; madein for 13
11301,Part13, StationASS4, SetupTime=(0),OpTime=(3.3) &
      StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
11302,Part13001, StationCLR, SetupTime=(5.5),OpTime=(2.5) &
      StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
11303,Part13002, StationCLR, SetupTime=(3.5),OpTime=(3.8) &
      StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11304,Part13003, StationMIX, SetupTime=(5),OpTime=(3) &
      StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
11305,Part13005, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11306,Part13006, StationASS1, SetupTime=(0),OpTime=(1) & ExitSystem:
11307,Part13007, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
11308,Part13010, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
11309,Part13020, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
      StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
      StationFIXA, SetupTime=(0),OpTime=(0) &
      StationFIXB, SetupTime=(0),OpTime=(0) &
      StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11310,Part13021, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
      StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
      StationFIXA, SetupTime=(0),OpTime=(0) &
      StationFIXB, SetupTime=(0),OpTime=(0) &
      StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11311,Part13023, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11312,Part13024, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11313,Part13025, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
11314,Part13029, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
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11315,Part13030, StationASS1, SetupTime=(0),OpTime=(1.3) &
        StationASS2, SetupTime=(0),OpTime=(1) &
        StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11316,Part13035, StationFIXC, SetupTime=(0),OpTime=(0) &
        StationFIXD, SetupTime=(0),OpTime=(0) &
        StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
        StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
11317,Part13037, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
11318,Part13038, StationFIXC, SetupTime=(0),OpTime=(0) &
        StationFIXD, SetupTime=(0),OpTime=(0) &
        StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationWELD, SetupTime=(0),OpTime=(2.2) &
        StationWELD, SetupTime=(10),OpTime=(2) &
        StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:

; madein for 14
11401,Part14, StationASS4, SetupTime=(0),OpTime=(5) &
        StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
11402,Part14001, StationCLR, SetupTime=(5.5),OpTime=(2.5) &
        StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
11403,Part14002, StationCLR, SetupTime=(3.5),OpTime=(3.6) &
        StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11404,Part14003, StationMIX, SetupTime=(5),OpTime=(3) &
        StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
11405,Part14005, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11406,Part14006, StationASS1, SetupTime=(0),OpTime=(1) & ExitSystem:
11407,Part14007, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
11408,Part14008, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
11409,Part14019, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationFIXA, SetupTime=(0),OpTime=(0) &
        StationFIXB, SetupTime=(0),OpTime=(0) &
        StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11410,Part14020, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationFIXA, SetupTime=(0),OpTime=(0) &
        StationFIXB, SetupTime=(0),OpTime=(0) &
        StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11411,Part14022, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11412,Part14023, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11413,Part14024, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
11414,Part14028, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11415,Part14029, StationASS1, SetupTime=(0),OpTime=(1.3) &
        StationASS2, SetupTime=(0),OpTime=(1) &
        StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11416,Part14034, StationFIXC, SetupTime=(0),OpTime=(0) &
        StationFIXD, SetupTime=(0),OpTime=(0) &
        StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
        StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
11417,Part14036, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
11418,Part14037, StationFIXC, SetupTime=(0),OpTime=(0) &
        StationFIXD, SetupTime=(0),OpTime=(0) &
        StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationWELD, SetupTime=(0),OpTime=(2.2) &
        StationWELD, SetupTime=(10),OpTime=(2) &
        StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:

; madein for 15
11501,Part15,StationASS4, SetupTime=(0),OpTime=(3) &
        StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
11502,Part15001, StationCLR, SetupTime=(5.5),OpTime=(2.5) &
        StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
11503,Part15002, StationCLR, SetupTime=(3.5),OpTime=(3.1) &
        StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11504,Part15003, StationMIX, SetupTime=(5),OpTime=(3) &
        StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
11505,Part15005, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11506,Part15006, StationASS1, SetupTime=(0),OpTime=(1) & ExitSystem:
11507,Part15007, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
11508,Part15010, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
11509,Part15020, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationFIXA, SetupTime=(0),OpTime=(0) &
        StationFIXB, SetupTime=(0),OpTime=(0) &
        StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11510,Part15021, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationFIXA, SetupTime=(0),OpTime=(0) &
        StationFIXB, SetupTime=(0),OpTime=(0) &
        StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11511,Part15023, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11512,Part15024, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11513,Part15025, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
11514,Part15029, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11515,Part15030, StationASS1, SetupTime=(0),OpTime=(1.3) &
        StationASS2, SetupTime=(0),OpTime=(1) &
        StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
11516,Part15035, StationFIXC, SetupTime=(0),OpTime=(0) &
        StationFIXD, SetupTime=(0),OpTime=(0) &
        StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
        StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
11517,Part15037, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
11518,Part15038, StationFIXC, SetupTime=(0),OpTime=(0) &
        StationFIXD, SetupTime=(0),OpTime=(0) &
        StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationWELD, SetupTime=(0),OpTime=(2.2) &
        StationWELD, SetupTime=(10),OpTime=(2) &
        StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:

; madein for 16
11601,Part16, StationASS4, SetupTime=(0),OpTime=(8.5) &
        StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
11602,Part16001, StationCLR, SetupTime=(5.5),OpTime=(2.4) &
        StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
11603,Part16002, StationCLR, SetupTime=(3.5),OpTime=(3.6) &
        StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11604,Part16003, StationMIX, SetupTime=(5),OpTime=(3) &
        StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
11605,Part16005, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
11606,Part16006, StationASS1, SetupTime=(0),OpTime=(1.4) & ExitSystem:
11607,Part16007, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
11608,Part16008, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
11609,Part16020, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationFIXA, SetupTime=(0),OpTime=(0) &
        StationFIXB, SetupTime=(0),OpTime=(0) &
        StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
11610,Part16021, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
        StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
        StationFIXA, SetupTime=(0),OpTime=(0) &
        StationFIXB, SetupTime=(0),OpTime=(0) &
        StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
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        11611,Part16023, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11612,Part16024, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11613,Part16025, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        11614,Part16029, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11615,Part16030, StationASS1, SetupTime=(0),OpTime=(1.3) &
              StationASS2, SetupTime=(0),OpTime=(1) &
              StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11616,Part16034, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
        11617,Part16035, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(1.7) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(2.2) &
              StationWELD, SetupTime=(10),OpTime=(2) &
              StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        11618,Part16040, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
              StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:

; madein for 17
        11701,Part17, StationASS4, SetupTime=(0),OpTime=(9) &
              StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
        11702,Part17001, StationCLR, SetupTime=(5.5),OpTime=(3.5) &
              StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
        11703,Part17002, StationCLR, SetupTime=(3.5),OpTime=(4.4) &
              StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11704,Part17003, StationMIX, SetupTime=(5),OpTime=(3) &
              StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
        11705,Part17004, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11706,Part17005, StationASS1, SetupTime=(0),OpTime=(1.6) & ExitSystem:
        11707,Part17006, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
        11708,Part17009, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
        11709,Part17018, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11710,Part17020, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
        11711,Part17026, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11712,Part17028, StationASS1, SetupTime=(0),OpTime=(2.4) &
              StationASS2, SetupTime=(0),OpTime=(2.2) &
              StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11713,Part17033, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
              StationWELD, SetupTime=(0),OpTime=(0.6) &
              StationWELD, SetupTime=(0),OpTime=(2.2) &
              StationDBRR, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11714,Part17034, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(2.3) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(2.5) &
              StationWELD, SetupTime=(10),OpTime=(2) &
              StationDBRR, SetupTime=(0),OpTime=(1.5) & ExitSystem:

; madein for 18
        11801,Part18, StationASS4, SetupTime=(0),OpTime=(4) &
              StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
        11802,Part18001, StationCLR, SetupTime=(5.5),OpTime=(3.5) &
              StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
        11803,Part18002, StationCLR, SetupTime=(3.5),OpTime=(2.9) &
              StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11804,Part18003, StationMIX, SetupTime=(5),OpTime=(3) &
              StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
        11805,Part18005, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11806,Part18006, StationASS1, SetupTime=(0),OpTime=(1.6) & ExitSystem:
        11807,Part18007, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
        11808,Part18008, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
        11809,Part18018, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11810,Part18019, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11811,Part18020, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11812,Part18021, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        11813,Part18025, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11814,Part18031, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11815,Part18032, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
        11816,Part18034, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
              StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
        11817,Part18037, StationASS1, SetupTime=(0),OpTime=(1.3) &
              StationASS2, SetupTime=(0),OpTime=(1) &
              StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11818,Part18044, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(1.9) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(2.2) &
              StationWELD, SetupTime=(10),OpTime=(2) &
              StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:

; madein for 19
        11901,Part19, StationASS4, SetupTime=(0),OpTime=(2) &
              StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
        11902,Part19001, StationCLR, SetupTime=(3.5),OpTime=(3.5) &
              StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11903,Part19002, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
        11904,Part19003, StationASS1, SetupTime=(0),OpTime=(1.4) & ExitSystem:
        11905,Part19004, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11906,Part19005, StationMIX, SetupTime=(5),OpTime=(3) &
              StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
        11907,Part19007, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
        11908,Part19008, StationCLR, SetupTime=(5.5),OpTime=(3) &
              StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
        11909,Part19010, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11910,Part19011, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11911,Part19015, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11912,Part19017, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
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        11913,Part19018, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        11914,Part19027, StationASS1, SetupTime=(0),OpTime=(1.3) &
              StationASS2, SetupTime=(0),OpTime=(1) &
              StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11915,Part19028, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11916,Part19034, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
        11917,Part19035, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(1.7) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(2.2) &
              StationWELD, SetupTime=(10),OpTime=(2) &
              StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        11918,Part19040, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
              StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:

; madein for 20
        12001,Part20, StationASS4, SetupTime=(0),OpTime=(4) &
              StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
        12002,Part20001, StationCLR, SetupTime=(5.5),OpTime=(2.4) &
              StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
        12003,Part20002, StationCLR, SetupTime=(3.5),OpTime=(3.6) &
              StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        12004,Part20003, StationMIX, SetupTime=(5),OpTime=(3) &
              StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
        12005,Part20005, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        12006,Part20006, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
        12007,Part20007, StationASS1, SetupTime=(0),OpTime=(0.9) & ExitSystem:
        12008,Part20008, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
        12009,Part20014, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        12010,Part20015, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        12011,Part20023, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(2.2) &
              StationWELD, SetupTime=(10),OpTime=(2) &
              StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        12012,Part20024, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
        12013,Part20030, StationASS1, SetupTime=(0),OpTime=(1.5) & ExitSystem:
        12014,Part20035, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        12015,Part20031, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
              StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
        12016,Part20034, StationASS1, SetupTime=(0),OpTime=(1.5) & ExitSystem;

FILES:  1, MRPFile,"c:\doeinput\OriRank.txt",SEQ,FRE,DIS:
        2, OutOut,"Results.txt",SEQ,FOR;

REPLICATE, 1,0,...;

END;
```

```
; -------------------- STOCHASTIC MODEL FILE --------------------
BEGIN;
          CREATE;

; ---------- PARAMETERS LEVELS INPUT SECTION ----------

          ASSIGN:        PDL = 0;
          ASSIGN:        TOTParts = 49659;

          ASSIGN:        GP1AP = 0.0122; !Frequency for LDFS
          ASSIGN:        GP1AM = 960; !Magnitude for LDFS
          ASSIGN:        GP1BP = 0.01; !Frequency for INSC
          ASSIGN:        GP1BM = 240; !Magnitude for INSC
          ASSIGN:        GP2P = 0.05; !Frequency for PSE
          ASSIGN:        GP2M = 45; !Magnitude for PSE
          ASSIGN:        GP3P = 0.05; !Frequency for WFL
          ASSIGN:        GP3M = 15; !Magnitude for WLF
          ASSIGN:        GP4P = 0.0025; !Frequency for WFT
          ASSIGN:        GP4M = 5; !Magnitude for WFT
          ASSIGN:        GP5P = 0.10; !Frequency for WFINS
          ASSIGN:        GP5M = 300; !Magnitude for WFINS
          ASSIGN:        GP6P = 0.01; !Frequency for CDC
          ASSIGN:        BSML = 2.9;
                         !Batch size multiplier coefficient (Labour)
          ASSIGN:        BSMM = 2.225;
                         !Batch size multiplier coefficient (Machine)
          ASSIGN:        BSMLabour = 1;
                         !Subjection of BSML to labour resource
          ASSIGN:        BSMMachine = 1;
                         !Subjection of BSMM to machine resource

ReadNext  READ, MRPFile:
                    PartNo, ParentTag, OrderNo, PartType, BatchSize,
                    ReleaseDate, DueDate, PartTag, Child, HoldSeq;

          IF:            (Child == 0);
            ASSIGN:      Category = 0;
          ELSEIF:        (Child > 0);
            ASSIGN:      Category = 1;

; ---------- LA AND MA SUBMODEL ----------

            IF:          (HoldSeq == 1);
              IF:        ((OrderNo == 11534) || (OrderNo == 11462) ||
                         (OrderNo == 11183) || (OrderNo == 11372) ||
                         (OrderNo == 11408) || (OrderNo == 11327) ||
                         (OrderNo == 11255) || (OrderNo == 11471) ||
                         (OrderNo == 11075) || (OrderNo == 11093));
                IF:      (((PartNo == 11) || (PartNo == 11004) ||
                         (PartNo == 11005) || (PartNo == 11006) ||
                         (PartNo == 11016) || (PartNo == 11021) ||
                         (PartNo == 11020) || (PartNo == 11019) ||
                         (PartNo == 11018) || (PartNo == 11028)) &&
                         BSMLabour);
                  !Made-in parts of repeaters that require labour resource
                  ASSIGN:  BatchSize = BatchSize * BSML;
                ELSEIF:  (((PartNo == 11010) || (PartNo == 11011) ||
                         (PartNo == 11012) || (PartNo == 11029) ||
                         (PartNo == 11030)) && BSMMachine);
                  !Made-in parts of repeaters that require machine resource
                  ASSIGN:  BatchSize = BatchSize * BSMM;
                ENDIF;
              ENDIF;
            ELSEIF:      (HoldSeq == 2);
              IF:        ((OrderNo == 12499) || (OrderNo == 12379) ||
                         (OrderNo == 12079) || (OrderNo == 12319) ||
                         (OrderNo == 12289) || (OrderNo == 12169) ||
                         (OrderNo == 12199) || (OrderNo == 12049) ||
                         (OrderNo == 12259) || (OrderNo == 12349));
                IF:      (((PartNo == 12) || (PartNo == 12004) ||
                         (PartNo == 12005) || (PartNo == 12006) ||
                         (PartNo == 12016) || (PartNo == 12018) ||
                         (PartNo == 12019) || (PartNo == 12020) ||
                         (PartNo == 12021)) && BSMLabour);
                  !Made-in parts of repeaters that require labour resource
                  ASSIGN:  BatchSize = BatchSize * BSML;
                ELSEIF:  (((PartNo == 12010) || (PartNo == 12011) ||
                         (PartNo == 12012) || (PartNo == 12028) ||
                         (PartNo == 12029)) && BSMMachine);
                  !Made-in parts of repeaters that require machine resource
                  ASSIGN:  BatchSize = BatchSize * BSMM;
                ENDIF;
              ENDIF;
            ELSEIF:      (HoldSeq == 6);
              IF:        ((OrderNo == 16491) || (OrderNo == 16311) ||
                         (OrderNo == 16371) || (OrderNo == 16511) ||
                         (OrderNo == 16191) || (OrderNo == 16131) ||
                         (OrderNo == 16071) || (OrderNo == 16411) ||
                         (OrderNo == 16431) || (OrderNo == 16111));
                IF:      (((PartNo == 16) || (PartNo == 16003) ||
                         (PartNo == 16005) || (PartNo == 16006) ||
                         (PartNo == 16007) || (PartNo == 16008) ||
                         (PartNo == 16023) || (PartNo == 16024) ||
                         (PartNo == 16025) || (PartNo == 16029) ||
                         (PartNo == 16030) || (PartNo == 16034)) &&
                         BSMLabour);
                  !Made-in parts of repeaters that require labour resource
                  ASSIGN:  BatchSize = BatchSize * BSML;
                ELSEIF:  (((PartNo == 16001) || (PartNo == 16002) ||
                         (PartNo == 16020) || (PartNo == 16021) ||
                         (PartNo == 16040) || (PartNo == 16035)) &&
                         BSMMachine);
                  !Made-in parts of repeaters that require machine resource
                  ASSIGN:  BatchSize = BatchSize * BSMM;
                ENDIF;
              ENDIF;
            ELSEIF:      (HoldSeq == 7);
              IF:        ((OrderNo == 17260) || (OrderNo == 17135) ||
                         (OrderNo == 17225) || (OrderNo == 17070) ||
                         (OrderNo == 17330) || (OrderNo == 17410) ||
                         (OrderNo == 17245) || (OrderNo == 17130) ||
                         (OrderNo == 17460) || (OrderNo == 17155));
                IF:      (((PartNo == 17) || (PartNo == 17003) ||
                         (PartNo == 17004) || (PartNo == 17005) ||
                         (PartNo == 17006) || (PartNo == 17009) ||
                         (PartNo == 17028) || (PartNo == 17018) ||
                         (PartNo == 17020)) && BSMLabour);
                  !Made-in parts of repeaters that require labour resource
                  ASSIGN:  BatchSize = BatchSize * BSML;
                ELSEIF:  (((PartNo == 17001) || (PartNo == 17002) ||
```

```
                    (PartNo == 17026) || (PartNo == 17033) ||
                    (PartNo == 17034)) && BSMMachine);
                !Made-in parts of repeaters that require machine resource
            ASSIGN:   BatchSize = BatchSize * BSMM;
          ENDIF;
        ENDIF;
      ENDIF;
    ENDIF;

    IF:             ((PartNo >= 11) && (PartNo <= 20));
      ASSIGN:       Category = 2;
    ENDIF;

; ---------- CDC SUBMODEL ----------

    IF:             (((PartType >= 11101) && (PartType <= 11214)) ||
                    ((PartType >= 11501) && (PartType <= 11918)));
                    !Ranges of repeaters and strangers
      ASSIGN:       PartType = DISC(1.00 -  GP6P, PartType, 1.00,
                    (PartType + 100000));
        IF:         (PartType > 100000);
          COUNT:    GROUP6;
        ENDIF;
    ENDIF;

; ---------- LDFS SUBMODEL ----------

    ASSIGN:         GPONEA = 0;
    IF:             ((PartType >= 1101) && (PartType <= 2028));
                    !Ranges of bought-out parts
      ASSIGN:       GPONEA = DISC(1.00 - GP1AP, 0, 1.00, GP1AM);
        IF:         (GPONEA > 0);
          COUNT:    GROUP1A;
        ENDIF;
    ENDIF;

; ---------- INSC SUBMODEL ----------

    ASSIGN:         GPONEB = 0;
    ASSIGN:         GPONEB = DISC(1.00 - GP1BP, 0, 1.00, GP1BM);
    IF:             (GPONEB > 0);
      COUNT:        GROUP1B;
    ENDIF;

; ---------- PARENT-CHILD RELEASE CONTROL ----------

    IF:             (Child <> 0);
      COUNT:        ParentParts;
      ASSIGN:       NS = HoldSeq;
      DUPLICATE:    1, ReadNext;
      ROUTE;
    ELSE;
      ASSIGN:       NS = PartType;
      DUPLICATE:    1, ReadNext;
      DELAY:        ReleaseDate + GPONEA + GPONEB - TNOW;
      ROUTE;
    ENDIF;

; ========== OPERATIONS SUBMODEL ==========

    STATION,          StationSet;
    ASSIGN:           SetIndex = MemIdx(StationSet,M);
    ASSIGN:           TimeIn = TNOW;
    QUEUE,            QueueSet(SetIndex);
    SEIZE:            MachineSet(SetIndex);

; ---------- PSE SUBMODEL ----------

    ASSIGN:           GPTWO = 0;
    IF:               (((IS==1) && ((M==1) || (M==4) || (M==14))) ||
                      ((IS==3) && (M==10)));
                      !Subjection to one operation
      ASSIGN:         GPTWO = DISC(1.00 - GP2P, 0, 1.00, GP2M);
        IF:           (GPTWO > 0);
          COUNT:      GROUP2;
        ENDIF;
    ENDIF;

; ---------- WFL SUBMODEL ----------

    ASSIGN:           GPTHREE = 0;
    IF:               (IS==1);
      IF:             ((PartType >= 11101) && (PartType <= 111918));
                      !Ranges of made-in parts
        ASSIGN:       GPTHREE = DISC(1.00 - GP3P, 0, 1.00, GP3M);
          IF:         (GPTHREE > 0);
            COUNT:    GROUP3;
          ENDIF;
      ENDIF;
    ENDIF;

; ---------- WFT SUBMODEL ----------

    ASSIGN:           GPFOUR = 0;
    IF:               ((M==17) || (M==18) || (M==19) || (M==20));
                      !Ranges of tooling resource
      ASSIGN:         GPFOUR = DISC(1.00 - GP4P, 0, 1.00, GP4M);
        IF:           (GPFOUR > 0);
          COUNT:      GROUP4;
        ENDIF;
    ENDIF;

; ---------- WFINS SUBMODEL ----------

    ASSIGN:           GPFIVE = 0;
    IF:               (M==16); !Inspection resource
      ASSIGN:         GPFIVE = DISC(1.00 - GP5P, 0, 1.00, GP5M);
        IF:           (GPFIVE > 0);
          COUNT:      GROUP5;
        ENDIF;
    ENDIF;

; ---------- RELEASE TIMELINESS ----------

    IF:               (IS == 1);
      ASSIGN:         TARDYREL = TNOW - ReleaseDate;
        IF:           (TARDYREL <= 480);
          ASSIGN:     ReleaseCat = 1;
```

```
              COUNT:        OnTimeRel;
            ELSEIF:         (TARDYREL > 480);
              ASSIGN:       ReleaseCat = 2;
              COUNT:        LateRel;
            ENDIF;
          ENDIF;

          DELAY:            SetupTime + (BatchSize * OpTime) + GPTWO + GPTHREE +
                            GPFOUR + GPFIVE;
          RELEASE:          MachineSet(SetIndex);
          ROUTE;

; ========== END OF OPERATIONS SUBMODEL ==========

; ----------- PARENT RELEASE CONTROL ------------

          STATION,          SDependentSet;
          ASSIGN:           DsetIndex = MemIdx(SDependentSet,M);
          QUEUE,            DependentQSet(DSetIndex);
          WAIT:             DSetIndex;

CSOP      ASSIGN:           IS=0;
          ASSIGN:           Child = Child - 1;
          IF:               (Child == 0);
            ASSIGN:         NS = PartType;
              IF:           ((ReleaseDate + GPONEB) > TNOW);
                DELAY:      ReleaseDate + GPONEB - TNOW;
              ENDIF;
              ROUTE;
          ELSE;
            ROUTE;
          ENDIF;

; ---------- EXITSYSTEM ----------

Finish    STATION,          ExitSystem;
          TALLY:            FlowTime,Int(ReleaseDate);
          TALLY:            OverallThruTime,Int(TimeIn);

; ---------- RELEASE TIMELINESS AND DELAY COLLECTIONS ----------

          ASSIGN:           TARDYDUE = TNOW-DueDate;

          IF:               (TARDYDUE > 480);
            COUNT:          PartDueLate;
              IF:           (ReleaseCat == 2);
                IF:         (Category == 0);
                  ASSIGN:   PDLRLBO = PDLRLBO + 1;
                ELSEIF:     (Category == 1);
                  ASSIGN:   PDLRLMI = PDLRLMI + 1;
                ELSEIF:     (Category == 2);
                  ASSIGN:   PDLRLFP = PDLRLFP + 1;
                ENDIF;
                COUNT:      PDLRL;
              ELSEIF:       (ReleaseCat == 1);
                IF:         (Category == 0);
                  ASSIGN:   PDLROBO = PDLROBO + 1;
                ELSEIF:     (Category == 1);
                  ASSIGN:   PDLROMI = PDLROMI + 1;
                ELSEIF:     (Category == 2);
                  ASSIGN:   PDLROFP = PDLROFP + 1;
                ENDIF;
                COUNT:      PDLRO;
              ENDIF;
          ELSEIF:           (TARDYDUE < -480);
            COUNT:          PartDueEarly;
              IF:           (ReleaseCat == 2);
                IF:         (Category == 0);
                  ASSIGN:   PDERLBO = PDERLBO + 1;
                ELSEIF:     (Category == 1);
                  ASSIGN:   PDERLMI = PDERLMI + 1;
                ELSEIF:     (Category == 2);
                  ASSIGN:   PDERLFP = PDERLFP + 1;
                ENDIF;
                COUNT:      PDERL;
              ELSEIF:       (ReleaseCat == 1);
                IF:         (Category == 0);
                  ASSIGN:   PDEROBO = PDEROBO + 1;
                ELSEIF:     (Category == 1);
                  ASSIGN:   PDEROMI = PDEROMI + 1;
                ELSEIF:     (Category == 2);
                  ASSIGN:   PDEROFP = PDEROFP + 1;
                ENDIF;
                COUNT:      PDERO;
              ENDIF;
          ELSEIF:           (TARDYDUE <= 480) && (TARDYDUE >= -480);
            COUNT:          PartDueOnTime;
            IF:             (ReleaseCat == 2);
              IF:           (Category == 0);
                ASSIGN:     POTRLBO = POTRLBO + 1;
              ELSEIF:       (Category == 1);
                ASSIGN:     POTRLMI = POTRLMI + 1;
              ELSEIF:       (Category == 2);
                ASSIGN:     POTRLFP = POTRLFP + 1;
              ENDIF;
              COUNT:        POTRL;
            ELSEIF:         (ReleaseCat == 1);
              IF:           (Category == 0);
                ASSIGN:     POTROBO = POTROBO + 1;
              ELSEIF:       (Category == 1);
                ASSIGN:     POTROMI = POTROMI + 1;
              ELSEIF:       (Category == 2);
                ASSIGN:     POTROFP = POTROFP + 1;
              ENDIF;
              COUNT:        POTRO;
            ENDIF;
          ENDIF;

; ---------- SIGNALING PARENT FOR A COMPLETED CHILD ----------

          ASSIGN:           CompletedTag = ParentTag;
          SEARCH,           DependentQSet(HoldSeq):(CompletedTag == PartTag);
          REMOVE:           J, DependentQSet(HoldSeq), CSOP;

; ---------- SIMULATION OUTPUT CALCULATIONS ----------

          COUNT:            TotalParts;
          IF:               ((NC(TotalParts) == TOTParts));
            ASSIGN:         PDL = (NC(PartDueLate) / TOTParts) * 100;
            ASSIGN:         PDE = (NC(PartDueEarly) / TOTParts) * 100;
```

```
        ASSIGN:         POT = (NC(PartDueOnTime) / TOTParts) * 100;

; Formula for Late Release
        ASSIGN:         LTR = (NC(LateRel) / TOTParts) * 100;
        ASSIGN:         OTR = (NC(OnTimeRel) / TOTParts) * 100;
        ASSIGN:         PDLMIO = (PDLRLMI / TOTParts) * 100;
        ASSIGN:         PDLBOO = (PDLRLBO / TOTParts) * 100;
        ASSIGN:         PDLFPO = (PDLRLFP / TOTParts) * 100;
        ASSIGN:         PDEMIO = (PDERLMI / TOTParts) * 100;
        ASSIGN:         PDEBOO = (PDERLBO / TOTParts) * 100;
        ASSIGN:         PDEFPO = (PDERLFP / TOTParts) * 100;
        ASSIGN:         POTMIO = (POTRLMI / TOTParts) * 100;
        ASSIGN:         POTBOO = (POTRLBO / TOTParts) * 100;
        ASSIGN:         POTFPO = (POTRLFP / TOTParts) * 100;

; Formula for Ontime Release
        ASSIGN:         PDLROMIO = (PDLROMI / TOTParts) * 100;
        ASSIGN:         PDLROBOO = (PDLROBO / TOTParts) * 100;
        ASSIGN:         PDLROFPO = (PDLROFP / TOTParts) * 100;
        ASSIGN:         PDEROMIO = (PDEROMI / TOTParts) * 100;
        ASSIGN:         PDEROBOO = (PDEROBO / TOTParts) * 100;
        ASSIGN:         PDEROFPO = (PDEROFP / TOTParts) * 100;
        ASSIGN:         POTROMIO = (POTROMI / TOTParts) * 100;
        ASSIGN:         POTROBOO = (POTROBO / TOTParts) * 100;
        ASSIGN:         POTROFPO = (POTROFP / TOTParts) * 100;

; ---------- WRITE SECTION ----------

        WRITE,          OutOut,"\n\nREP No: %3.0f\n": NREP;
        WRITE,          OutOut,"%%PDL: %5.2f %%PDE: %5.2f %%PDOT: %5.2f
                        %%PRL: %5.2f %%PROT: %5.2f\n\n":
                        PDL, PDE, POT, LTR, OTR;

; PDL and POT and PDE due to PRL
        WRITE,          OutOut,"\n--- PDL     POT     PDE due to RL\n";
        WRITE,          OutOut,"%7.0f %7.0f %7.0f\n":
                        NC(PDLRL), NC(POTRL), NC(PDERL);
        WRITE,          OutOut,"\t   MadeIn   BoughtOut
FinishProduct\n";
        WRITE,          OutOut,"PDL\t%9.0f %11.0f %15.0f\n":
                        PDLRLMI, PDLRLBO, PDLRLFP;
        WRITE,          OutOut,"%%PDLO\t%9.2f %11.2f %15.2f\n":
                        PDLMIO, PDLBOO, PDLFPO;
        WRITE,          OutOut,"POT\t%9.0f %11.0f %15.0f\n":
                        POTRLMI, POTRLBO, POTRLFP;
        WRITE,          OutOut,"%%POTO\t%9.2f %11.2f %15.2f\n":
                        POTMIO, POTBOO, POTFPO;
        WRITE,          OutOut,"PDE\t%9.0f %11.0f %15.0f\n":
                        PDERLMI, PDERLBO, PDERLFP;
        WRITE,          OutOut,"%%PDEO\t%9.2f %11.2f %15.2f\n":
                        PDEMIO, PDEBOO, PDEFPO;

; PDL and POT and PDE due to PRO
        WRITE,          OutOut,"\n--- PDL     POT     PDE due to RO\n";
        WRITE,          OutOut,"%7.0f %7.0f %7.0f\n":
                        NC(PDLRO), NC(POTRO), NC(PDERO);
        WRITE,          OutOut,"\t   MadeIn   BoughtOut   FinishProduct\n";
        WRITE,          OutOut,"PDL\t%9.0f %11.0f %15.0f\n":
                        PDLROMI, PDLROBO, PDLROFP;
        WRITE,          OutOut,"%%PDLO\t%9.2f %11.2f %15.2f\n":
                        PDLROMIO, PDLROBOO, PDLROFPO;
        WRITE,          OutOut,"POT\t%9.0f %11.0f %15.0f\n":
                        POTROMI, POTROBO, POTROFP;
        WRITE,          OutOut,"%%POTO\t%9.2f %11.2f %15.2f\n":
                        POTROMIO, POTROBOO, POTROFPO;
        WRITE,          OutOut,"PDE\t%9.0f %11.0f %15.0f\n":
                        PDEROMI, PDEROBO, PDEROFP;
        WRITE,          OutOut,"%%PDEO\t%9.2f %11.2f %15.2f\n":
                        PDEROMIO, PDEROBOO, PDEROFPO;
      ENDIF;

      DISPOSE;
END;
```

```
BEGIN;

PROJECT,      STOCHASTIC DOMAIN, SIAU CHING LENNY KOH;

ATTRIBUTES:         PartNo:
                    ParentTag:
                    OrderNo:
                    PartType:
                    BatchSize:
                    ReleaseDate:
                    DueDate:
                    PartTag:
                    Child:
                    HoldSeq:
                    SetIndex:
                    DSetIndex:
                    SetupTime:
                    OpTime:
                    TimeIn:
                    TARDYREL:
                    TARDYDUE:
                    GPONEA:
                    GPONEB:
                    GPTWO:
                    GPTHREE:
                    GPFOUR:
                    GPFIVE:
                    ReleaseCat:
                    Category;

VARIABLES:          CompletedTag:
                    TOTParts:
                    BSML:
                    BSMM:
                    BSMLabour:
                    BSMMachine:
                    GP1AP: GP1AM: GP1BP: GP1BM: GP2P: GP2M: GP3P: GP3M: GP4P: GP4M: GP5P:
                    GP5M: GP6P:
                    LTR: OTR: PDL: PDE: POT:
                    PDLRLMI: PDLRLBO: PDLRLFP: PDERLMI: PDERLBO: PDERLFP: POTRLMI:
                    POTRLBO: POTRLFP: PDLMIO: PDLBOO: PDLFPO: PDEMIO: PDEBOO: PDEFPO:
                    POTMIO: POTBOO: POTFPO:
                    PDLROMI: PDLROBO: PDLROFP: PDEROMI: PDEROBO: PDEROFP: POTROMI:
                    POTROBO: POTROFP: PDLROMIO: PDLROBOO: PDLROFPO: PDEROMIO: PDEROBOO:
                    PDEROFPO: POTROMIO: POTROBOO: POTROFPO;

QUEUES:       GUILQ:
              BRKPRSQ,LIFO:
              DRLQ,LIFO:
              CLRQ:
              ASS1Q,LIFO:
              ASS2Q:
              ASS3Q:
              ASS4Q,LIFO:
              FCLRQ,LIFO:
              TPCHQ:
              WELDQ:
              DBRRQ,LIFO:
              SCLRQ,LIFO:
              MIXQ:
              SETTGQ:
              INSQ:
              FIXAQ:
              FIXBQ:
              FIXCQ:
              FIXDQ:
              C11001Q:  }
              C11002Q:  }
              .         }
              .         }   Part number queues
              .         }
              C20045Q:  }
              C20047Q:  }
              DependentQ11:
              DependentQ12:
              DependentQ13:
              DependentQ14:
              DependentQ15:
              DependentQ16:
              DependentQ17:
              DependentQ18:
              DependentQ19:
              DependentQ20;

RANKINGS:     BRKPRSQ,LIFO:
              DRLQ,LIFO:
              ASS1Q,LIFO:
              ASS4Q,LIFO:
              FCLRQ,LIFO:
              DBRRQ,LIFO:
              SCLRQ,LIFO;

STATESETS:    GUILState, Working(Busy):
              BRKPRSState, Breakdown(FailBRKPRS), Working(Busy):
              DRLState, Working(Busy):
              CLRState, Breakdown(FailCLR), Working(Busy):
              ASS1State, Working(Busy):
              ASS2State, Working(Busy):
              ASS3State, Working(Busy):
              ASS4State, Working(Busy):
              FCLRState, Working(Busy):
              TPCHState, Working(Busy):
              WELDState, Breakdown(FailWELD), Working(Busy):
              DBRRState, Working(Busy):
              SCLRState, Working(Busy):
              MIXState, Working(Busy):
              SETTGState, Working(Busy):
              INSState, Working(Busy):
              FIXAState, Working(Busy):
              FIXBState, Working(Busy):
              FIXCState, Working(Busy):
              FIXDState, Working(Busy):
              C11001State, Working(Busy):  }
              C11002State, Working(Busy):  }
              .                            }
              .                            }   Part number statesets
              .                            }
              C20045State, Working(Busy):  }
              C20047State, Working(Busy);  }

RESOURCES:    GUIL,1,GUILState:
              BRKPRS,1,BRKPRSState,, FAILURE(FailBRKPRS,Preempt):
```

```
                DRL,1,DRLState:
                CLR,4,CLRState,, FAILURE(FailCLR,Preempt):
                ASS1,12,ASS1State:
                ASS2,1,ASS2State:
                ASS3,1,ASS3State:
                ASS4,2,ASS4State:
                FCLR,1,FCLRState:
                TPCH,2,TPCHState:
                WELD,3,WELDState,, FAILURE(FailWELD,Preempt):
                DBRR,1,DBRRState:
                SCLR,1,SCLRState:
                MIX,5,MIXState:
                SETTG,1,SETTGState:
                INS,1,INSState:
                FIXA,1,FIXAState:
                FIXB,1,FIXBState:
                FIXC,2,FIXCState:
                FIXD,2,FIXDState:
                C11001,200,C11001State:  }
                C11002,200,C11002State:  }
                .                        }
                .                        }  Part number resources
                .                        }
                C20045,200,C20045State:  }
                C20047,200,C20047State;  }

FAILURES:       FailBRKPRS, TIME(EXPO(60000),GAMM(300,2),Working):
                FailCLR, TIME(EXPO(24000),GAMM(120,2),Working):
                FailWELD, TIME(EXPO(30000),GAMM(150,2),Working);

FREQUENCIES: STATE(GUIL), GUIL Statistics,,,Working & Idle,,Exclude:
                STATE(BRKPRS), BRKPRS Statistics,,,Breakdown & Working & Idle,,Exclude:
                STATE(DRL), DRL Statistics,,,Working & Idle,,Exclude:
                STATE(CLR), CLR Statistics,,,Breakdown & Working & Idle,,Exclude:
                STATE(ASS1), ASS1 Statistics,,,Working & Idle,,Exclude:
                STATE(ASS2), ASS2 Statistics,,,Working & Idle,,Exclude:
                STATE(ASS3), ASS3 Statistics,,,Working & Idle,,Exclude:
                STATE(ASS4), ASS4 Statistics,,,Working & Idle,,Exclude:
                STATE(FCLR), FCLR Statistics,,,Working & Idle,,Exclude:
                STATE(TPCH), TPCH Statistics,,,Working & Idle,,Exclude:
                STATE(WELD), WELD Statistics,,,Breakdown & Working & Idle,,Exclude:
                STATE(DBRR), DBRR Statistics,,,Working & Idle,,Exclude:
                STATE(SCLR), SCLR Statistics,,,Working & Idle,,Exclude:
                STATE(MIX), MIX Statistics,,,Working & Idle,,Exclude:
                STATE(SETTG), SETTG Statistics,,,Working & Idle,,Exclude:
                STATE(INS), INS Statistics,,,Working & Idle,,Exclude:
                STATE(FIXA), FIXA Statistics,,,Working & Idle,,Exclude:
                STATE(FIXB), FIXB Statistics,,,Working & Idle,,Exclude:
                STATE(FIXC), FIXC Statistics,,,Working & Idle,,Exclude:
                STATE(FIXD), FIXD Statistics,,,Working & Idle,,Exclude;

STATIONS:       StationGUIL:
                StationBRKPRS:
                StationDRL:
                StationCLR:
                StationASS1:
                StationASS2:
                StationASS3:
                StationASS4:
                StationFCLR:
                StationTPCH:
                StationWELD:
                StationDBRR:
                StationSCLR:
                StationMIX:
                StationSETTG:
                StationINS:
                StationFIXA:
                StationFIXB:
                StationFIXC:
                StationFIXD:
                ExitSystem:
                StationC11001:  }
                StationC11002:  }
                .               }
                .               }  Part number stations
                .               }
                StationC20045:  }
                StationC20047:  }
                SDependent11:
                SDependent12:
                SDependent13:
                SDependent14:
                SDependent15:
                SDependent16:
                SDependent17:
                SDependent18:
                SDependent19:
                SDependent20;

SETS:           StationSet,
                      StationGUIL,
                      StationBRKPRS,
                      StationDRL,
                      StationCLR,
                      StationASS1,
                      StationASS2,
                      StationASS3,
                      StationASS4,
                      StationFCLR,
                      StationTPCH,
                      StationWELD,
                      StationDBRR,
                      StationSCLR,
                      StationMIX,
                      StationSETTG,
                      StationINS,
                      StationFIXA,
                      StationFIXB,
                      StationFIXC,
                      StationFIXD,
                      StationC11001,  }
                      StationC11002,  }
                      .               }
                      .               }  Part number stationsets
                      .               }
                      StationC20045,  }
                      StationC20047:  }
                 QueueSet,
                      GUILQ,
                      BRKPRSQ,
                      DRLQ,
```

```
          CLRQ,
          ASS1Q,
          ASS2Q,
          ASS3Q,
          ASS4Q,
          FCLRQ,
          TPCHQ,
          WELDQ,
          DBRRQ,
          SCLRQ,
          MIXQ,
          SETTGQ,
          INSQ,
          FIXAQ,
          FIXBQ,
          FIXCQ,
          FIXDQ,
          C11001Q,  ┐
          C11002Q,  │
          .         │
          .         ├ Part number queuesets
          .         │
          C20045Q,  │
          C20047Q:  ┘
     MachineSet,
          GUIL,
          BRKPRS,
          DRL,
          CLR,
          ASS1,
          ASS2,
          ASS3,
          ASS4,
          FCLR,
          TPCH,
          WELD,
          DBRR,
          SCLR,
          MIX,
          SETTG,
          INS,
          FIXA,
          FIXB,
          FIXC,
          FIXD,
          C11001,   ┐
          C11002,   │
          .         │
          .         ├ Part number machinesets
          .         │
          C20045,   │
          C20047:   ┘
     SDependentSet,
          SDependent11,
          SDependent12,
          SDependent13,
          SDependent14,
          SDependent15,
          SDependent16,
          SDependent17,
          SDependent18,
          SDependent19,
          SDependent20:
     DependentQSet,
          DependentQ11,
          DependentQ12,
          DependentQ13,
          DependentQ14,
          DependentQ15,
          DependentQ16,
          DependentQ17,
          DependentQ18,
          DependentQ19,
          DependentQ20;

TALLIES:  FlowTime:
          OverallThruTime;

DSTATS:   (NR(GUIL)/1)*100, GUIL Utilisation,"GUILUtil.dat":
          (NR(BRKPRS)/1)*100, BRKPRS Utilisation,"BRKPRSUtil.dat":
          (NR(DRL)/1)*100, DRL Utilisation,"DRLUtil.dat":
          (NR(CLR)/4)*100, CLR Utilisation,"CLRUtil.dat":
          (NR(ASS1)/12)*100, ASS1 Utilisation,"ASS1Util.dat":
          (NR(ASS2)/1)*100, ASS2 Utilisation,"ASS2Util.dat":
          (NR(ASS3)/1)*100, ASS3 Utilisation,"ASS3Util.dat":
          (NR(ASS4)/2)*100, ASS4 Utilisation,"ASS4Util.dat":
          (NR(FCLR)/1)*100, FCLR Utilisation,"FCLRUtil.dat":
          (NR(TPCH)/2)*100, TPCH Utilisation,"TPCHUtil.dat":
          (NR(WELD)/3)*100, WELD Utilisation,"WELDUtil.dat":
          (NR(DBRR)/1)*100, DBRR Utilisation,"DBRRUtil.dat":
          (NR(SCLR)/1)*100, SCLR Utilisation,"SCLRUtil.dat":
          (NR(MIX)/5)*100, MIX Utilisation,"MIXUtil.dat":
          (NR(SETTG)/1)*100, SETTG Utilisation,"SETTGUtil.dat":
          (NR(INS)/1)*100, INS Utilisation,"INSUtil.dat":
          (NR(FIXA)/1)*100, FIXA Utilisation,"FIXAUtil.dat":
          (NR(FIXB)/1)*100, FIXB Utilisation,"FIXBUtil.dat":
          (NR(FIXC)/2)*100, FIXC Utilisation,"FIXCUtil.dat":
          (NR(FIXD)/2)*100, FIXD Utilisation,"FIXDUtil.dat":
          NQ(GUILQ), Buffer GUIL,"GUILQueue.dat":
          NQ(BRKPRSQ), Buffer BRKPRS,"BRKPRSQueue.dat":
          NQ(DRLQ), Buffer DRL,"DRLQueue.dat":
          NQ(CLRQ), Buffer CLR,"CLRQueue.dat":
          NQ(ASS1Q), Buffer ASS1,"ASS1Queue.dat":
          NQ(ASS2Q), Buffer ASS2,"ASS2Queue.dat":
          NQ(ASS3Q), Buffer ASS3,"ASS3Queue.dat":
          NQ(ASS4Q), Buffer ASS4,"ASS4Queue.dat":
          NQ(FCLRQ), Buffer FCLR,"FCLRQueue.dat":
          NQ(TPCHQ), Buffer TPCH,"TPCHQueue.dat":
          NQ(WELDQ), Buffer WELD,"WELDQueue.dat":
          NQ(DBRRQ), Buffer DBRR,"DBRRQueue.dat":
          NQ(SCLRQ), Buffer SCLR,"SCLRQueue.dat":
          NQ(MIXQ), Buffer MIX,"MIXQueue.dat":
          NQ(SETTGQ), Buffer SETTG,"SETTGQueue.dat":
          NQ(INSQ), Buffer INS,"INSQueue.dat":
          NQ(FIXAQ), Buffer FIXA,"FIXAQueue.dat":
          NQ(FIXBQ), Buffer FIXB,"FIXBQueue.dat":
          NQ(FIXCQ), Buffer FIXC,"FIXCQueue.dat":
          NQ(FIXDQ), Buffer FIXD,"FIXDQueue.dat":
          NQ(DependentQ11), Buffer DependentQ11:
          NQ(DependentQ12), Buffer DependentQ12:
          NQ(DependentQ13), Buffer DependentQ13:
          NQ(DependentQ14), Buffer DependentQ14:
```

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            NQ(DependentQ15), Buffer DependentQ15:
            NQ(DependentQ16), Buffer DependentQ16:
            NQ(DependentQ17), Buffer DependentQ17:
            NQ(DependentQ18), Buffer DependentQ18:
            NQ(DependentQ19), Buffer DependentQ19:
            NQ(DependentQ20), Buffer DependentQ20;

COUNTERS:   ParentParts:
            TotalParts:
            PartDueLate:
            PartDueEarly:
            PartDueOnTime:
            GROUP1A:
            GROUP1B:
            GROUP2:
            GROUP3:
            GROUP4:
            GROUP5:
            GROUP6:
            OnTimeRel:
            LateRel:
            PDLRL:
            PDERL:
            POTRL:
            PDLRO:
            PDERO:
            POTRO;

SEQUENCES:
; holdseq for madein parts
            1,Hold11, SDependent11:
            2,Hold12, SDependent12:
            3,Hold13, SDependent13:
            4,Hold14, SDependent14:
            5,Hold15, SDependent15:
            6,Hold16, SDependent16:
            7,Hold17, SDependent17:
            8,Hold18, SDependent18:
            9,Hold19, SDependent19:
            10,Hold20, SDependent20:

; boughtout for 11
            1101,Part11001, StationC11001, SetupTime=(14400),OpTime=(0) & ExitSystem:
            1102,Part11002, StationC11002, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1103,Part11003, StationC11003, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1104,Part11007, StationC11007, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1105,Part11008, StationC11008, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1106,Part11009, StationC11009, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1107,Part11013, StationC11013, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1108,Part11014, StationC11014, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1109,Part11015, StationC11015, SetupTime=(2400),OpTime=(0) & ExitSystem:
            1110,Part11017, StationC11017, SetupTime=(7200),OpTime=(0) & ExitSystem:
            1111,Part11022, StationC11022, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1112,Part11023, StationC11023, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1113,Part11024, StationC11024, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1114,Part11025, StationC11025, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1115,Part11026, StationC11026, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1116,Part11027, StationC11027, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1117,Part11031, StationC11031, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1118,Part11032, StationC11032, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1119,Part11033, StationC11033, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1120,Part11034, StationC11034, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1121,Part11035, StationC11035, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1122,Part11045, StationC11045, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1123,Part11046, StationC11046, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1124,Part11047, StationC11047, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1125,Part11048, StationC11048, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1126,Part11050, StationC11050, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1127,Part11051, StationC11051, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 12
            1201,Part12001, StationC12001, SetupTime=(14400),OpTime=(0) & ExitSystem:
            1202,Part12002, StationC12002, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1203,Part12003, StationC12003, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1204,Part12007, StationC12007, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1205,Part12008, StationC12008, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1206,Part12009, StationC12009, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1207,Part12013, StationC12013, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1208,Part12014, StationC12014, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1209,Part12015, StationC12015, SetupTime=(2400),OpTime=(0) & ExitSystem:
            1210,Part12017, StationC12017, SetupTime=(7200),OpTime=(0) & ExitSystem:
            1211,Part12022, StationC12022, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1212,Part12023, StationC12023, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1213,Part12024, StationC12024, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1214,Part12025, StationC12025, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1215,Part12026, StationC12026, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1216,Part12027, StationC12027, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1217,Part12030, StationC12030, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1218,Part12031, StationC12031, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1219,Part12032, StationC12032, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1220,Part12033, StationC12033, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1221,Part12034, StationC12034, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1222,Part12044, StationC12044, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1223,Part12045, StationC12045, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1224,Part12047, StationC12047, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1225,Part12048, StationC12048, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 13
            1301,Part13004, StationC13004, SetupTime=(7200),OpTime=(0) & ExitSystem:
            1302,Part13008, StationC13008, SetupTime=(14400),OpTime=(0) & ExitSystem:
            1303,Part13009, StationC13009, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1304,Part13011, StationC13011, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1305,Part13012, StationC13012, SetupTime=(4800),OpTime=(0) & ExitSystem:
            1306,Part13013, StationC13013, SetupTime=(7200),OpTime=(0) & ExitSystem:
            1307,Part13014, StationC13014, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1308,Part13015, StationC13015, SetupTime=(12000),OpTime=(0) & ExitSystem:
            1309,Part13016, StationC13016, SetupTime=(14400),OpTime=(0) & ExitSystem:
            1310,Part13017, StationC13017, SetupTime=(21600),OpTime=(0) & ExitSystem:
            1311,Part13018, StationC13018, SetupTime=(21600),OpTime=(0) & ExitSystem:
            1312,Part13019, StationC13019, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1313,Part13022, StationC13022, SetupTime=(6720),OpTime=(0) & ExitSystem:
            1314,Part13026, StationC13026, SetupTime=(6720),OpTime=(0) & ExitSystem:
            1315,Part13027, StationC13027, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1316,Part13028, StationC13028, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1317,Part13031, StationC13031, SetupTime=(7200),OpTime=(0) & ExitSystem:
            1318,Part13032, StationC13032, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1319,Part13033, StationC13033, SetupTime=(14400),OpTime=(0) & ExitSystem:
            1320,Part13034, StationC13034, SetupTime=(14400),OpTime=(0) & ExitSystem:
            1321,Part13036, StationC13036, SetupTime=(9600),OpTime=(0) & ExitSystem:
            1322,Part13039, StationC13039, SetupTime=(7200),OpTime=(0) & ExitSystem:
            1323,Part13040, StationC13040, SetupTime=(1920),OpTime=(0) & ExitSystem:
            1324,Part13041, StationC13041, SetupTime=(1920),OpTime=(0) & ExitSystem:
```

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        1325,Part13042, StationC13042, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1326,Part13043, StationC13043, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1327,Part13044, StationC13044, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1328,Part13045, StationC13045, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 14
        1401,Part14004, StationC14004, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1402,Part14009, StationC14009, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1403,Part14010, StationC14010, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1404,Part14011, StationC14011, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1405,Part14012, StationC14012, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1406,Part14013, StationC14013, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1407,Part14014, StationC14014, SetupTime=(12000),OpTime=(0) & ExitSystem:
        1408,Part14015, StationC14015, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1409,Part14016, StationC14016, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1410,Part14017, StationC14017, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1411,Part14018, StationC14018, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1412,Part14021, StationC14021, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1413,Part14025, StationC14025, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1414,Part14026, StationC14026, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1415,Part14027, StationC14027, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1416,Part14030, StationC14030, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1417,Part14031, StationC14031, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1418,Part14032, StationC14032, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1419,Part14033, StationC14033, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1420,Part14035, StationC14035, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1421,Part14038, StationC14038, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1422,Part14039, StationC14039, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1423,Part14040, StationC14040, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1424,Part14041, StationC14041, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1425,Part14042, StationC14042, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1426,Part14043, StationC14043, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1427,Part14044, StationC14044, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 15
        1501,Part15004, StationC15004, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1502,Part15008, StationC15008, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1503,Part15009, StationC15009, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1504,Part15011, StationC15011, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1505,Part15012, StationC15012, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1506,Part15013, StationC15013, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1507,Part15014, StationC15014, SetupTime=(12000),OpTime=(0) & ExitSystem:
        1508,Part15015, StationC15015, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1509,Part15016, StationC15016, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1510,Part15017, StationC15017, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1511,Part15018, StationC15018, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1512,Part15019, StationC15019, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1513,Part15022, StationC15022, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1514,Part15026, StationC15026, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1515,Part15027, StationC15027, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1516,Part15028, StationC15028, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1517,Part15031, StationC15031, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1518,Part15032, StationC15032, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1519,Part15033, StationC15033, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1520,Part15034, StationC15034, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1521,Part15036, StationC15036, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1522,Part15039, StationC15039, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1523,Part15040, StationC15040, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1524,Part15041, StationC15041, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1525,Part15042, StationC15042, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1526,Part15043, StationC15043, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1527,Part15044, StationC15044, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1528,Part15045, StationC15045, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 16
        1601,Part16004, StationC16004, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1602,Part16009, StationC16009, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1603,Part16010, StationC16010, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1604,Part16011, StationC16011, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1605,Part16012, StationC16012, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1606,Part16013, StationC16013, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1607,Part16014, StationC16014, SetupTime=(12000),OpTime=(0) & ExitSystem:
        1608,Part16015, StationC16015, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1609,Part16016, StationC16016, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1610,Part16017, StationC16017, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1611,Part16018, StationC16018, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1612,Part16019, StationC16019, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1613,Part16022, StationC16022, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1614,Part16026, StationC16026, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1615,Part16027, StationC16027, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1616,Part16028, StationC16028, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1617,Part16031, StationC16031, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1618,Part16032, StationC16032, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1619,Part16033, StationC16033, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1620,Part16036, StationC16036, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1621,Part16037, StationC16037, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1622,Part16038, StationC16038, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1623,Part16039, StationC16039, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1624,Part16041, StationC16041, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1625,Part16042, StationC16042, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1626,Part16043, StationC16043, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1627,Part16044, StationC16044, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1628,Part16045, StationC16045, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1629,Part16046, StationC16046, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1630,Part16047, StationC16047, SetupTime=(1920),OpTime=(0) & ExitSystem:

; boughtout for 17
        1701,Part17007, StationC17007, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1702,Part17008, StationC17008, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1703,Part17010, StationC17010, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1704,Part17011, StationC17011, SetupTime=(4800),OpTime=(0) & ExitSystem:
        1705,Part17012, StationC17012, SetupTime=(8640),OpTime=(0) & ExitSystem:
        1706,Part17013, StationC17013, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1707,Part17014, StationC17014, SetupTime=(9600),OpTime=(0) & ExitSystem:
        1708,Part17015, StationC17015, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1709,Part17016, StationC17016, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1710,Part17017, StationC17017, SetupTime=(21600),OpTime=(0) & ExitSystem:
        1711,Part17019, StationC17019, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1712,Part17021, StationC17021, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1713,Part17022, StationC17022, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1714,Part17023, StationC17023, SetupTime=(14400),OpTime=(0) & ExitSystem:
        1715,Part17025, StationC17025, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1716,Part17027, StationC17027, SetupTime=(6720),OpTime=(0) & ExitSystem:
        1717,Part17031, StationC17031, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1718,Part17044, StationC17044, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1719,Part17045, StationC17045, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1720,Part17049, StationC17049, SetupTime=(1920),OpTime=(0) & ExitSystem:
        1721,Part17050, StationC17050, SetupTime=(4800),OpTime=(0) & ExitSystem:

; boughtout for 18
        1801,Part18004, StationC18004, SetupTime=(7200),OpTime=(0) & ExitSystem:
        1802,Part18009, StationC18009, SetupTime=(14400),OpTime=(0) & ExitSystem:
```

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     1803,Part18010,  StationC18010,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1804,Part18011,  StationC18011,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     1805,Part18012,  StationC18012,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     1806,Part18013,  StationC18013,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     1807,Part18014,  StationC18014,  SetupTime=(12000),OpTime=(0)  & ExitSystem:
     1808,Part18015,  StationC18015,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     1809,Part18016,  StationC18016,  SetupTime=(21600),OpTime=(0)  & ExitSystem:
     1810,Part18017,  StationC18017,  SetupTime=(21600),OpTime=(0)  & ExitSystem:
     1811,Part18022,  StationC18022,  SetupTime=(6720),OpTime=(0)  & ExitSystem:
     1812,Part18023,  StationC18023,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1813,Part18024,  StationC18024,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1814,Part18026,  StationC18026,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     1815,Part18027,  StationC18027,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1816,Part18028,  StationC18028,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1817,Part18029,  StationC18029,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     1819,Part18030,  StationC18030,  SetupTime=(6720),OpTime=(0)  & ExitSystem:
     1820,Part18033,  StationC18033,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     1821,Part18035,  StationC18035,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1822,Part18036,  StationC18036,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1823,Part18038,  StationC18038,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     1824,Part18039,  StationC18039,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1825,Part18040,  StationC18040,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1826,Part18055,  StationC18055,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1827,Part18056,  StationC18056,  SetupTime=(1920),OpTime=(0)  & ExitSystem:

; boughtout for 19
     1901,Part19006,  StationC19006,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     1902,Part19009,  StationC19009,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1903,Part19012,  StationC19012,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1904,Part19013,  StationC19013,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     1905,Part19014,  StationC19014,  SetupTime=(6720),OpTime=(0)  & ExitSystem:
     1906,Part19016,  StationC19016,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1907,Part19019,  StationC19019,  SetupTime=(21600),OpTime=(0)  & ExitSystem:
     1908,Part19020,  StationC19020,  SetupTime=(21600),OpTime=(0)  & ExitSystem:
     1909,Part19021,  StationC19021,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     1910,Part19022,  StationC19022,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     1911,Part19023,  StationC19023,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     1912,Part19024,  StationC19024,  SetupTime=(6720),OpTime=(0)  & ExitSystem:
     1913,Part19025,  StationC19025,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1914,Part19026,  StationC19026,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1915,Part19029,  StationC19029,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     1916,Part19030,  StationC19030,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     1917,Part19031,  StationC19031,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1918,Part19032,  StationC19032,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1919,Part19033,  StationC19033,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     1920,Part19036,  StationC19036,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1921,Part19037,  StationC19037,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1922,Part19038,  StationC19038,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     1923,Part19039,  StationC19039,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     1924,Part19041,  StationC19041,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     1925,Part19042,  StationC19042,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1926,Part19043,  StationC19043,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     1927,Part19044,  StationC19044,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1928,Part19045,  StationC19045,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     1929,Part19046,  StationC19046,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     1930,Part19047,  StationC19047,  SetupTime=(1920),OpTime=(0)  & ExitSystem:

; boughtout for 20
     2001,Part20004,  StationC20004,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     2002,Part20009,  StationC20009,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     2003,Part20010,  StationC20010,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     2004,Part20011,  StationC20011,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     2005,Part20012,  StationC20012,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     2006,Part20013,  StationC20013,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     2007,Part20016,  StationC20016,  SetupTime=(6720),OpTime=(0)  & ExitSystem:
     2008,Part20017,  StationC20017,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     2009,Part20018,  StationC20018,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     2010,Part20019,  StationC20019,  SetupTime=(4800),OpTime=(0)  & ExitSystem:
     2011,Part20020,  StationC20020,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     2012,Part20022,  StationC20022,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     2013,Part20025,  StationC20025,  SetupTime=(21600),OpTime=(0)  & ExitSystem:
     2014,Part20026,  StationC20026,  SetupTime=(21600),OpTime=(0)  & ExitSystem:
     2015,Part20027,  StationC20027,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     2016,Part20028,  StationC20028,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     2017,Part20029,  StationC20029,  SetupTime=(6720),OpTime=(0)  & ExitSystem:
     2018,Part20032,  StationC20032,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     2019,Part20033,  StationC20033,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     2020,Part20036,  StationC20036,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     2021,Part20037,  StationC20037,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     2022,Part20038,  StationC20038,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     2023,Part20039,  StationC20039,  SetupTime=(1920),OpTime=(0)  & ExitSystem:
     2024,Part20042,  StationC20042,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     2025,Part20043,  StationC20043,  SetupTime=(9600),OpTime=(0)  & ExitSystem:
     2026,Part20044,  StationC20044,  SetupTime=(7200),OpTime=(0)  & ExitSystem:
     2027,Part20045,  StationC20045,  SetupTime=(14400),OpTime=(0)  & ExitSystem:
     2028,Part20047,  StationC20047,  SetupTime=(9600),OpTime=(0)  & ExitSystem:

; madein for 11
     11101,Part11,  StationASS4,  SetupTime=(0),OpTime=(4) &
            StationINS,  SetupTime=(0),OpTime=(2) & ExitSystem:
     11102,Part11004,  StationMIX,  SetupTime=(5),OpTime=(3) &
            StationSETTG,  SetupTime=(120),OpTime=(0) & ExitSystem:
     11103,Part11005,  StationASS1,  SetupTime=(0),OpTime=(1.2) &
            StationASS2,  SetupTime=(0),OpTime=(1.4) &
            StationASS3,  SetupTime=(0),OpTime=(0.8) & ExitSystem:
     11104,Part11006,  StationASS1,  SetupTime=(0),OpTime=(2) & ExitSystem:
     11105,Part11010,  StationFIXC,  SetupTime=(0),OpTime=(0) &
            StationFIXD,  SetupTime=(0),OpTime=(0) &
            StationTPCH,  SetupTime=(6.5),OpTime=(1.5) &
            StationBRKPRS,  SetupTime=(12),OpTime=(0.4) &
            StationWELD,  SetupTime=(0),OpTime=(2.2) &
            StationWELD,  SetupTime=(10),OpTime=(2) &
            StationDBRR,  SetupTime=(0),OpTime=(1.2) & ExitSystem:
     11106,Part11011,  StationFIXC,  SetupTime=(0),OpTime=(0) &
            StationFIXD,  SetupTime=(0),OpTime=(0) &
            StationTPCH,  SetupTime=(6.5),OpTime=(0.7) &
            StationBRKPRS,  SetupTime=(12),OpTime=(0.4) &
            StationWELD,  SetupTime=(0),OpTime=(2.2) & ExitSystem:
     11107,Part11012,  StationFIXC,  SetupTime=(0),OpTime=(0) &
            StationFIXD,  SetupTime=(0),OpTime=(0) &
            StationTPCH,  SetupTime=(6.5),OpTime=(0.7) &
            StationBRKPRS,  SetupTime=(12),OpTime=(0.4) &
            StationWELD,  SetupTime=(0),OpTime=(0.8) &
            StationDBRR,  SetupTime=(0),OpTime=(2.2) & ExitSystem:
     11108,Part11016,  StationASS1,  SetupTime=(0),OpTime=(4.5) & ExitSystem:
     11109,Part11018,  StationASS1,  SetupTime=(2),OpTime=(0.5) & ExitSystem:
     11110,Part11019,  StationASS1,  SetupTime=(2),OpTime=(0.5) & ExitSystem:
     11111,Part11020,  StationASS1,  SetupTime=(0),OpTime=(0.2) & ExitSystem:
     11112,Part11021,  StationASS1,  SetupTime=(0),OpTime=(0.1) & ExitSystem:
     11113,Part11028,  StationASS1,  SetupTime=(0),OpTime=(2.2) & ExitSystem:
     11114,Part11029,  StationCLR,  SetupTime=(5.5),OpTime=(1.5) &
            StationFCLR,  SetupTime=(0),OpTime=(0.5) & ExitSystem:
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        11115,Part11030, StationSCLR, SetupTime=(5.5),OpTime=(1.2) & ExitSystem:

; madein for 12
        11201,Part12,StationASS4, SetupTime=(0),OpTime=(12) &
              StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
        11202,Part12004, StationMIX, SetupTime=(5),OpTime=(3) &
              StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
        11203,Part12005, StationASS1, SetupTime=(0),OpTime=(1.2) &
              StationASS2, SetupTime=(0),OpTime=(1.4) &
              StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11204,Part12006, StationASS1, SetupTime=(0),OpTime=(2) & ExitSystem:
        11205,Part12010, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(2.2) &
              StationWELD, SetupTime=(10),OpTime=(2) &
              StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        11206,Part12011, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.7) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
        11207,Part12012, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.7) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(0.8) &
              StationDBRR, SetupTime=(0),OpTime=(2.2) & ExitSystem:
        11208,Part12016, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
        11209,Part12018, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11210,Part12019, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11211,Part12020, StationASS1, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11212,Part12021, StationASS1, SetupTime=(0),OpTime=(0.1) & ExitSystem:
        11213,Part12028, StationCLR, SetupTime=(5.5),OpTime=(1.5) &
              StationFCLR, SetupTime=(0),OpTime=(0.5) & ExitSystem:
        11214,Part12029, StationSCLR, SetupTime=(5.5),OpTime=(1.2) & ExitSystem:

; madein for 13
        11301,Part13, StationASS4, SetupTime=(0),OpTime=(3.3) &
              StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
        11302,Part13001, StationCLR, SetupTime=(5.5),OpTime=(2.5) &
              StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
        11303,Part13002, StationCLR, SetupTime=(3.5),OpTime=(3.8) &
              StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11304,Part13003, StationMIX, SetupTime=(5),OpTime=(3) &
              StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
        11305,Part13005, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11306,Part13006, StationASS1, SetupTime=(0),OpTime=(1) & ExitSystem:
        11307,Part13007, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
        11308,Part13010, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
        11309,Part13020, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11310,Part13021, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11311,Part13023, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11312,Part13024, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11313,Part13025, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        11314,Part13029, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11315,Part13030, StationASS1, SetupTime=(0),OpTime=(1.3) &
              StationASS2, SetupTime=(0),OpTime=(1) &
              StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11316,Part13035, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
              StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
        11317,Part13037, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
        11318,Part13038, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationWELD, SetupTime=(0),OpTime=(2.2) &
              StationWELD, SetupTime=(10),OpTime=(2) &
              StationDBRR, SetupTime=(0),OpTime=(1.2) & ExitSystem:

; madein for 14
        11401,Part14, StationASS4, SetupTime=(0),OpTime=(5) &
              StationINS, SetupTime=(0),OpTime=(2) & ExitSystem:
        11402,Part14001, StationCLR, SetupTime=(5.5),OpTime=(2.5) &
              StationFCLR, SetupTime=(0),OpTime=(0.3) & ExitSystem:
        11403,Part14002, StationCLR, SetupTime=(3.5),OpTime=(3.6) &
              StationFCLR, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11404,Part14003, StationMIX, SetupTime=(5),OpTime=(3) &
              StationSETTG, SetupTime=(120),OpTime=(0) & ExitSystem:
        11405,Part14005, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11406,Part14006, StationASS1, SetupTime=(0),OpTime=(1) & ExitSystem:
        11407,Part14007, StationASS1, SetupTime=(0),OpTime=(4.5) & ExitSystem:
        11408,Part14008, StationASS1, SetupTime=(0),OpTime=(0.25) & ExitSystem:
        11409,Part14019, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11410,Part14020, StationGUIL, SetupTime=(6.5),OpTime=(0.2) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
              StationFIXA, SetupTime=(0),OpTime=(0) &
              StationFIXB, SetupTime=(0),OpTime=(0) &
              StationDRL, SetupTime=(0),OpTime=(0.2) & ExitSystem:
        11411,Part14022, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11412,Part14023, StationASS1, SetupTime=(2),OpTime=(0.5) & ExitSystem:
        11413,Part14024, StationASS1, SetupTime=(0),OpTime=(1.2) & ExitSystem:
        11414,Part14028, StationASS1, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11415,Part14029, StationASS1, SetupTime=(0),OpTime=(1.3) &
              StationASS2, SetupTime=(0),OpTime=(1) &
              StationASS3, SetupTime=(0),OpTime=(0.8) & ExitSystem:
        11416,Part14034, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(0.8) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.8) &
              StationWELD, SetupTime=(0),OpTime=(2.2) & ExitSystem:
        11417,Part14036, StationASS1, SetupTime=(0),OpTime=(0.5) & ExitSystem:
        11418,Part14037, StationFIXC, SetupTime=(0),OpTime=(0) &
              StationFIXD, SetupTime=(0),OpTime=(0) &
              StationTPCH, SetupTime=(6.5),OpTime=(1.5) &
              StationBRKPRS, SetupTime=(12),OpTime=(0.4) &
```