

**POLITECNICO DI MILANO**

Scuola di Ingegneria Industriale e dell'Informazione

Corso di Laurea Magistrale in  
Mechanical Engineering



**A MODELLING APPROACH TO ESTIMATE  
THE IMPACT OF PALLETS WITH ZERO  
POINTS CLAMPING IN A FMS**

Relatore: prof. Marcello URGO  
Correlatore: ing. Walter TERKAJ

Tesi di Laurea di:

Giorgio Luigi MOTTA Matr. 836888

**Anno Accademico 2015 – 2016**



# Index

<b>Table of Figures</b> .....	<b>IV</b>
<b>Table of Tables</b> .....	<b>V</b>
<b>Table of Graphs</b> .....	<b>VII</b>
<b>Table of Equations</b> .....	<b>VIII</b>
<b>Abstract</b> .....	<b>IX</b>
<b>Sommario</b> .....	<b>XI</b>
<b>Ampio estratto in lingua italiana</b> .....	<b>XIII</b>
<b>1 Introduction</b> .....	<b>1</b>
1.1 Flexible Manufacturing System .....	1
1.1.1 Types of FMS.....	3
1.2 Reconfigurable Pallet .....	4
1.3 Problem Statement.....	6
1.4 System Modeling.....	7
<b>2 FMS Model</b> .....	<b>11</b>
2.1 FMS Features and Modeling .....	11
2.1 Model definition .....	13
2.2 Model choice .....	14
<b>3 Model Description</b> .....	<b>21</b>
3.1 Introduction .....	21
3.2 Algorithm procedure .....	21
3.3 Features of the FMS modeled.....	22
3.4 Queuing Networks model.....	24
3.5 Features and constraints of the algorithm.....	27
3.5.1 Events classification.....	27
3.5.2 Classification of periods.....	28
<b>4 Transition analysis</b> .....	<b>29</b>
4.1 Introduction .....	29
4.2 Transition between states .....	29

4.2.1	Reconfigurable Transition .....	29
4.2.2	Ghost State.....	35
4.2.3	Demand Fluctuation.....	38
<b>5</b>	<b>Simulation model.....</b>	<b>41</b>
5.1	Java Modelling Tools.....	41
5.2	Integration of algorithm and JMT.....	43
5.3	Simulated time and results acquisition .....	44
5.4	Positions of Jobs in the system .....	49
<b>6</b>	<b>Validation of the model.....</b>	<b>53</b>
6.1	KPI (Key Performance Indicators) .....	53
6.1.1	Throughput and Time Elapsed .....	53
6.1.2	Utilization .....	54
6.1.3	PUT (Pallets Unused over Time).....	55
6.2	Validation Experiments .....	56
6.2.1	Single pallet validation .....	59
6.2.2	Multiple pallets of the same class.....	64
6.2.3	Multiple states with single classes.....	66
6.2.4	Multiple states with multiple classes .....	68
6.3	Conclusion .....	70
<b>7</b>	<b>Performance Evaluation .....</b>	<b>71</b>
7.1	Introduction.....	71
7.2	Performance comparison.....	71
7.2.1	Factorial Experiment .....	74
7.2.2	Factors Description.....	76
7.2.3	Performance Indicators .....	77
7.2.4	Experiments Results (Exploitation Factor).....	79
7.2.5	Experiments Results (Adjusted Throughput) .....	88
7.2.6	Experiments Results (Pallets Unused over Time) .....	92
7.3	Economic Analysis .....	97
7.3.1	Zero Reconfiguration Time Strategy .....	97

7.3.2	Performance Comparison.....	99
7.3.3	Comparison of costs of different production strategies .....	101
7.3.4	Conclusion.....	109
	<b>Conclusion.....</b>	<b>111</b>
	<b>Appendix .....</b>	<b>113</b>
	<b>Bibliography .....</b>	<b>121</b>

# Table of Figures

Figure 1.1 Generic FMS Scheme .....	1
Figure 1.2 Single machine cell with one CNC machining center and parts storage unit.....	3
Figure 1.3 Flexible manufacturing cell with three identical processing stations, a load/unload station, and parts handling system .....	4
Figure 1.4 Tombstone with calibrated holes.....	5
Figure 1.5 Zero point clamp .....	5
Figure 1.6 Tombstone with zero point clamps .....	6
Figure 2.1 Graphical representation of a station in Queueing Theory .....	14
Figure 3.1 Example of succession of periods .....	22
Figure 3.2 Queueing Networks model for FMS (1) .....	24
Figure 3.3 Queueing Networks model for FMS (2) .....	25
Figure 3.4 Blocks' description of type of events .....	27
Figure 4.1 Graph of transitions between two states.....	31
Figure 4.2 Graph of transitions between two states: compatible transitions (B completed) .....	33
Figure 4.3 Graph of transitions between two states: compatible transitions (A completed) .....	34
Figure 4.4 Transitions tree of a simple system .....	36
Figure 4.5 Evolutions of transitions tree to a Ghost State .....	37
Figure 5.1 Graph of Queueing Network Model used in Java Modelling Tools ..	42
Figure 5.2 Logger positions in the model.....	50
Figure 7.1 Example of Zero Reconfiguration Time Strategy .....	98

## Table of Tables

Table 2.1 Short description of methods to solve Queueing Networks with Blocking .....	18
Table 2.2 Review of methods to solve Queueing Networks with Blocking .....	18
Table 3.1 Description of different kinds of periods .....	28
Table 4.1 Sequence of states .....	30
Table 4.2 Description of state 1 (Table 4.1).....	30
Table 4.3 Boolean Possibility Matrix.....	32
Table 4.4 Fluctuating Demand .....	38
Table 5.1 Example of Log file .....	44
Table 5.2 Example of Log file for system Throughput of Class 1 .....	46
Table 5.3 Example of Log file for system Throughput of Class 2.....	46
Table 5.4 Example of input Log file .....	51
Table 5.5 Example of output Log file .....	51
Table 6.1 Service Times of Classes in each Station [minutes] .....	56
Table 6.2 Probabilistic Routing Matrix (Class 1) .....	57
Table 6.3 Probabilistic Routing Matrix (Class 2) .....	57
Table 6.4 Probabilistic Routing Matrix (Class 3) .....	58
Table 6.5 Demand of each Class .....	58
Table 6.6 Capacity of Queues .....	58
Table 6.7 Possibility Matrix .....	59
Table 6.8 Throughput and Time Elapsed over runs (Single pallet) .....	60
Table 6.9 Utilization of Machines (Single Pallet).....	61
Table 6.10 Mean Statistical Value of Throughput and Utilization (Single Pallet) .....	62
Table 6.11 Mean Statistical Values (Multiple Pallets).....	64
Table 6.12 States compositions (Multiple states with single classes).....	66
Table 6.13 Pallets Unused over Time (Multiple States with single classes) .....	66
Table 6.14 Throughput and Duration over periods (Multiple States with single classes) .....	67
Table 6.15 Utilization of machines over periods (Multiple States with single classes) .....	67
Table 6.16 States composition (Multiple States with multiple classes).....	68
Table 6.17 Pallets Unused Time (Multiple States with multiple classes).....	68
Table 6.18 Throughput and Duration over periods (Multiple States with multiple classes) .....	69
Table 6.19 Utilization of machines (Multiple States with multiple classes).....	69
Table 6.20 Periods Composition (Multiple States with multiple classes) .....	70

Table 7.1 Fixed data for experiments .....	72
Table 7.2 Fixed Possibility Matrix for experiments .....	72
Table 7.3 Fixed Carrier and L/U Service Times for experiments .....	73
Table 7.4 Fixed Capacity of queues for experiments .....	73
Table 7.5 Fixed Probabilistic Routing Matrix for experiments.....	73
Table 7.6 2 <sup>k</sup> Factorial Plan.....	75
Table 7.7 Factors Levels (Factors NS - K - NC - RD - TREC).....	76
Table 7.8 Factors Levels (Factor TMAC) .....	76
Table 7.9 Experiments Results (Exploitation Factor) .....	81
Table 7.10 Experiments Results (Adjusted Throughput) .....	88
Table 7.11 Experiments Results (PUT %).....	93
Table 7.12 Couples of Performance Samples with 20 and 0 minutes of TREC (Adjusted Throughput) .....	100
Table 7.13 Extra Pallets percentages of replicates .....	102
Table 7.14 Descriptive Statistics of $\Delta K\%$ .....	103
Table 7.15 Exact Probabilities for $\Delta MC$ values chosen .....	109



## Table of Graphs

Graph 5.1 Throughput plot for both classes .....	48
Graph 5.2 Pieces-over-Time plot for both classes .....	48
Graph 6.1 Throughput Plot .....	61
Graph 6.2 Utilization Plot (Single Pallet) .....	62
Graph 6.3 Throughput Plot (Multiple Pallets) .....	64
Graph 6.4 Utilization of machines (Multiple pallets) .....	65
Graph 7.1 Main Effects Plot (Exploitation Factor) .....	82
Graph 7.2 Interaction Plot (Exploitation Factor) .....	82
Graph 7.3 Main Effects Plot (Adjusted Throughput).....	89
Graph 7.4 Interactions Plot (Adjusted Throughput).....	89
Graph 7.5 Approximated Model for Adjusted Throughput .....	92
Graph 7.6 Main Effects Plot (PUT %) .....	94
Graph 7.7 Interaction Plot (PUT %) .....	94
Graph 7.8 Differential Cost .....	104
Graph 7.9 Differential Cost Plot ( $\Delta K\%$ min = 0.66) .....	105
Graph 7.10 Differential Cost Plot ( $\Delta K\%$ mean = 0.92) .....	105
Graph 7.11 Differential Cost Plot ( $\Delta K\%$ max = 1.00).....	106
Graph 7.12 Region of Profitability of Zero Points Clamping .....	107
Graph 7.13 Cumulative Probability Plot of $\Delta K\%$ .....	108
Graph 7.14 Probability that zero points are the best choice, in function of $\Delta MC$ .....	109

## Table of Equations

Equation 3.1 Traffic Equations.....	26
Equation 5.1 Evaluation of jobs left in a station.....	50
Equation 6.1 Throughput .....	54
Equation 6.2 Utilization.....	54
Equation 6.3 Pallets Unused over Time .....	55
Equation 6.4 PUT Percentage.....	55
Equation 6.5 Expected Cycle Time .....	63
Equation 7.1 Reference Machining Rate (RMR) .....	78
Equation 7.2 Mean Machining Rate (MMR).....	78
Equation 7.3 Adjusted Throughput (THadj).....	78
Equation 7.4 Exploitation Factor (EF).....	79
Equation 7.5 Approximated Model for Adjusted Throughput .....	91
Equation 7.6 System of Equations for Cost Analysis.....	102
Equation 7.7 Differential Cost equation for Cost Analysis .....	103

# Abstract

This thesis is mainly concerned with assessment of benefits brought by the employment of a new innovative type of pallet for Flexible Manufacturing Systems. This pallet is characterized by peculiar clamps, called zero points, able to decrease considerably the time needed for reconfiguration of the pallet itself. This analysis could be useful for those companies interested in investing in this type of production system.

The main aspect of the thesis is the evaluation of performances of the FMS applying these modern pallets. A tool done for this purpose has been built: it divides the whole production campaign in periods, using an algorithm. A simulation software evaluates performances of each period. The algorithm is implemented in MATLAB software, while the simulation is conducted by Java Modelling Tools, a software developed by Politecnico di Milano.

Several evaluations have been conducted to compare performances achieved using zero points with standard pallets' ones. The comparison is realized with a statistical analysis, the ANOVA test. It is demonstrated that performances are better when the FMS works with modern pallets. A linear model is built to describe the increment of throughput in function of the reconfiguration time.

Then the thesis concerns an additional performance comparison between throughputs achieved with zero points clamps and the highest ones reachable with standard pallets. This comparison proves that there are no differences in throughputs. The research ends with an economic analysis demonstrating that modern pallets are preferable in many cases.

Key words: Flexible Manufacturing System, performance evaluation, pallet, zero points



## Sommario

Questa tesi riguarda principalmente la valutazione dell'impatto di un nuovo innovativo tipo di pallet sulle prestazioni dei sistemi di produzione flessibili (Flexible Manufacturing Systems). Questo pallet è caratterizzato da prese particolari, chiamate zero points, in grado di ridurre notevolmente il tempo necessario per la riconfigurazione del pallet stesso. Questa analisi potrebbe essere utile ad aziende interessate ad investire in questo tipo di sistema di produzione.

L'aspetto principale della ricerca è la valutazione delle prestazioni del sistema di produzione FMS al fine di stimare i possibili benefici portati dai moderni pallet. È stato appositamente costruito uno strumento di modellazione: esso suddivide la campagna di produzione in periodi, tramite un algoritmo. Per ogni periodo viene condotta una valutazione delle prestazioni tramite un software di simulazione. L'algoritmo è implementato nel software MATLAB, mentre la simulazione è condotta da Java Modelling Tools, un software sviluppato dal Politecnico di Milano.

Sono stati effettuati diversi esperimenti per confrontare le prestazioni ottenute con gli zero points con quelle ottenute con i pallet standard. Il confronto è stato realizzato con un'analisi statistica, il test ANOVA. È stato, quindi, dimostrato che le prestazioni sono migliori quando il sistema lavora con pallet moderni. In seguito è stato costruito un modello lineare per descrivere l'incremento della velocità di produzione in funzione del tempo di riconfigurazione.

La tesi si conclude con un confronto delle velocità di produzione ottenute con gli zero points rispetto alle massime raggiungibili con pallet standard. Questo confronto dimostra che non ci sono differenze di velocità. Infine è stata condotta un'analisi economica che dimostra che i pallet moderni sono preferibili in molti casi realistici.

Parole chiave: Flexible Manufacturing System, valutazione delle prestazioni, pallet, zero points



## Ampio estratto in lingua italiana

La tesi riguarda la valutazione delle prestazioni di un sistema FMS, al fine di stimare i possibili benefici portati dall'utilizzo di un pallet di nuova generazione. Un FMS è un sistema di produzione basato su macchine utensili automatizzate, collegate tra loro da un trasportatore. I pallet sono le strutture che vengono movimentate tra le stazioni, sulla quale sono supportati i pezzi da lavorare tramite determinati agganci e prese. Il progetto mira a valutare l'effetto dell'utilizzo di particolari prese, chiamate zero points: esse permettono di riconfigurare il pallet, quindi modificarne il setup per sostenere parti diverse, molto più velocemente rispetto ai pallet standard.

Per la valutazione delle performance è necessario un modello in grado di riprodurre l'andamento della produzione nel FMS e la riconfigurazione dei pallet. Un metodo ampiamente utilizzato per la valutazione di sistemi di questo tipo è il modello a reti di code (Queueing Networks): è un modello analitico basato su stazioni interconnesse tra loro, ognuna composta da uno o più server e da una coda. Sono stati analizzati diversi modelli di Queueing Networks al fine di selezionarne uno aderente al sistema in questione: le caratteristiche principali richieste sono la presenza di blocking (code a capacità finita) e la possibilità di riconfigurazione. Mentre il blocking è presente in diversi modelli, la riconfigurazione dei "clienti", cioè la modifica delle loro caratteristiche, è attuabile solo con un metodo probabilistico, che non rispecchia il vero andamento di un FMS.

La riconfigurazione dei pallet è stata valutata tramite un particolare algoritmo sviluppato in ambiente MATLAB. Esso divide la campagna di produzione in periodi, ognuno dei quali riproduce la lavorazione di una particolare composizione di pallet nel sistema. Le diverse configurazioni dei pallet sono chiamate "classi" ed ognuna di esse ha una richiesta di produzione. L'algoritmo valuta la composizione e la durata dei periodi basandosi sui risultati delle valutazioni delle prestazioni effettuate sui singoli periodi: ogni periodo finisce quando la domanda di una classe di pallet è stata soddisfatta. I pallet terminati vengono quindi riconfigurati, i rimanenti continuano la produzione fino al loro reinserimento nel sistema. Un esempio è visibile in Figura 1: ogni riga corrisponde a un pallet ed ogni lettera ad una classe. La timeline scandisce il tipo di periodi: semplice (S), cioè di durata variabile in base alla richiesta di produzione, e di riconfigurazione (R), cioè di durata fissata pari al tempo di riconfigurazione dei pallet estratti dal sistema precedentemente.

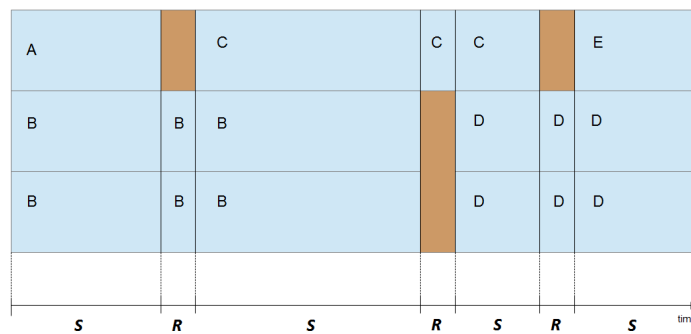


Figura 1 Esempio di successione dei periodi produttivi

La campagna di produzione è stabilita da una successione di stati predefiniti: ognuno rappresenta un periodo con una particolare composizione di classi di pallet attraverso il quale il sistema deve obbligatoriamente passare. L'algoritmo determina le riconfigurazioni in base a questo input.

La valutazione delle prestazioni dei singoli periodi non può essere effettuata con metodi analitici, in quanto essi calcolano le performance del sistema a regime. La condizione di regime non è verificabile per i singoli periodi, data la loro durata variabile. Per questo motivo è stato adottato Java Modelling Tools, un software di simulazione basato sulle reti di code, opportunamente integrato con MATLAB, in grado di valutare le prestazioni del sistema ad un tempo definito.

Lo strumento di valutazione delle prestazioni è, quindi, composto da un algoritmo per dividere la produzione in periodi e da un software di simulazione per valutare le performance dei singoli periodi. È stato validato tramite casi semplici per verificare l'affidabilità dei risultati.

È stata progettata ed effettuata una campagna sperimentale utilizzando lo strumento costruito: essa è atta a valutare l'eventuale impatto dei pallet di nuova generazione sul sistema. La caratteristica che distingue i pallet moderni è il tempo di riconfigurazione: è stato fissato a 20 minuti, rispetto alle due ore dei pallet standard. Il piano sperimentale scelto è fattoriale di tipo  $2^k$ : sono stati selezionati sei fattori, tra cui il tempo di riconfigurazione, ognuno con due livelli. Per ogni combinazione dei livelli dei fattori sono state valutate le prestazioni di tre diverse campagne di produzione (casi) generate casualmente. L'obiettivo è stimare l'effetto dei fattori sulle prestazioni del sistema, in particolare quello dato dal fattore tempo di riconfigurazione.

I risultati ottenuti dagli esperimenti sono stati studiati con il test ANOVA, basato sull'analisi della varianza. Esso è in grado di valutare non solo gli effetti singoli dei fattori ma anche le loro possibili interazioni. Gli indicatori delle prestazioni



adottati sono l'Exploitation Factor (EF), che valuta la frazione di tempo impiegato per la lavorazione dei pezzi rispetto al tempo totale, e l'Adjusted Throughput (THadj), cioè la velocità di produzione del sistema adattata rispetto ai tempi di lavorazione delle macchine utensili.

La prima analisi è stata effettuata utilizzando l'Exploitation Factor. Alcuni effetti sono risultati significativi: i principali sono il numero di pallet nel sistema, il tempo di riconfigurazione e il tempo di lavorazione delle macchine utensili. Le prestazioni migliorano quando aumenta il numero dei pallet od il tempo di lavorazione oppure quando diminuisce il tempo di riconfigurazione. Da un'analisi dell'interazione tra tempo di lavorazione e tempo di riconfigurazione si è scoperto che l'effetto di quest'ultimo è significativo solo per valori bassi del tempo di lavorazione. Per questo motivo, è stata effettuata un ulteriore studio dei dati.

La seconda analisi è stata effettuata con l'indicatore THadj. L'ANOVA test è stato svolto su 5 fattori, eliminando il tempo di lavorazione ed utilizzando solo gli esperimenti con il livello più basso di questo fattore. Gli effetti significativi principali sono il numero di pallet ed il tempo di riconfigurazione, confermando i risultati dello studio precedente. L'analisi dimostra che i pallet di nuova generazione migliorano le prestazioni del sistema FMS: è possibile affermare che il loro utilizzo aumenta in media la velocità di produzione dell'8 %. Utilizzando i dati, è stato costruito un modello lineare approssimato che descrive l'andamento dell'Adjusted Throughput in funzione del numero di pallet e dei minuti risparmiati sul tempo di riconfigurazione. Il suo piano è visibile sul Grafico 1.

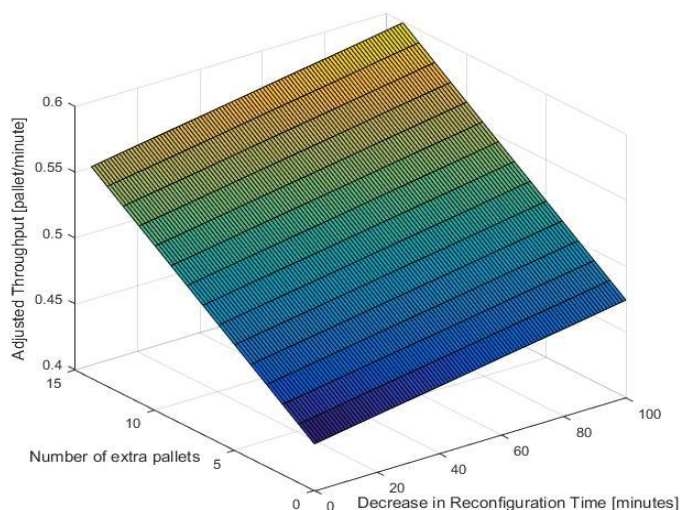


Grafico 1 Modello Approssimato dell'Adjusted Throughput

La tesi si conclude con un'analisi economica relativa all'utilizzo dei pallet con prese "zero points" rispetto a quelli standard. Le prestazioni ottenute da questi ultimi vengono massimizzate tramite una nuova strategia di produzione: essa prevede un tempo di riconfigurazione pari a zero raggiungibile tramite l'acquisto di un numero maggiore di pallet. Le performance raggiungibili con questa nuova strategia sono state confrontate con quelle dei pallet di nuova generazione con un Paired T-test. Il risultato del test dimostra che non ci sono differenze tra le velocità di produzione. L'analisi economica verte, quindi, sul confronto tra i costi prodotti dai pallet standard aggiuntivi richiesti e quelli dati dal prezzo d'acquisto maggiore dei pallet moderni. Tramite i dati degli esperimenti e un'analisi degli andamenti dei costi, è stato possibile sviluppare un modello che descrive la probabilità che i pallet di nuova generazione siano la scelta più redditizia. Esso è costruito in funzione dell'aumento percentuale di prezzo dei pallet moderni rispetto a quelli standard ( $\Delta MC$ ). La curva descritta dal modello è visibile sul Grafico 2. Si nota che per  $\Delta MC$  minori di 0.75, la probabilità che i pallet con prese "zero points" siano la scelta migliore è maggiore del 90 %.

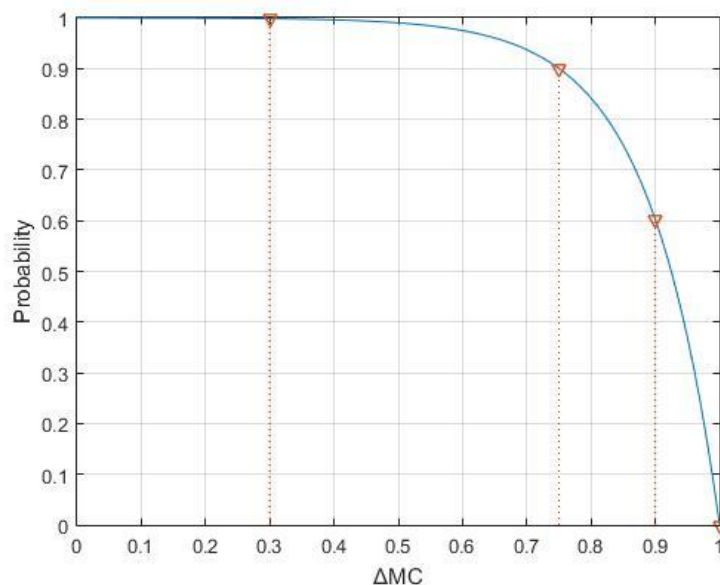


Grafico 2 Probabilità che i pallet moderni siano la scelta ragionevole, in funzione di  $\Delta MC$

È stato dimostrato, quindi, che i pallet di nuova generazione non solo aumentano le prestazioni del sistema FMS ma spesso sono anche economicamente vantaggiosi.

# 1 Introduction

The object of this thesis is the evaluation of performances of a generic Flexible Manufacturing System and the analysis of the possible improvements brought by the employment of a new kind of pallet.

The main goals are the analysis of the performance of the production program in terms of time elapsed, optimization in utilization of machines and throughputs achieved and the numeric and economic estimation of improvements of the new pallet compared with the utilization of a standard pallet.

## 1.1 Flexible Manufacturing System

A Flexible Manufacturing System is a composition of different service stations, each one with a different function such as machining, loading/unloading, quality check, connected by a generic vector: its common scope is machining parts that entered in the system. This kind of production system is widely used thanks to its high flexibility that provides capability to manage together a good variety of parts.

The idea of an FMS was proposed in England (1960s) under the name "System 24", a flexible machining system that could operate without human operators 24 hours a day under computer control. From the beginning the emphasis was on automation rather than the "reorganization of workflow".

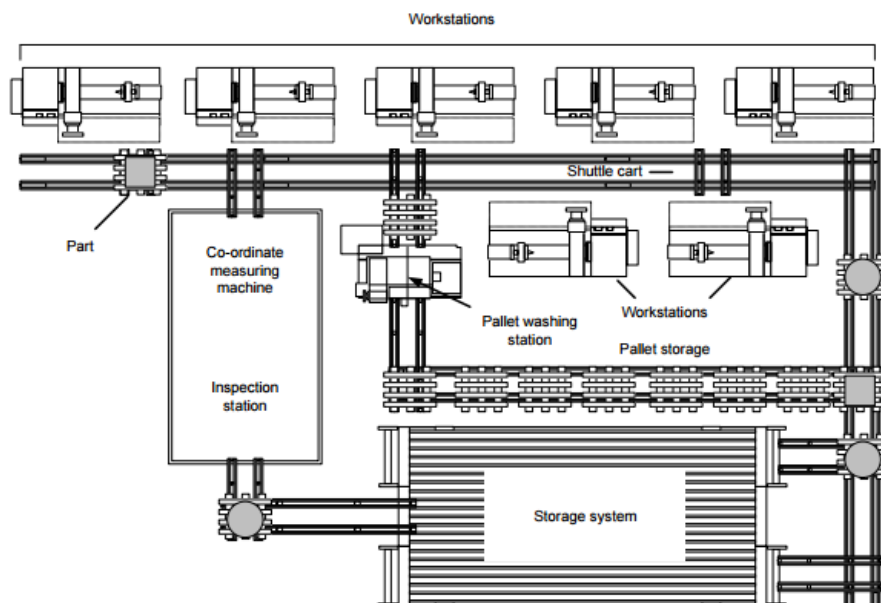


Figure 1.1 Generic FMS Scheme

“An FMS consists of a group of processing work stations interconnected by means of an automated material handling and storage system and controlled by integrated computer control system” [1]. A simple scheme of a generic FMS is shown in Figure 1.1.

As already said, at start the idea of FMS was only strictly linked to the one of automation, but after some time the concept of flexibility rose and became more important. Recently, many new manufacturing facilities have been labelled FMS. This has caused some confusion about what constitutes an FMS. Flexibility and automation are the key conceptual requirements. However, it is the extent of automation and the diversity of the parts that are important; some systems are termed FMS just because they contain automated material handling. For example, dedicated, fixed, transfer lines or systems containing only automated storage and retrieval are not FMSs. Other systems only contain several (unintegrated) NC or CNC machines. Still other systems use a computer to control the machines, but often require long set-ups or have no automated parts transfer. The key feature to identify an FMS are automation and flexibility, but it is the definition of that last concept that is not so easy to face. It is an idea that can be linked to multiple situations and sectors. To help clarify the situation, eight types of flexibilities have been defined and described by Browne, Dubois, Rathmill, Sethi and Stecke [1].

- *Machine Flexibility*: the ease of making the changes required to produce a given set of part types.
- *Process Flexibility*: the ability to produce a given set of part types, each possibly using different materials, in several ways.
- *Product Flexibility*: the ability to changeover to produce a new (set of) product(s) very economically and quickly.
- *Routing Flexibility*: the ability to handle breakdowns and to continue producing the given set of part types.
- *Volume Flexibility*: the ability to operate an FMS profitably at different production volumes.
- *Expansion Flexibility*: the capability of building a system and expanding it as needed, easily and modularly.
- *Operation Flexibility*: the ability to interchange the ordering of several operations for each part type.
- *Production Flexibility*: the universe of part types that the FMS can produce.

### 1.1.1 Types of FMS

Flexible Manufacturing Systems are different one from each other because of shape, machines used, handling system, pallets, control system but they can be classified approximately basing on size and productive capability. Three types have been recognized: single machine cell, flexible manufacturing cell and flexible manufacturing system.

- *Single machine cell*: it contains one machine (often a CNC machining center) connected to a parts storage system, which can load and unload parts to and from the storage system. It is designed to operate in batch mode, flexible mode, or a combination of the two. An example is shown in Figure 1.2.

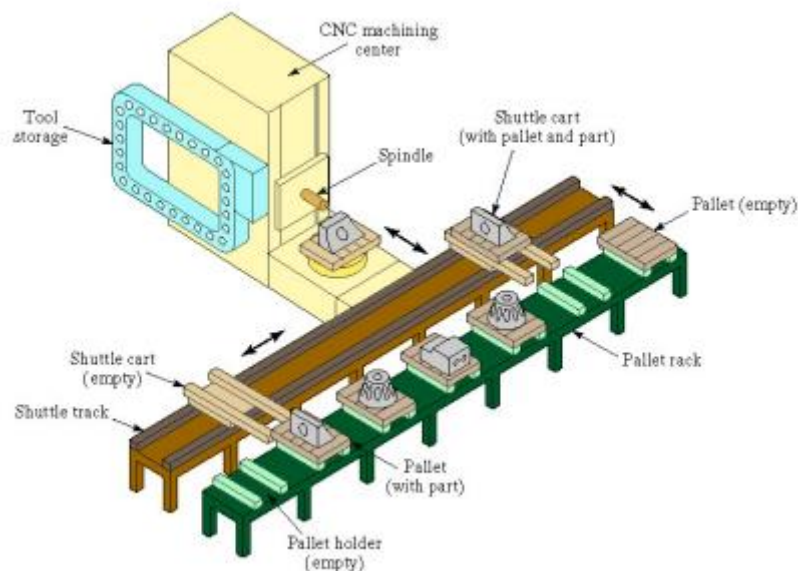


Figure 1.2 Single machine cell with one CNC machining center and parts storage unit

- *Flexible manufacturing cell*: it contains two or three processing workstations (often CNC machining or turning centers), plus a parts handling system. This set-up can operate in flexible mode and batch mode, as necessary, and can readily adapt to evolving production schedule and increased production volumes. Figure 1.3 describes a possible flexible manufacturing cell.

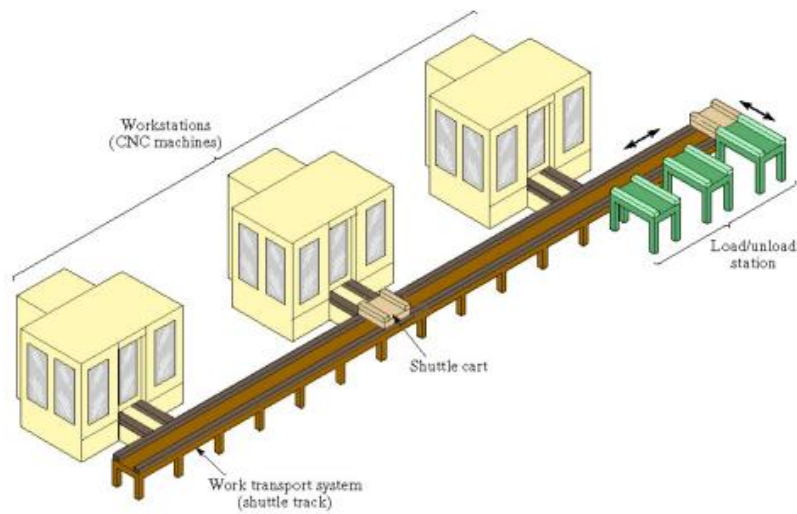


Figure 1.3 Flexible manufacturing cell with three identical processing stations, a load/unload station, and parts handling system

→ *Flexible manufacturing system*: consists of four or more processing stations connected mechanically by a common parts handling system and electronically by a distributed computer system. FMS is larger than the flexible manufacturing cell, not only in the number of workstations it may contain, but also in the number of supporting stations in the system, such as part/pallet washing stations, co-ordinate measuring machines, storage stations and so on. Computer control is also more sophisticated; it includes functions not found in the flexible manufacturing cell such as diagnostics and tool monitoring.

## 1.2 Reconfigurable Pallet

Pallets and baseplates are main actors of a Flexible Manufacturing Systems together with machines. They are responsible for holding pieces and parts perfectly to let them be machined accurately. There are different types of pallets, everyone is studied for a specific group of parts and to be adaptable to a certain genre of machining centers. Baseplates are those metal panels, mounted on pallets, that physically support pieces. The most used pallet shape is the so-called *tombstone*: a sort of turret where baseplates can be fixed on each side. An example of that type can be seen on Figure 1.4.



Figure 1.4 Tombstone with calibrated holes

The thesis focuses on the utilization of a new tombstone pallet. This pallet is not a specific one, so designed and configured to accept only a certain family of parts or at least to be reconfigured in a long time, but it has been conceived to be reconfigurable in a short time. Different types of baseplates can be mounted on it to achieve setup desired quickly and when it's needed it can be reconfigured with new baseplates and so new part types. This quick setup is made possible by the presence of zero points clamps on tombstone's surfaces. These kinds of clamps can fix and align baseplates in a perfect way without long mechanical actions or additional checks. This clamp is simply based on hydraulic or pneumatic system to fasten the baseplate with great accuracy. An example of a zero point clamp is visible in Figure 1.5, while a tombstone with them on is shown in Figure 1.6.

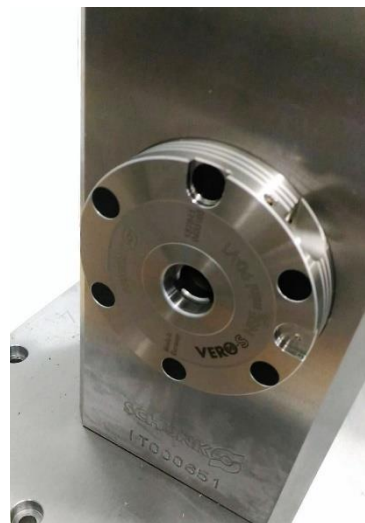
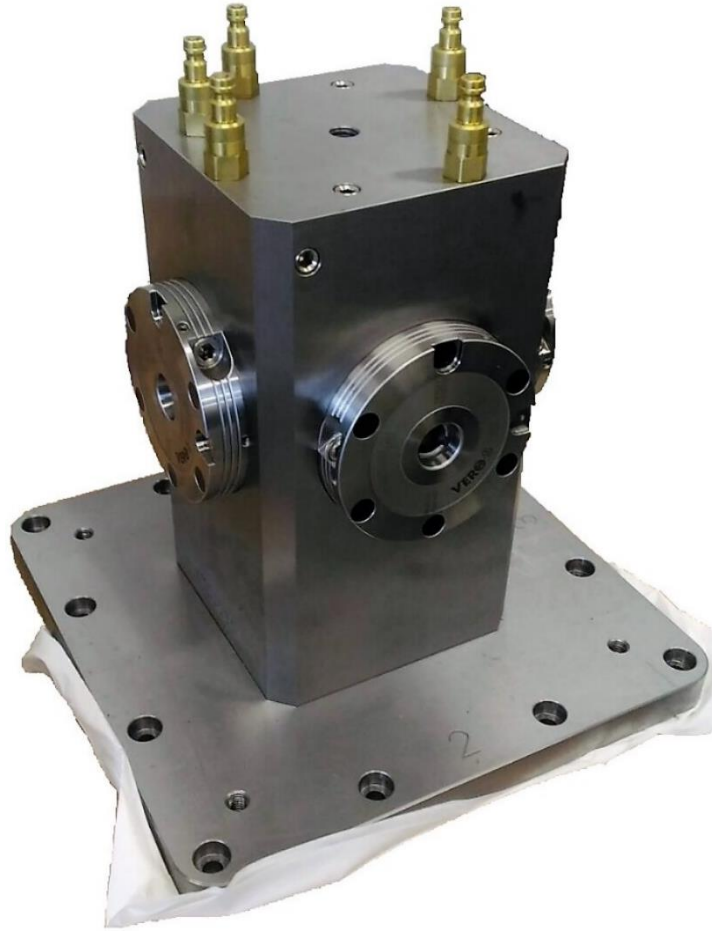


Figure 1.5 Zero point clamp



*Figure 1.6 Tombstone with zero point clamps*

The principal aim is to evaluate the gain obtained by the application of this new type of tombstone in terms of time and productivity against its cost, which it is higher than simple pallet's one.

### **1.3 Problem Statement**

The main issue of this thesis is the performance evaluation of a productive system with reconfigurations of clients. It means that features of pallets are not fixed all over the production campaign, but they change whenever is needed. The principal aim of the research is the estimation of the impact of reconfiguration duration on performances of the system.



The first problem is the numeric evaluation of the progress of one or more pallets among stations of the FMS. This aspect can be defined concretely by some performance indicators such as time elapsed into the system or parts' throughput of the system. Estimation of these values is the critical aspect of the research. It must consider a lot of different aspects: service time, presence of buffers, transportation system, different kinds of stations and parts, human intervention, reliability of machines, scraps.

The second issue is the employment of the new futuristic pallet. As already said, this kind of pallet is not specific for some parts, but it can be configured to accept any kind of parts. This fact implies that pallets in the system can change their classes of parts and so their features when needed. This is the critical aspect of the introduction of this new pallet: the variability in time of its features.

Those two issues must be considered together with the inputs of the performance evaluation; these are the production program, which classes of parts must be produced and their sequence for machining, and the demand, how many parts must be produced for each class. Tools presented in this thesis will be capable to evaluate performances of a production program on a Flexible Manufacturing System.

## **1.4 System Modeling**

The first problem concerns several aspects of the Flexible Manufacturing System. The easiest method to model the system and to evaluate its performances is considering it as a sequence of machining times, each one related to a station where pallets go through. This is clearly an extreme approximation that is never like the real system, because there are several critical aspects about this modeling procedure that should be taken into account.

The first issue is the distribution and features of machining times. This concept is strictly related to the one of human intervention: in an FMS, human role is limited to supervision and loading/unloading. For this reason, times have not a high variance, nevertheless they cannot be considered deterministic and fixed. Even automated machines can incur in some delays provoked by changing tools or whatever similar.

The transportation system cannot be neglected: time elapsed in moving pallets between stations in general is not so low. It is also variable, it depends on type of vector, distances between stations and loading/unloading method.

Another problem is the presence of buffers and so interactions between pallets: pallets can't be considered as moving in a free system, they can incur in another pallet that occupies the station they need and so their progress delays. The presence of buffers is crucial to manage these situations, so the model must comprehend these features.

Last issues are easier to be governed. Reliability can be approximated to 1 because those types of machines are not often affected by failures, while scraps can be included in demands of parts, after an empirical evaluation of their percentage.

A good solution to approximate the Flexible Manufacturing System in these constraints is the employment of Queueing Networks. It is an analytical method that reproduces behavior of clients moving in a network of stations; in every station, each client spends time for waiting, if there are some others clients already in the station, and for service. Results obtained from this type of method concern the steady state condition of the system. Transportation system can be easily approximated as a station: the duration of the travel between stations is emulated by service time. There are several models for Queueing Networks, each one with different peculiarities to be good for different situations; an analysis is done in Chapter 2.

Once chosen a good QN model, the thesis focuses on the next issue, linked to the new reconfigurable pallet. The main constraint introduced is the variability in time of features and data of pallets: this fact modifies completely every interaction between clients and stations of the model. The thesis must take in account that after a certain period, defined in general by demand fulfilling, pallets can be extracted from the system and reconfigured with other fixtures and parts, and so with other characteristics. Some Queueing Network models have the chance to introduce a variability of features of the jobs of the network, but they are not suitable for this research. Those models, indeed, can emulate the change of attributes of clients, but they are governed by a probabilistic law and so they may reproduce some situations of the system which never happen or maybe they could avoid some other ones that will always arise. In other terms, a probabilistic law is not appropriate to reproduce a reconfiguration which is ruled by time. In order to respect the reconfiguration constraint, the performance evaluation has been divided in different time periods, each one with a different configuration of jobs and so with a different calculation of results. The passage between a period and the next one is the result of a reconfiguration of one or more pallets.

This new attribute of the performance evaluation is a strong innovation: the estimation is not done once for each group, made by system, production program and demand, but there are several evaluations to be done for the same group. These are constrained by time: this is an extra restriction for the model. As already said Queueing Networks model is an analytical method that releases only steady state conditions' results; these kinds of results don't fit well that new duration

constraint. It is not possible to know a priori the duration of each period, except for some of them, and so it is not easy to guess if system can reach steady state during the period. The thesis needs an evaluation model that gives results obtained after a certain time, even if steady state has not been attained. A possible solution is a simulation model: it can check the trend and values of performance indicators along time and so it can provide results at the end of the period, whatever condition has been reached. The simulation model and software employed in this thesis is Java Modelling Tools (Chapter 5).

This research applies a simulation model, based on Queueing Networks, to evaluate performance of each group composed by FMS, production program and demand; every period, with its unique configuration, is simulated singularly, then results are combined to get an overall outcome.



## 2 FMS Model

### 2.1 FMS Features and Modeling

Performance evaluation of productive systems is one of the most critical topics of manufacturing engineering. Especially talking about FMS, it is complicated to manage this type of system because of the quantity of different parameters and features that it involves.

Grieco, Semeraro and Tollio [5] defined that these components can describe a Flexible Manufacturing System:

- Machines
- Transportation System
- Control System
- Tools and tool handling system
- Parts, pallets, and fixtures

Machines in the system strongly affects performance and functioning. The first FMSs were composed of different machines with different capabilities. Slowly, this diversity was reduced and now many FMSs have identical machines. New machining centers are more versatile and they can work on different part types using different tools. All the operations needed by a part can often be done by a single machine.

The main issue about machines regards setup. In some cases, machining centers are tuned in different ways to have better accuracy on some specific parts.

Transportation system is always automated in a FMS. Depending on the type of pallet the system can have different kind of handling system. Modeling this part of the FMS mainly affects the time for handling pallets between stations.

Control System influences behavior of the manufacturing system. At present, the control system of most of the existing FMSs is based on a “supervisor” coordinating the behavior of the various devices (machines, transport system, etc.) and on a set of Computerized Numerical Controls (CNCs) and Programmable Logic Controllers (PLCs), each of which controls a specific device.

The main problem is the integration between software, often supplied by different companies, and hardware, but during last years a great development in terms of standardization of CNC has been made.

Other important issues regarding control system concern how CNC manages part programs and operations. It affects possibility to split part programs over multiple machines, to apply a variable sequence of operations or to define alternative activities for the same product part.

Tools management is a critical issue of Flexible Manufacturing Systems and it is often neglected during performance evaluation or loading decision phase. It's strictly related to its life and tools storing system. Every tool used by machines is worn after some usage and so it should be reconditioned or changed: the main problem is the forecast of the life of the tool. The recent evolution of machining operations has provoked an increased difficulty in this type of analysis, due to the higher cutting speed reached.

Since tools are quite expensive, it is very important to decide how many copies of the same tool the system needs. Furthermore, it is crucial to develop an adequate storage system on every machine and a handling system that brings tools from and to machining centers.

Parts, pallets, and fixtures are different levels of the object that is worked by FMS. Machining centers work on parts, which are hooked to fixtures that are clamped on the pallet. It is important to check how many and which fixtures our parts need. The main issue regards the choice of the "unit" of the model between them and its connection with the other levels in terms of compatibility and time.

## 2.1 Model definition

The most used model to evaluate performance of an FMS is the Queuing Networks.

Queueing Networks is an analytical model based on a group of queues, linked basing on customer routing. Balsamo gave this definition [3]: “Queueing Networks models a set of service centers representing the system *resources* that provide service to a collection of customers that represent the *users*”.

Every station is based on the Queuing Theory. Queueing theory is a set of tools to analyze systems where clients arrive at service centers. This theory was initiated by A.K. Erlang in 1908 to solve problems in the telecommunication field. Since then the theory was extended and applied to many different fields including production systems and logistic systems. This theory determines the interaction between customers and a simple system made by a queue and one or multiple server, considering stochasticity of activities' time. The user simply arrives at the station and waits for service in the queue.

A queue is composed by a certain number of servers and the place where clients wait for service. A station is completely specified when six features are defined: statistics of the stochastic arrival, statistics of the stochastic service process, number of servers, queue capacity, total number of clients and dispatching policy. Generally, the Kendall's notation is applied to describe a queue quickly: **A/S/m/K/N/ω**. A and S, respectively statistics of arrival and service, can have those following values:

- M → Exponential distribution
- Er → Erlang distribution
- D → Deterministic distribution
- G → General distribution

While m stays for number of servers and it can assume any value between 1 and  $+\infty$ ; the same behavior is assumed by K and N, which are respectively queue capacity and total number of clients in the station ( $+\infty$  is the standard value assumed if no amount is defined). The last value  $\omega$  represents the dispatching policy and it can be designated by any discipline, such as FCFS or similar (FCFS is standard one if it's not specified). A graphical representation of that kind of queue is shown in Figure 2.1.

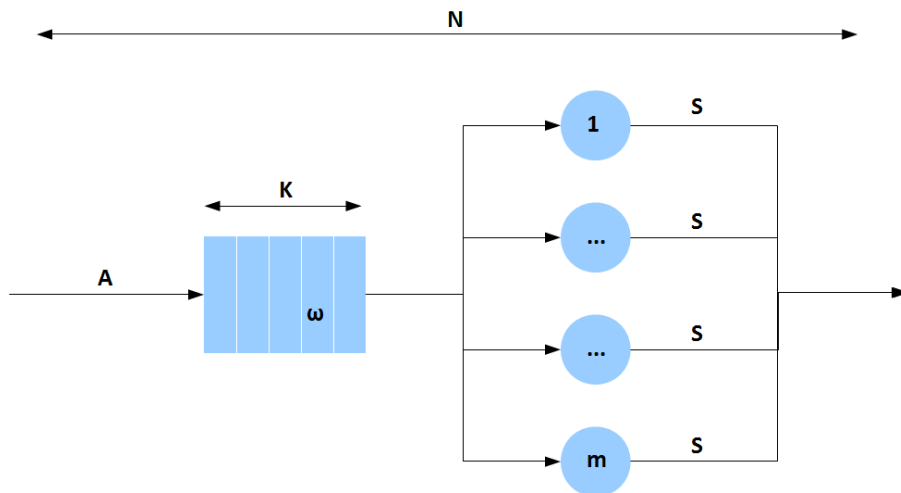


Figure 2.1 Graphical representation of a station in Queueing Theory

Big development introduced by Queueing Networks is that it takes into consideration interactions between stations. It evaluates different parameters of steady state behavior of the model in an analytical way. We can have three different types of Queueing Networks: open, closed and mixed. Open model considers the arrival of jobs from outside of the network, closed one does not accept external arrivals or jobs leaving network, number of jobs is always constant. Mixed model is in the middle between open and closed one.

## 2.2 Model choice

A lot of different Queueing Networks models has been implemented over years, each one with dissimilar peculiarities. This thesis studied some of them to choose one suitable for this problem.

Jackson's Networks is the oldest and simplest model [6]. It can be used for open models and it is easy to be implemented due to the product-form solution. Product-form networks have a simple closed form of the stationary state probability distribution, which allow the definition of efficient algorithms to evaluate their performance.

Jackson's Networks suffer for three principal limitations: customers are identical, service time distributions are mandatorily exponential (all stations are equal) and queues have infinite capacities.



The first limit could be easily bypassed by approximating different classes of customers into one average class.

This thesis discards this type of network, because an FMS is better to be modeled as a closed model: pallets never go out of the system.

Gordon-Newell's Theorem proposed a closed queueing networks with features very similar to Jackson's ones [7]. Its solution is the same of Jackson's open model removing unfeasible states through a normalization. This normalization is based on a convolution algorithm that could bring to a high computational effort, especially if jobs and stations are several.

Gordon-Newell's model has been widely used for performance evaluation of FMS, due to its simple implementation that suits perfectly a system with low quantity of stations and customers such as Flexible Manufacturing Systems. However, its results are always altered due to limitations. Exponential service times is a feature that can be accepted by our model, but infinite capacity servers are not compatible with an FMS system. Stations have not a storage area before them acting as a queue.

Another model taken into consideration is BCMP Networks (Baskett, Chandy, Muntz and Palacios [8]). This was an important evolution into queueing networks' world, because of its introduction of different types of stations. Jackson's and Gordon-Newell's consider always a FCFS policy (First Come First Served) on stations' queues, BCMP model analyses four types of stations instead. These are:

- FCFS discipline where all customers have the same negative exponential service time distribution. (The service rate can be state dependent.)
- Processor sharing queues (Jobs in stations are served contemporarily)
- Infinite server queues
- LCFS (Last Come First Served) with pre-emptive resume (work is not lost)

As for Jackson, also BCMP can be considered as a product-form network. It is suitable for open, closed or mixed models with multiple classes of customers and various service disciplines and service time distributions. Its resolution can be achieved as usual with a convolution algorithm, but in 1980 Lavenberg and Reiser [9] developed a new method called Mean Value Analysis (MVA) that avoids the direct evaluation of the normalization constant. This is a recursive computational algorithm based on a set of recurrence equations between average performance

measures. MVA is preferred when the quantity of entities in the system loads heavily computational effort of convolution algorithm.

Another feature of BCMP is the multi-class analysis. Using this type of networks different type of classes can be considered without averaging them into a mean one, but computational cost grows exponentially with number of classes.

Main limit of classic BCMP Theorem is the absence of blocking, as for precedent models. In the recent past several researchers have tried to develop new solutions for these types of networks including blocking evaluation. One of the first was Akyildiz in 1988 [10], he suggested an approximate method to reproduce blocking mechanism. It is based on the application of a non-blocking solution evaluated with a fictitious number of jobs, different from the real one. This quantity of jobs is the one that reproduces several possible states equal to the one of a blocked system, estimated with the real quantity of customers. It is a weak method due to the high level of approximation.

Blocking solutions implemented till now are founded on various methods such as recursive and convolution algorithms depending on type of network studied. Main exponent of this research field is Simonetta Balsamo, who implemented a good convolution algorithm in 1998 [11] suitable for all types of blocking mechanism. Then she collected and compared some blocking solutions for closed queueing networks [2000] [12] as can be seen in Table 2.1 and 2.2 (Tables taken from [12]).

These algorithms are:

- Throughput Approximation (Onvural and Perros [13])
- Network Decomposition (Frein and Dallery [14])
- Variable Queue Capacity Decomposition (Suri and Diehl [15])
- Matching State Space (Akyildiz [10])
- Approximate MVA (Akyildiz [16])
- Maximum Entropy Algorithm (Kouvatsos and Xenios [17]).

The first three methods (Onvural and Perros, Frein and Dallery, Suri and Diehl) evaluate the throughput of cyclic networks with exponential service time distribution. The first and the third algorithm compute the throughput as a function of network population. The throughput approximation method applies to cyclic networks with BBS or BAS blocking. It assumes that the throughput is a symmetrical function of the population network. In the Frein and Dallery's algorithm the throughput of the cyclic network with BBS blocking is approximated with a network decomposition method. The Variable Queue Capacity Decomposition by Suri and Diehl can be applied to cyclic networks with

BBS blocking and where one node has infinite capacity ( $B_1 = \infty$ ). The algorithm is based on the network decomposition principle applied to nested subnetworks. The key idea is that given a node  $i$ , all the downstream nodes  $\{i+1, \dots, M\}$  are aggregated in a single composite node  $C_{i+1}$  with load dependent service rate and a variable queue capacity.

Next three methods (both by Akyildiz, Kouvatso and Xenios) apply to arbitrary topology networks. The first two methods assume BAS blocking and exponential service time and evaluate the network throughput. The third method assumes RS-RD blocking, generalized exponential service time, and it evaluates the queue length distribution and average performance indices.

The first Akyildiz method has been already explained in this chapter. The Approximate MVA by this author, instead, is different: Network with BAS blocking and exponential service times are analyzed with a modification of the MVA algorithm originally defined for product-form networks with unlimited queue capacities. The MVA algorithm is based in the Little theorem and the arrival theorem (Raiser and Lavenberg). Last method compared, the Maximum Entropy Algorithm, evaluates the queue length distribution and average performance indices of a network with RS-RD blocking and generalized exponential service time. The approximation is based on the principle of maximum entropy and is an extension of an algorithm defined for open networks. It has successively been extended to multiclass exponential networks.

Method	Network Constraint		Blocking Type	Approximation key idea
	Topology	Node type		
Throughput Approximation	cyclic	G/M/1/B	BAS or BBS-SO	Exact model analysis for some network population. Interpolation of the throughput values by varying network population
Network Decomposition	cyclic	G/M/1/B	BBS-SO	Network decomposition into single nodes analyzed in isolation as M/M/1/B queues
Variable Queue Capacity Decomposition	cyclic a node with unlimited capacity	G/M/1/B	BBS-SO	Network aggregation of the set of finite capacity queue nodes in a single composite node having state dependent service rate and variable buffer size
Matching State Space	general	G/M/1/B	BAS	Analysis of the network with unlimited queue capacity and by choosing the network population to approximately match the same state space cardinality
Approximate MVA	general	G/M/1/B	BAS	Modification of the MVA algorithm to take into account blocking
Maximum Entropy Algorithm	general	G/GE/1/B	RS-RD	Approximate product-form for the queue length distribution

Table 2.1 Short description of methods to solve Queueing Networks with Blocking

Method	Performance Indices	Accuracy	Efficiency
Throughput Approximation	$X(N)$ : network throughput as a function of the network population	Very good	Poor for networks with more than 5 nodes
Network Decomposition	$X$ : network throughput	Good	Good
Variable Queue Capacity Decomposition	$X(N)$ : network throughput as a function of the network population	Good for networks with up to 4 nodes, inaccurate otherwise.	Fair
Matching State Space	$X_i$ : node throughput	Fair	Good
Approximate MVA	$L_i$ : mean queue length $X_i$ : node throughput $T_i$ : node mean response time	Fair for throughput, poor for other performance indices	Very good
Maximum Entropy Algorithm	$\pi_i$ : queue length distribution $L_i$ : mean queue length $X_i$ : node throughput $R_i$ : node mean response time	Fair for all the performance indices.	Fair

Table 2.2 Review of methods to solve Queueing Networks with Blocking

There are three main blocking mechanism types:

-Blocking After Service (BAS): After a job completion at queue *i*, if the job attempts to enter to queue *j* which has reached the capacity constraint, then it is forced to wait at *i* (i.e. queue *i* is blocked). When a space becomes available at *j*, the job goes to queue *j* and service at queue *i* is resumed.

-Blocking Before Service (BBS): A job declares its destination queue *j* before it starts receiving service at queue *i*. If the job finds node *j* full, then queue *i* is blocked.

-Repetitive Service (RS): After a job completion at queue *i*, if the job attempts to enter to queue *j* which has reached the capacity constraint, then it starts a new and independent service at *i* (according to center *i* discipline).

FMS studied in this analysis can be reasonably modeled with a BAS blocking. In this manufacturing structure, jobs must wait for next machine availability before releasing the actual station. Some methods such as convolution algorithm developed by Balsamo or approximate MVA (Akyildiz) can be adequately used to model Flexible Manufacturing Systems.

Last issue of the system is the possible continuous reconfiguration. The new kind of pallet can be reconfigured as many times as the owner wants, so it is crucial to contemplate a continuous change of conditions into the system. This aspect implies that the performance evaluation cannot be always completed in steady-state conditions, as analytical methods concern, but an analysis of trend of parameters over time must be done. For this reason, the analysis has turned to a simulation model.

A discrete-event simulation approach has been chosen, based on Montecarlo Method, that reproduces stochastic events which happen in the Queueing Network system.

This procedure is well implemented in Java Modelling Tools (JMT). This is a software based on Java language for performance evaluation of any kind of systems using queueing models, born in Politecnico of Milan in collaboration with Imperial College of London [18].

The simulation section of this tool suits perfectly the FMS system, because it has several parameters that can be modified and adapted to situations. Moreover, it can achieve more accurate results.

It is also fundamental to consider a possible continuous change of classes into the system. This situation is accounted into BCMP networks and JMT simulation: it

is possible to study a probabilistic switching of classes. As already said a probabilistic approach does not suit the system in question, because it could reproduce some situations into the manufacturing system that are not possible in the real one.

Therefore, a simple performance evaluation system such as simulation or analytical method is not enough to properly study this procedure.

## 3 Model Description

### 3.1 Introduction

This research applies an algorithm that integrates simulation approach with reconfiguration issue. It recreates the production process of the FMS over time, taking into consideration reconfiguration events.

It receives demand and production program as inputs and it releases production performances of the system over time, such as throughput and utilization, and reconfiguration events as outputs. The main idea of the algorithm is splitting time in different periods; in each period a different configuration of the system is simulated.

The algorithm is responsible for periods sequence and succession, basing on analysis of simulation results of periods. It is the agent that links the simulation of a period with the next one. After an examination of performance values of the last simulated period, it generates duration of that period and configuration of the next one to be used as an input for simulation. Its main operations are the estimation of pallets to be extracted from the system: number and type of pallets to be inserted in the system, their composition, and positions of tombstones in the system.

### 3.2 Algorithm procedure

Sequence of period is defined by scheduling and reconfiguration events, which correspond to start and end of each period.

Periods can be distinguished into two categories: simple and reconfiguration.

*Simple* ones are those periods when FMS produces parts till fulfilling demand of one of the pallets' class. Their lengths are not fixed, but they depend on throughput performance simulated in each period.

*Reconfiguration* periods are fixed duration ones. They represent those periods in which the system produces meanwhile reconfiguration takes part on some pallets. A peculiar reconfiguration period is the blank one: it is so called because no pallets are machined in the FMS.

These two types of periods are often alternated, except for periods when no new classes of pallets could be introduced or when a certain class finishes its production during a reconfiguration period. The example in Figure 3.1 demonstrates in a better way the succession of periods.

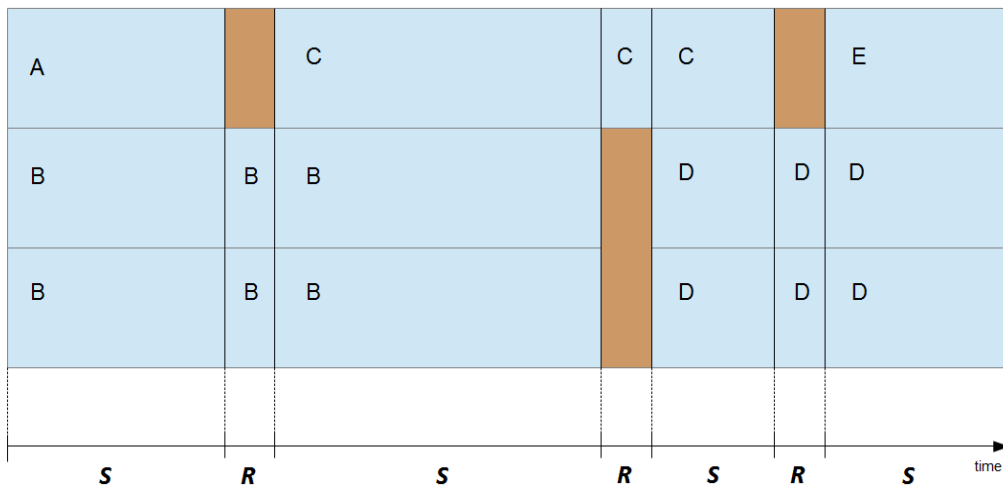


Figure 3.1 Example of succession of periods

The example describes an FMS working with three pallets; each blue line in the figure represents one of them. The capital letter on the blue area defines the type (class) of the pallet during each period. Each class represents a certain configuration of baseplates, and so of parts, on a pallet. Orange area means that the pallet is subdued to reconfiguration outside the system.

Trend of different types of periods ('S' stands for Simple and 'R' for Reconfiguration) can be seen on the timeline.

This model divides evaluation in two activities: algorithm defines the succession of periods and simulation calculates performances in each period.

### 3.3 Features of the FMS modeled

This model can be adapted to different Flexible Manufacturing Systems, especially thanks to high flexibility of Java Modelling Tools. In this research a certain FMS model has been studied, with these characteristics:

*-Machines:* any quantity of machining centers can be considered. They are identical machines with different and variable setups, for this reason pallets cannot be sent to any machine but they have a peculiar route. Nonetheless alternative operations are treated. The Load/Unload station can be considered as any other machining center.



*-Transportation System:* a simple automated carrier is considered. It can handle only one pallet per trip. Its time parameters are evaluated as weighted average values of different trips' durations, depending on routing of each class and speed of the carrier.

*-Control System:* type and functioning of CNC are not important for performance evaluation, for this reason Control System is not contemplated into this analysis.

*-Tools and tool handling system:* tool management has not been addressed in this model. Loss of time due to unavailability or change of tools can be approximated to a certain value to be added to processing times.

*-Parts, pallets, and fixtures:* the model assumes pallets as units of production of the manufacturing system. Each configuration of the pallet is defined as a class: all processing, routing and demand parameters change depending on class. Parts hooked to pallets are not accounted in this model. However, fixtures are a crucial part of the reconfiguration process. Different types of fixtures can be identified and each class of pallets has its own needed fixtures. This connection between pallets and fixtures is the main actor of the reconfiguration events that it is explained later.

*-Storage and capacities:* there are no external buffers in the system. All the stations of the model (carrier, machines, load/unload) have their own capacity; for this reason, the system can incur into blocking that has been determined as a BAS one. FCFS policy has been chosen for all queues.

### 3.4 Queuing Networks model

As already said, the FMS system can be modeled as a network of queues. There are two principal ways to model a Flexible Manufacturing System applying Queuing Networks. These two solutions have different features and approximations, but they are both good for FMS modeling.

The first model is the one drawn in Figure 3.2.

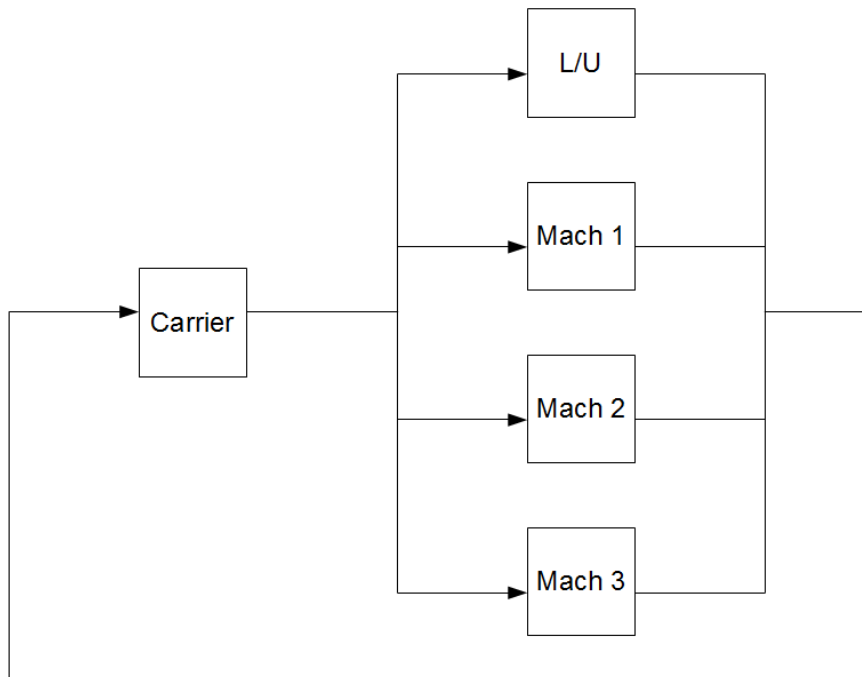


Figure 3.2 Queuing Networks model for FMS (1)

The reference station is the Carrier, all the other queues are connected to it in the same way and their outputs become the input of the carrier, in order to close the network.

The second solution for FMS modeling is shown in Figure 3.3.

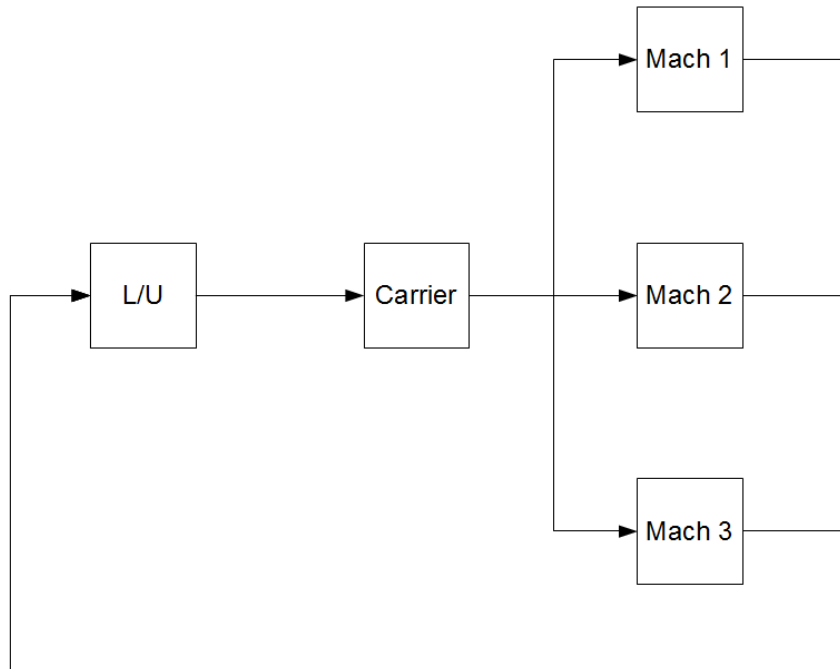


Figure 3.3 Queuing Networks model for FMS (2)

In this case the reference station is the Load/Unload station: it is directly linked to the Carrier that brings the flow to Machines in the same way. Outputs of machines close the network returning to L/U queue.

These methods have different advantages and disadvantages. The second one is more affected by the route of the single pallet: it is loaded in the L/U station, then it is taken by the Carrier and brought to the Machines. There is no chance that the pallet doesn't visit the Load/Unload station during each cycle; this fact makes the model more adherent to the real behavior of the system. The great approximation of this model is related to the Carrier: its station connects Load/Unload station to other machines but it doesn't link the outputs of these machines to the input of L/U. This fact means that the model reproduces a behavior which is not possible in the real system: jobs are transported from machines to load/unload station without any carrier. The absence of the Carrier station after machines is compensated by the duplication of the service time of the Carrier. In this way, the service time of the Carrier simulates not only the travel between Load/Unload and the Machines, but also the inverse trip. Another lack of this model is associated

to number of machines needed by each job for machining: this model permits only one machine per pallet (without considering L/U).

The first model is more affected by the real composition of stations in the Flexible Manufacturing System: every travel between a L/U station and a machine station, or between machines, needs the passage through the Carrier. This fact makes this model more adherent to reality than the second one: there are no approximations from the point of view of the system's connections between stations.

The main deficiency of this type of model is associated to the route of pallets. Each Queueing Networks cycle does not simulate the whole production cycle of each single pallet, but it represents only a fraction. If each pallet needs to be machined by one machine only, the fraction is one half; if the number of machines needed is two, the fraction is one third. This problem affects inputs and results of the simulation: throughput and demand should be adapted. Throughput, for example, must be halved, if the quantity of machines needed for machining is two.

This fact is strictly associated with another feature of this model: there is no obligation for pallets to pass through the Load/Unload station. When each job exits from the Carrier station it's assigned to a machine station or to load/unload one depending on probabilistic routing. It is obvious that the probability that it goes to L/U station can't be equal to 1. The unique possible solution is the application of a well thought out probabilistic routing matrix. Visit Ratios are crucial to build it. The Visit Ratio  $V_i$  of the  $i$ -th queue  $Q_i$  in the queueing network is defined as the mean number of times  $Q_i$  is visited by a job for every visit it makes to a given reference queue (in this case the reference station is the Carrier). Visit ratios are linked to probabilistic routing by a simple formula (Traffic Equations), shown in Eq. 3.1.

$$V_i = \sum_{j=1}^M V_j \times r_{ji}$$

*Equation 3.1 Traffic Equations*

It is trivial to find the solution of this system of equations, only if adequate constraints are imposed. First, the visit ratio of the Carrier is imposed equal to one, in order to make it as the reference for all the other visit ratios. The crucial point is the visit ratio of the Load/Unload station: it represents the mean number of times is visited for each visit to the Carrier. This estimation is linked to the idea of fraction of cycle explained before: if the model cycle is one half of the real pallet cycle, so the visit ratio of the Load/Unload must be one half. In this way, the mean number of visits to the L/U for each real pallet cycle is equal to one. Last values needed are the probabilistic routing ones related to passage from the

Carrier to Machines, which must be decided after an analysis of the real system's flows. If the system employs identical machines, these values can be simply evaluated dividing percentage by the number of machining centers.

In this thesis, the first model has been chosen. The choice is related to the fact that this model is more adherent to the real system's possible movements and to the possible utilization of stations. In this way, the simulation model can reproduce real pallets flows without any approximation.

### 3.5 Features and constraints of the algorithm

#### 3.5.1 Events classification

Crucial point of the process are reconfiguration events. They are distinguished into two categories: *start* and *end* events. Start events are those ones that determine the beginning of a Simple period; end ones define the conclusion of a period and the beginning of a Reconfiguration one, as can be seen in Figure 3.4.

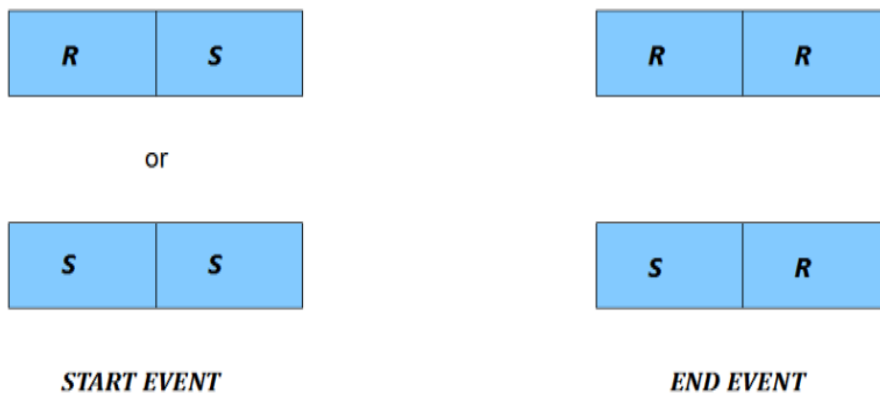


Figure 3.4 Blocks' description of type of events

Incoming of an event relies on different factors. As already explained Reconfiguration period's duration is fixed, so the Start event that set the passage from a Reconfiguration period to a Simple period is easy to be determined. Time length of Simple periods is evaluated in a simple way: once known the throughput of each class processed and so the quantity of jobs manufactured during the period, time needed to fulfill demand of each class can be calculated. The shortest time needed fixes the length of the Simple period and so the incoming of an event.

### 3.5.2 Classification of periods

During each reconfiguration event a certain number of pallet is injected or brought outside the FMS, depending on total number of pallets and ratio of classes in the system. This action provides another classification for periods: *full* and *fractioned*. In a full period, the system operates with the maximum number of pallets affordable, in a fractioned one only with a fraction of that value.

In Table 3.1 different mixes of period's types are determined and so all the possible situations in which the system incurs are explained.

	FULL	FRACTIONED
SIMPLE	Pallets' quantity is at maximum. It always begins with a Start event.	Only a fraction of pallets is worked. It happens often after a Full Simple period and it begins always with a Start event.
RECONFIGURATION		Only a fraction of pallets is worked. It always begins with an End event.

Table 3.1 Description of different kinds of periods

The algorithm can approximate adequately the production process of a Flexible Manufacturing System but it is subjected to a simple constraint: Reconfiguration takes part on a whole class each time, so single pallets' inputs and outputs are not considered.

## 4 Transition analysis

### 4.1 Introduction

The main issue of this analysis and of the algorithm is the transition between periods. This operation must abide by several defined rules. It describes the transition between established periods, called *states*, which the process must incur. It is connected to the traditional concept of FMS' production process: production manager defines a list of configurations of the system with their durations and/or demands to fulfill. System is obliged to work following these indications.

This statement can resume transition analysis:

“When a Simple period ends, the transition analysis evaluates which and how many pallets can be introduced in the system: if relationships are compatible with the system state and class suggestion, a Reconfiguration period starts, unless it incurs into a new Simple period or into a blank period.”

### 4.2 Transition between states

#### 4.2.1 Reconfigurable Transition

This type of method is related to the traditional idea for FMS production that can be resumed as “some pallets for a defined time”. The production is not seen as a continuous and unpredictable change of pallets and periods but it is determined by some fixed periods, called *states*. The system receives the sequence of states as an input and it analyzes transitions between them. It is crucial to highlight the difference between this method and the previous one: in this case the production process is obliged to pass through predefined states.

Three elements simply detail a state: type of classes, their ratio, and the total number of pallets. In a simple way, the state designates a set of pallets for each chosen class that should be machined together. The strict rule is that at a certain instant, following the sequence designated, the composition of classes and pallets of the FMS must be the same of the state. A simple example of sequence of states and description of a state can be seen on Table 4.1 and 4.2 respectively.

State 1	State 2	State 3	State 4
A	C	E	F
A	C	E	G
A	D	E	G
B	D	E	G

Table 4.1 Sequence of states

Classes	Ratio	Total number of pallets
A	0.75	4
B	0.25	

Table 4.2 Description of state 1 (Table 4.1)

Once defined these states, that the system receives as an input, the only changeable operation is the passage between a state and the next one.

This method, called Reconfigurable Transition, is adherent to reality and to the actual use of a Flexible Manufacturing System where predefined set of pallets are machined for a certain duration or till the end of demand.

The main criterion used by this method is demand fulfilling: once a class completes its demand, new classes are introduced in the system. The process of introduction of new classes must bring the system to reach a set of pallets and classes equal to the one described by the next state: this procedure can be composed of one or more transitions, depending on states. Since states are fixed, the quantity of possible transitions is fixed and it depends on number of classes and pallets.

The algorithm implemented in MATLAB that manages this transition is conceptually simple. Once the demand of a class being machined is fulfilled, the algorithm creates a list of all the possible set of classes and pallets that can be



introduced to reach next state's composition and it chooses randomly one of them. This list of transitions depends on several factors: the number of free pallets, the number of pallets required in the next state, classes and ratio of actual and next state.

About the number of pallets, it is crucial to consider how many free pallets are available; this number is not always equal to the number of jobs going out of the system. It can be lower if the next state needs less pallets than actual one or it can be higher if the last period is a fractioned one. Classes and ratio of the following state are essential to find a possible transition that brings the system to the next state. The range of transitions between two contiguous states can be easily described by a graph like the one in Figure 4.1.

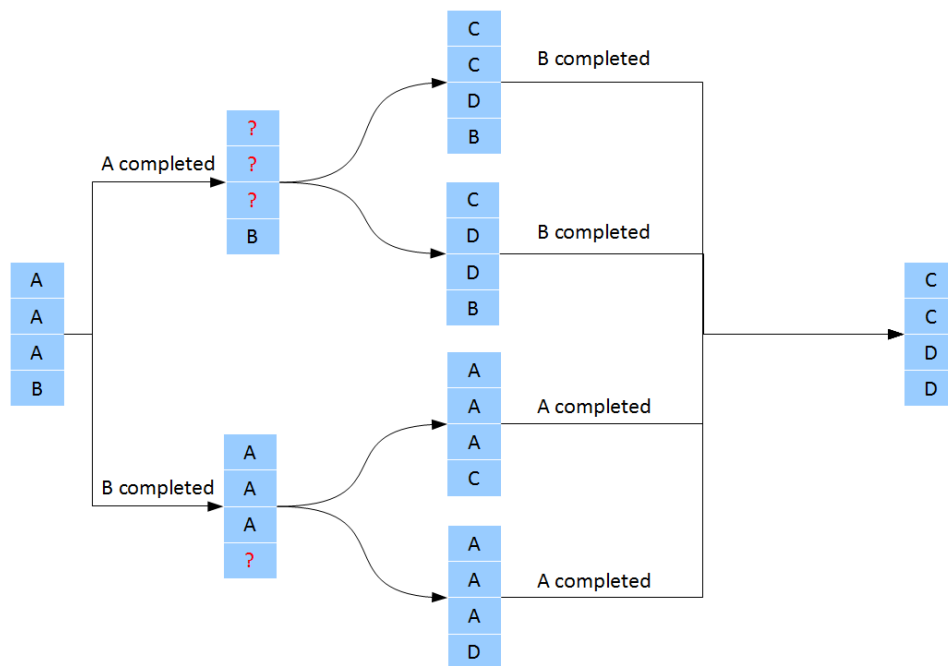


Figure 4.1 Graph of transitions between two states

The set of transitions described in Figure 4.1 is done without regard to the compatibility of classes. Classes are characterized by some relations that determine the chance to machine them together. This research does not face any matter about compatibility, because it is a topic strictly related to specific production processes. For the sake of simplicity, a simple Boolean possibility

matrix is employed, where 1 means that it is possible to machine them together. A simple example is shown in Table 4.3.

	A	B	C	D
A		1	0	1
B	1		1	0
C	0	1		1
D	1	0	1	

*Table 4.3 Boolean Possibility Matrix*

The presence of a possibility matrix is a further bond for the algorithm. After the generation of the list of transitions, it analyzes their compatibility using the matrix, to discard inappropriate transitions.

The example of Figure 4.1 can be analyzed using Table 4.3 to get compatible transitions. If the first demand completed is the one of class B, the algorithm must check two couples using the matrix: A-C and A-D. The first one is inappropriate and so the solution A-A-A-C is rejected, while the couple A-D is a possible one and A-A-A-D is a good transition; Figure 4.2 adequately shows the passage.

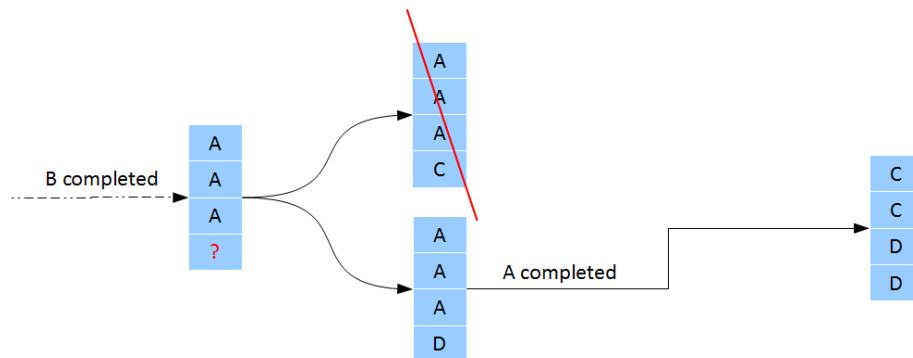


Figure 4.2 Graph of transitions between two states: compatible transitions (B completed)

During this process the algorithm can incur in a remarkable situation: no one of the transitions is compatible. In this case, the number of available pallets is reduced by one unit and the algorithm generates another time a list of transitions and checks their compatibility. This recursive operation could be repeated till the number of pallets becomes equal to zero, in that case the system does not receive any new pallet and it continues production till the end of another class demand. An example of that situation can be taken from example Figure 4.2 when class A is completed. Since there are classes B, C, and D in both the solutions, there is no transition available because A-D is an incompatible couple. The algorithm reduces number of free pallets from three to two and then it creates another time a list of transition. This process is perfectly shown in Figure 4.3.

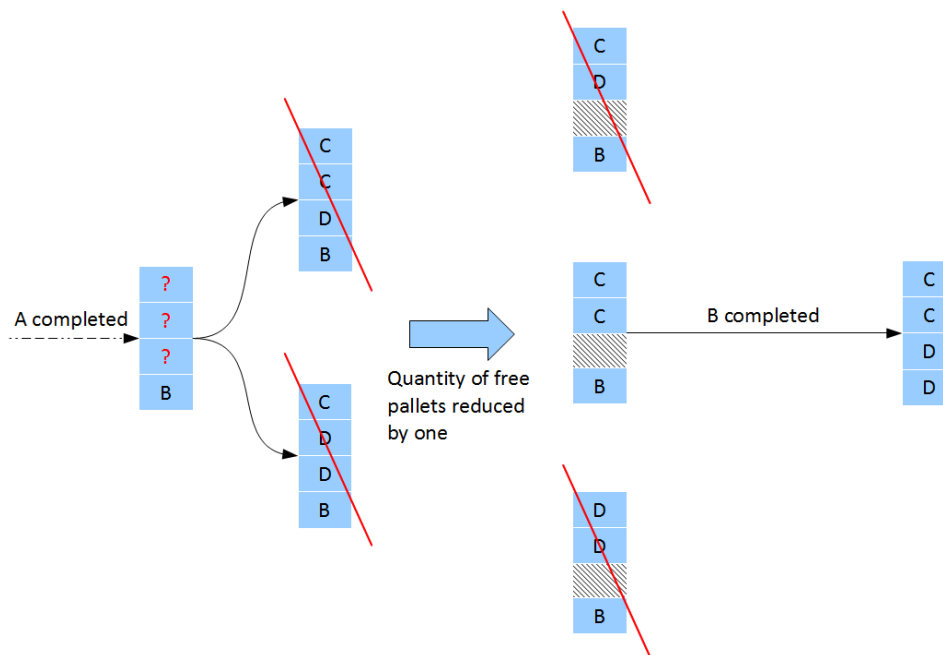


Figure 4.3 Graph of transitions between two states: compatible transitions (A completed)

After the reduction of available pallets, the algorithm originates three different solutions. For the same reason of the previous step, solutions C-D-B and D-D-B are not agreeable and so the only one that can be applied is C-C-B.

Compatibility check makes transition's algorithm harder and harder, especially if the number of classes and pallets is not so low. The advantage is that the higher is the number of classes and pallets the bigger is the advantage in terms of optimization.

As a conclusion, it can be said that the Reconfigurable Transition is the best solution if the target is the reduction and optimization of time and pallets' utilization. It can be used with simple and reconfigurable pallets: in the first case the reconfiguration time is simply imposed equal to zero.

#### 4.2.2 Ghost State

As already said, the passage from the first transition method to Reconfigurable Transition is a sort of limitation to possible evolutions of the system during production. States are constraints that impose certain ways to the tree of transitions.

The problem arises when the system incurs in a peculiar situation: the demand of a class of the next state ends before the fulfillment of one or more classes of the current state. In this case the achievement of the next state's composition is useless, because no more pallets of one of its classes must be machined. Nonetheless, the system must pass through that state. In those cases, the state is called Ghost State.

A Ghost State is a state that appears in the model evaluation of the system, but it never emerges in the real system. Its duration is equal to zero and its throughput is fixed to zero for compatibility. Even if it is a "non-productive" period, the algorithm defines its presence because the system is obliged to pass through all the states.

A simple example is shown in Figure 4.4, where the transitions tree of a simple system with two pallets is visible. The first state is one pallet of class A and one of B, while the second state is one pallet of class C and one of class D. Let's suppose that A can't be machined together with C.

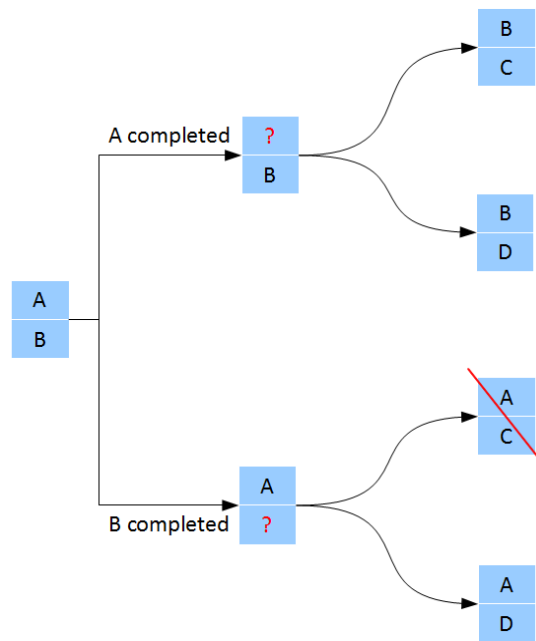


Figure 4.4 Transitions tree of a simple system

Due to compatibility constraints, after the first period there are only three possible situations for the system: B-C, B-D, and A-D. The example will analyze only the first one (B-C) to explain Ghost State, but the same reasoning can be done for the other situations.

The incoming of the Ghost State is observable in Figure 4.5, where the evolution of the system from the situation B-C is described.

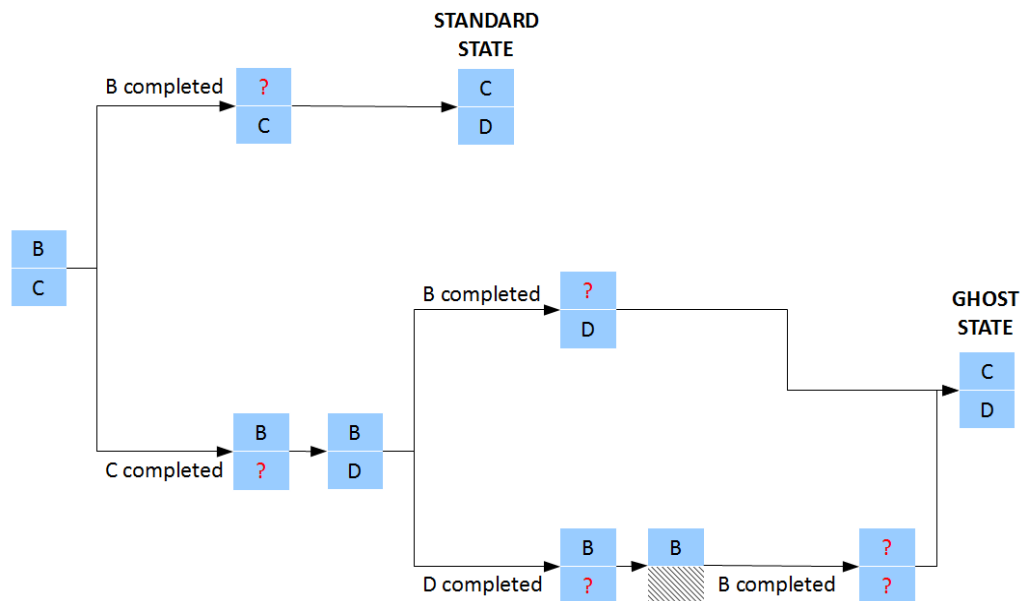


Figure 4.5 Evolutions of transitions tree to a Ghost State

The mandatory condition to reach a Ghost State is that a next state's class fulfills its demand before an actual state's one. In this case, there are two ways that satisfy this condition. In the first one C has been completed before B, while in the second demands of classes C and D are both fulfilled before one of class B. Only after extraction of class B from the system, the algorithm inserts another time classes already fulfilled: in the first way C, in the second one both C and D.

In the first way, a *simple* Ghost State is reached: there is at least one class with a demand higher than zero. In this case the class is D, while C has been already fulfilled. In the second route the system attains a *total* Ghost State: all the classes of the state have a demand equal to zero. The total one is the worst Ghost State that can be reached: there is no trace of it in the real production system and the FMS passes directly from the actual state to the state after the next one.

The presence of Ghost States in the system is the symptom of unbalanced workloads. Therefore, demands of classes are not well distributed over periods.

### 4.2.3 Demand Fluctuation

Each class has its own demand: it is not fixed, but it can raise over time. The fluctuation of the demand must be compatible with the production program: pallets of the same class may need machining operations on different periods of the production campaign to fulfill increments of demand. The algorithm must manage these fluctuations to give a realistic scenario of FMS production.

Initial demands are fixed inputs of the algorithm. They will be successively modified during performance evaluation basing on another input: it defines how and when the demand changes. It is a simple matrix as the one described in the example of Table 4.4.

State	Class	Quantity
3	A	+95
4	B	+190
5	A	+240

*Table 4.4 Fluctuating Demand*

The table defines when the modification takes place, which class' demand is changed and how much is increased. The algorithm will apply these modifications when it reaches the state indicated in the first column.



Even if fluctuations are known, demands cannot be cumulated and fixed as initial total demands. The algorithm must follow the production program together with increments of demands. This feature introduces a modification in the algorithm: the passage from one state to the next one is not linked to the total demand of classes over the whole production campaign, but it considers the fluctuation of the demand along states. Completion of a state could be reached even if one of its classes has not fulfilled the whole demand. The minimum condition for completion of a state is that its classes have fulfilled the demand requested from start of campaign to the achievement of that state; any increment of demand linked to future states is not considered. This is a mandatory condition to give the chance to produce the same class on contiguous states without necessarily incurring in a ghost state.



## 5 Simulation model

### 5.1 Java Modelling Tools

The algorithm's core is a simulation process realized by Java Modelling Tools. Java Modelling Tools (JMT) is a free open source suite consisting of six tools for performance evaluation, capacity planning, workload characterization, and modelling of computer and communication systems. The suite implements several state-of-the-art algorithms for the exact, approximate, asymptotic, and simulative analysis of queueing network models, either with or without product-form solution. Models can be described either through wizard dialogs or with a graphical user-friendly interface. The workload analysis tool is based on clustering techniques.

As already said, the analysis uses the simulation tool, called JSIM: it is a discrete-event simulator for the analysis of queueing network models. The JSIM simulation engine supports several probability distributions for characterizing service and inter-arrival times. Load-dependent strategies using arbitrary functions of the current queue-length can be specified. It supports state-independent routing strategies, e.g., Markovian or round robin, as well as state-dependent strategies, e.g., routing to the server with minimum utilization, or with the shortest response time or with minimum queue length, and load dependent routing. The simulation engine supports several extended features not allowed in product-form models, namely, finite capacity regions (blocking), fork-join servers (parallelism), class switching and priority classes. The flexibility of this software is perfectly described by the quantity and variety of stations that are available (Source, Sink, Queue, Delay, Fork, Join, Route, Logger, Class-switch). The JSIM performs automatically the transient detection, based on spectral analysis, then it computes and plots on-line the estimated values within the confidence intervals. What-if analyses, where a sequence of simulations is run for different values of control parameters, are also supported.

There is difference between the analytical resolution for queueing networks and the simulation solving. An analytical solution is always the same for the same data input and it is evaluated considering only mean values and trend of probability distributions.

The simulative approach tries to reproduce the real behavior of the system. JMT simulation is a discrete-event simulation: it means that time is divided in periods basing on a succession of discrete events.

The exponential distribution has been chosen for service times of stations of the model. Its main parameters are mean value ( $1/\lambda$ ) and variance ( $1/\lambda^2$ ). So once defined by tests and samples the mean value for service time of a certain job in a machine, it is possible to develop its exponential distribution to be used by JMT.

Furthermore, JMT model used in this analysis assumes a FCFS policy on all its stations and a BAS blocking approach. It makes use only of Router stations, Queue stations and successively of Logger stations as it can be seen in Figure 5.1.

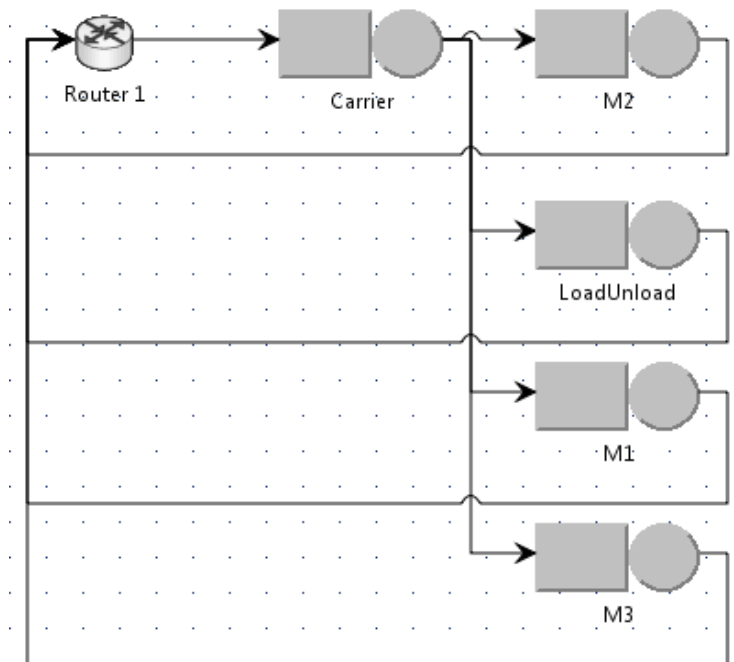


Figure 5.1 Graph of Queueing Network Model used in Java Modelling Tools

## 5.2 Integration of algorithm and JMT

Java Modelling Tools can be easily integrated with other software. The first reason is that Command Line can launch it. This feature provides to our algorithm the capability to make use of the software without opening its user interface. Command Line needs only a certain input file to be evaluated by the software and after computation it provides an output file ready to be examined. The other reason is that both input and output file are simple XML files. XML is a file extension for an Extensible Markup Language (XML) file format used to create common information formats and share both the format and the data.

JMT input file provides a data scheme arranged with a child-parent approach that defines all the features and links of the queueing network model to be computed. It must include classes of jobs, node definitions, connection and preload and measures requested as output (Appendix).

JMT output file is a very simple XML file with a list of different measure definitions, as required by input file, with their simulated value (Appendix).

These features of the JMT software simplify the integration with MATLAB. MATLAB manages the employment of the Command Line: there's a specific function that can afford that. MATLAB can also handle XML files. It has a class of functions born to manage this type of files: MATLAB can read, write, and analyze input and output files.

At last this integration means that at each algorithm cycle MATLAB writes an input file for JMT, launches it and read results on the output file.

### 5.3 Simulated time and results acquisition

The model analyzed in this thesis defines two different types of periods: simple and reconfiguration. The first ends only when the system fulfills the demand of one of the classes machined, the second stops when reconfiguration time is achieved. It is important to set a simulation that lasts for the same duration as the real system. Therefore, a reconfiguration period could be easily predefined by setting reconfiguration time, instead of simple period that needs an ending event approach, which is not integrated in JMT. There is so a problem regarding the duration of simulation of a simple period.

It is not feasible to apply steady-state results to simple periods, because it is not assured that the simulation reaches that condition before the ending event. The performance evaluation tool needs a method that can estimate simulation results in transient state.

A solution has been founded in the Log analysis. Java Modelling Tools can provide a Log file where the succession of events is shown. This type of file can be required for each station of the model and it represents the succession of events, i.e. passage of a job, that happens among the station. It can be considered as a monitoring tool that checks the transit of a job, before or after the station, and writes down it on a csv text file. Possible layout of this type of file is shown in the example of Table 5.1.

Timestamp	Interarrival time	ID Job	Class of the job
1,56	1,56	0	Class 1
5,89	4,33	2	Class 2
9,85	3,96	1	Class 1
11,24	1,39	3	Class 2
14,27	3,03	2	Class 2
17,65	3,38	0	Class 1
20,99	3,34	3	Class 2
24,1	3,11	1	Class 1
27,81	3,61	2	Class 2

*Table 5.1 Example of Log file*

The “timestamp” defines the time elapsed from simulation start, “interarrival time” is the time spent between that event and the previous one, “ID Job” is a sort of code assigned to each job and “Class of the job” describes the class of the job transiting on that event.

The Log file can describe the behavior of the system over time. All the simulation events can be reconstructed and so it is possible to analyze the whole simulation and not only end results. Variables such as Throughput or Utilization can be evaluated event-by-event and then they can be recomposed to examine their trend all over the simulation time.

This file is crucial for the model implementation. Since an ending event to stop the simulation in JMT cannot be imposed, the algorithm is forced to exploit a whole simulation and then analyze its Log files. Only from those it can extract needed parameters and values. As already said, Log files can be composed for each station, for its input or for its output. The JMT input to create Log files can be of two kinds: as Statistical Results of a Performance Index requested or with the use of one or more fictitious “Logging stations”. The second case will be widely faced in the next paragraph for its usefulness with single stations, instead the first input method is significant to analyze the whole system. Statistical Results will be represented graphically by Java Modelling Tools and they will be written in a Log file. This one describes the traffic flow at a certain point in the system with peculiar characteristics, depending on the type of Performance Index or on the choice made. For example, Statistical Results of Queue Time will show the traffic flow at the output of the queue of the station selected. For the algorithm's purpose, Statistical Results regarding the System Throughput of each different class are needed. In this way, the software releases a Log file about the traffic flow of certain class' jobs at the output of the Reference Station, that for the model studied is represented by the Router. As defined by Closed Queueing Network theory, the output of the Reference Station is applied to evaluate whole system throughput, i.e. total production of jobs by the manufacturing system.

The procedure to get results from those files is quite easy. The algorithm scans the Log file of each class, it finds the nth event, where “n” represents the quantity of missing jobs to fulfill demand of that class, and notes down its Timestamp. After doing that for all Log files, it evaluates the minimum time between ones annotated: this is the simulated time searched and its relative event is the “ending event” of the simulation. Then it scans another time all the Log files not linked to class that has fulfilled demand and finds the event with the maximum timestamp in the range of values between zero and simulated time. Counting events before that one provides the number of jobs produced for that class.

This example, based on data of Table 5.1, clarify phases of the process. Table 5.2 and Table 5.3 represent log files of classes.

Timestamp	Interarrival time	ID Job	Class of the job
1,56	1,56	0	Class 1
9,85	8,29	1	Class 1
17,65	7,8	0	Class 1
24,1	6,45	1	Class 1

*Table 5.2 Example of Log file for system Throughput of Class 1*

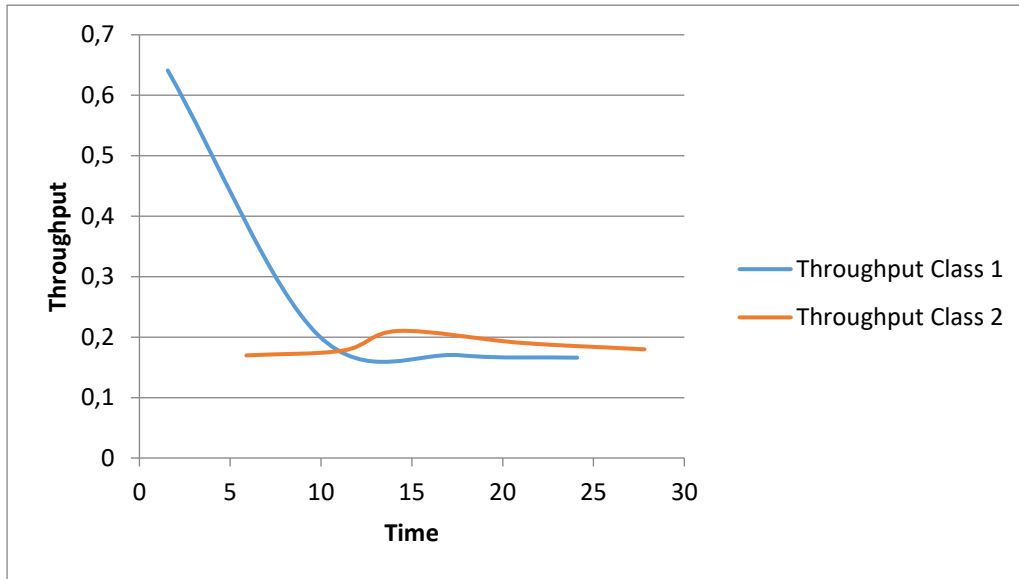
Timestamp	Interarrival time	ID Job	Class of the job
5,89	5,89	2	Class 2
11,24	5,35	3	Class 2
14,27	3,03	2	Class 2
20,99	6,72	3	Class 2
27,81	6,82	2	Class 2

*Table 5.3 Example of Log file for system Throughput of Class 2*

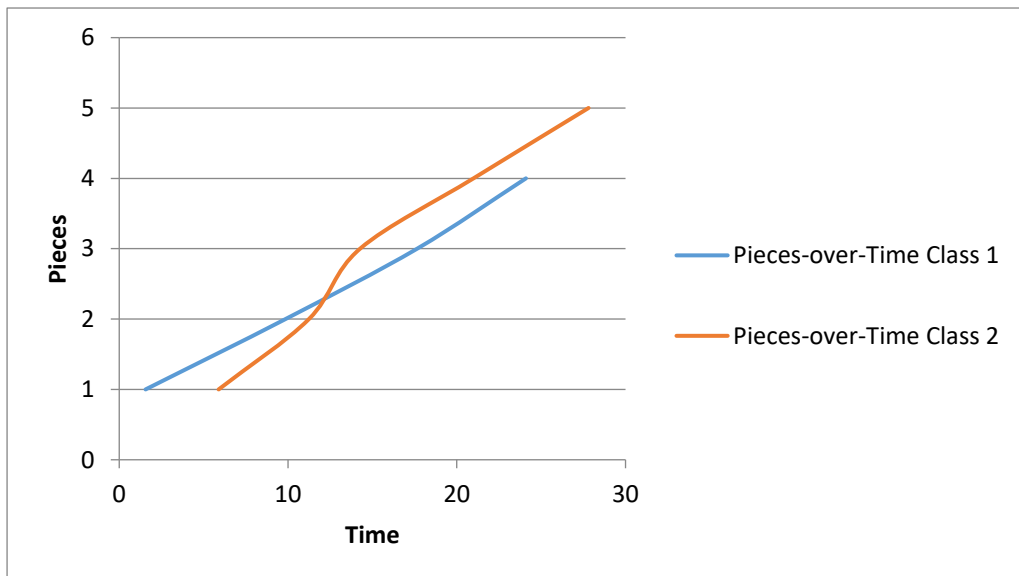


Demand of Class 1 is 3, instead the one of Class 2 is equal to 4 jobs. In the first phase the algorithm finds out the event relative to demand fulfilling of each class. In this case Class 1 is fulfilled in 17,65 minutes, whilst Class 2 finishes production in 20,99 minutes. The lower value is the one of Class 1 and so the simulated time is 17,65 minutes and the ending event is the end of production of Class 1's jobs. Now it re-scans the Log file of the second class and finds out that the last event of that class before simulated time is the 3<sup>rd</sup> one. Production of Class will be so equal to 3 pallets.

After that procedure, it is possible to evaluate all needed variables' behavior over time, from zero to simulated time. Throughput and Pieces-over-Time are plotted on Graphs 5.1 and 5.2.



Graph 5.1 Throughput plot for both classes



Graph 5.2 Pieces-over-Time plot for both classes

Log files are not only used to define the simulated time. Information about quantity of pieces produced and throughput can be extracted from this file in the way shown in the example. Results are so taken from those files and no other output file from Java Modelling Tools is needed.

## 5.4 Positions of Jobs in the system

Another peculiarity of Java Modelling Tools is the possibility to impose the initial position of jobs in the system. It is a simple feature that permits to decide where each job of each class is posed at the start of the production. This attribute can provide to the algorithm the chance to treat the succession of periods as a continuous simulation and not as a flow of discrete simulations.

The concept is that each period starts its simulation from the last situation left by the previous period: initial positions of  $i$ -th period are last positions of  $(i-1)$ -th period. Every period does not start from a blank situation, but it continues the simulation process conducted by previous periods. There is an approximation that must be done: time already spent by a pallet in its last node of a period cannot be considered in the next period. By default, new pallets of classes not already in the system are introduced at the Load/Unload station.

The unique problem is that JMT can establish the initial position of jobs but it does not release any output about last positions. The solution to this issue has been found in Log files, as for simulated time problem. These are generated by logging stations. A logging station (i.e. logger) reads information flowing through it and writes it to a Log file. In the simplest way, it is a tool to understand and debug the traffic flow moving through the interesting part(s) of the model. Once placed the logger station into the model and chosen the parameters, it can trace the data as it passes through the model.

The idea is to analyze flows of jobs around every node and find out which ones remain in the node at the simulated time. The jobs in the nodes at the simulated time represent the initial condition for the next period. Loggers must be posed adequately: one at the input and one at the output of each station as can be seen in Figure 5.2.

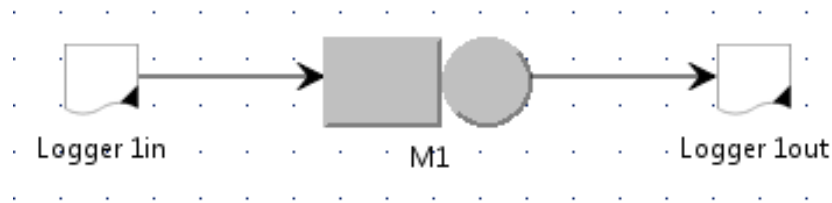


Figure 5.2 Logger positions in the model

The one at the input will read all the jobs entering in the station, whilst the one at the output will register all the jobs exiting the stations. Comparing these two Log files the algorithm can understand how many jobs are left in the station at the end of simulation.

The procedure can be easily explained. In the first phase the algorithm counts the quantity of jobs entered in the station (I) and the quantity of jobs came out from that (O). Then it evaluates the number of jobs left in the station by the Eq. 5.1, knowing starting quantity of jobs in the node (S).

$$L = S + I - O$$

Equation 5.1 Evaluation of jobs left in a station

Last passage is the scanning of the last L event of the input Log file to get classes of jobs left in the node. Once done this method for each station, the algorithm has the knowledge about positions and classes of jobs at the end of the period and it can assume them as the initial condition for the next period.

The idea can be easily explained by the next example for a single station. A hypothetical input file is shown in Table 5.4, while an output Log file is described by Table 5.5 (both cut by simulated time). The value “S” is equal to 1 job of Class 1.

Timestamp	ID Job	Class of the job
2,56	0	Class 1
5,59	2	Class 2
9,01	1	Class 1
11,78	3	Class 2
14,83	2	Class 2

Table 5.4 Example of input Log file

Timestamp	ID Job	Class of the job
5,42	1	Class 1
9,36	0	Class 1
12,42	2	Class 2
16,89	1	Class 1

Table 5.5 Example of output Log file

The algorithm begins with the evaluation of  $L$  using Eq. 5.1, after counting events of Log files.

$$S = 1$$

$$I = 5 \quad \longrightarrow \quad L = 1 + 5 - 4 = 2$$

$$O = 4$$

Then it checks last  $L$  events of input file, in this case last 2 ones. They are both belonging to Class 2. Therefore, the initial condition of this station for the next period simulation is 2 jobs of Class 2.



## **6 Validation of the model**

The model built in this thesis is composed by an algorithm implemented on MATLAB and a simulation evaluation done by Java Modelling Tools. The union between these two elements creates the performance evaluation model. In this chapter the model is subjected to a validation, to verify its capability to estimate real behavior of the Flexible Manufacturing System.

The validation consists in evaluation of simple cases: simple systems and inputs. Results obtained are analyzed and their objective compatibility with the real FMS is studied.

### **6.1 KPI (Key Performance Indicators)**

It is fundamental to define the outputs of the performance evaluation model to do the validation or every other type of evaluation with the tool created. A set of indicators (KPI) is determined, each one with a different function in describing the behavior of the system. Indeed, the performance of the model cannot be defined univocally as good or bad but it has different sides: the user should decide which indicators are more important regarding his study. The performance of a system can be high from the point of view of some indicators but it can have low values on other indicators.

#### **6.1.1 Throughput and Time Elapsed**

The first KPI is strictly related to production time and it is the main indicator of the speed of a production system. The Throughput of a FMS describes the quantity of pallets produced over time. It is the most important indicator if the user is interested in the production speed and if the target is to produce the highest number of pallets in a certain time.

Throughput is a sort of meter of the exploitation of time by the production system. Considering a fixed composition of classes and pallets, the lower is the throughput the higher is the waste of time of the system. This type of indicator is strictly linked to Time Elapsed, which indicates the duration of the whole production campaign. It is trivial to say that once known the Time Elapsed the Throughput can be easily evaluated: the principal difference between them is that Time Elapsed is a relative indicator (it needs demand to be compared) while Throughput is an absolute indicator.

The simple formula to evaluate Throughput is shown in Eq.6.1

$$TH = \frac{Total\ Demand}{Time\ Elapsed}$$

*Equation 6.1 Throughput*

The total demand corresponds to the sum of demands of all classes of parts machined during the production program selected. It is obviously equal to the quantity of pallets produced in the campaign, due to the fact the algorithm is obliged to satisfy the demand. The unit of measure of throughput is pallet/minute, while time is calculated in minutes.

This definition of Throughput is related to the whole campaign, but it is possible to analyze throughputs of single periods and single classes. This kind of analysis is strictly necessary to better analyze how the throughput changes and to identify the possible presence of periods with very low throughputs. In these cases, the formula employed is quite the same: total demand is substituted with pallets' production of the period (single class or totality of classes) and time elapsed becomes the duration of the period.

### **6.1.2 Utilization**

Another important KPI is the Utilization. It describes how much machines of the system are used during the campaign or during a single period. It is a dimensionless indicator, quite always expressed as a sort of percentage, that Java Modelling Tools, the simulation software, can give as an output of its evaluations.

Utilization can be a good meter to evaluate the importance of machines: a high utilization value means that the presence of the machine is quite compulsory in the system because it is often used. On the contrary, a low utilization value is the symptom of a machine rarely used: its contribution should be severally appraised and the user should consider a possible elimination due to inactivity.

Equation 6.2 defines the method to evaluate Utilization.

$$Utilization(machine) = \frac{Time\ machine\ working}{Time\ Elapsed}$$

*Equation 6.2 Utilization*



The Time Elapsed is the same used in Throughput definition, while the factor called “Time machine working” is the time elapsed by the machine for working all the parts passed through it. These two values are connected: “Time machine working” can be evaluated as the Time Elapsed minus the time spent by the machine waiting for next pallet.

As for Throughput, Utilization can be estimated for the whole campaign or for single periods.

### 6.1.3 PUT (Pallets Unused over Time)

The PUT is an indicator created appositely for this thesis. It measures the waste of reconfigurable pallets’ utilization during the production. Indeed, the quantity of pallets used on each period is not always equal to the maximum number of pallets that can be applied, due to several causes such as incompatibility or reconfiguration periods. The PUT indicator gives a meter of that lack of saturation in terms of number of pallets; quantities of pallets “missed” are weighted on periods’ durations to deliver a sensible result.

There are two measures of the PUT: the absolute one and the percentage one. Their formulas are shown in Eq.6.3 and Eq.6.4.

$$PUT = \sum_{i=1}^{n \text{ of periods}} [(Max \text{ number of pallets} - \text{pallets used}(i)) \times \text{duration of period}(i)]$$

Equation 6.3 Pallets Unused over Time

$$PUT\% = \frac{PUT}{Max \text{ number of pallets} \times \sum_{i=1}^{n \text{ of periods}} \text{duration of period}(i)}$$

Equation 6.4 PUT Percentage

The unit of measure of Pallets Unused over Time is pallet\*minute, while PUT Percentage is a simple rate. There is also another variant of that indicator that is called No Reconfiguration PUT: it is the same of Pallets Unused over Time but the reconfiguration periods are not considered in the estimation. This variant can be helpful because its percentage version can reach the unitary value and so it is

easier to understand how much the system is far from the best performance in terms of utilization of pallets.

## 6.2 Validation Experiments

As already said, validation experiments are simple tests made to verify the reliability of the tool. These are analyzed and compared to objective and trivial evaluations.

Data employed in these cases are not real or probable, they are only fictitious data invented for model validation. The Queueing Networks model applied is the same of Figure 3.2 (Queueing Networks model for FMS) with the same number of machines (equal to 5). Data are maintained over all the validations, except for states (number of pallets, ratio, classes). They are shown in Tables 6.1-7.

	Class 1	Class 2	Class 3
Carrier	1	1	1
L/U	4	4,2	2,1
M1	3,7	1	4,2
M2	5	5,7	4,6
M3	1	4,8	5,3

*Table 6.1 Service Times of Classes in each Station [minutes]*

<i>Class 1</i>	Carrier	L/U	M1	M2	M3
Carrier	0	0,5	0,2	0,3	0
L/U	1	0	0	0	0
M1	1	0	0	0	0
M2	1	0	0	0	0
M3	1	0	0	0	0

*Table 6.2 Probabilistic Routing Matrix (Class 1)*

<i>Class 2</i>	Carrier	L/U	M1	M2	M3
Carrier	0	0,5	0	0,25	0,25
L/U	1	0	0	0	0
M1	1	0	0	0	0
M2	1	0	0	0	0
M3	1	0	0	0	0

*Table 6.3 Probabilistic Routing Matrix (Class 2)*

<i>Class 3</i>	Carrier	L/U	M1	M2	M3
Carrier	0	0,5	0,1	0,3	0,1
L/U	1	0	0	0	0
M1	1	0	0	0	0
M2	1	0	0	0	0
M3	1	0	0	0	0

*Table 6.4 Probabilistic Routing Matrix (Class 3)*

Class 1	Class 2	Class 2
350	100	200

*Table 6.5 Demand of each Class*

Carrier	L/U	M1	M2	M3
1	4	2	2	2

*Table 6.6 Capacity of Queues*

	Class 1	Class 2	Class 3
Class 1	1	1	0
Class 2	1	1	1
Class 3	0	1	1

Table 6.7 Possibility Matrix

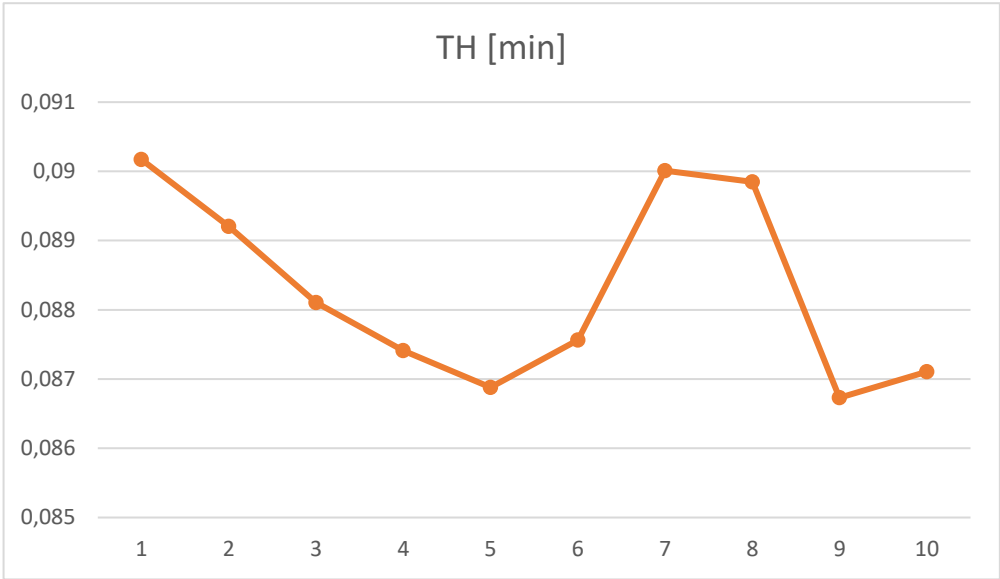
### 6.2.1 Single pallet validation

The single pallet's experiment consists in simulating the behavior of a single job of a certain class in the FMS model. It is trivial to show composition of the unique state: number of pallets is equal to 1, ratio is unitary and the class chosen is Class 2. This initial experiment is not important from the point of view of the algorithm, but it is crucial for testing reliability of simulation tool.

Results are evaluated over 10 runs: each run is the effect of 10 simulation cycles. Every type of PUT are not considered for the analysis: PUT are always equal to zero (no pallets wasted). Relevant outputs are shown in Tables 6.8-9 and Graphs 6.1-2.

	Average TH [job/min]	Total Time [min]	Average Time per Pallet [min]
1	0,090171	1108,65	11,09
2	0,089206	1120,67	11,21
3	0,088106	1134,73	11,35
4	0,087413	1143,821	11,44
5	0,086881	1151,153	11,51
6	0,087566	1142,28	11,42
7	0,090009	1111,004	11,11
8	0,089847	1112,681	11,13
9	0,08673	1153,236	11,53
10	0,087108	1148,206	11,48

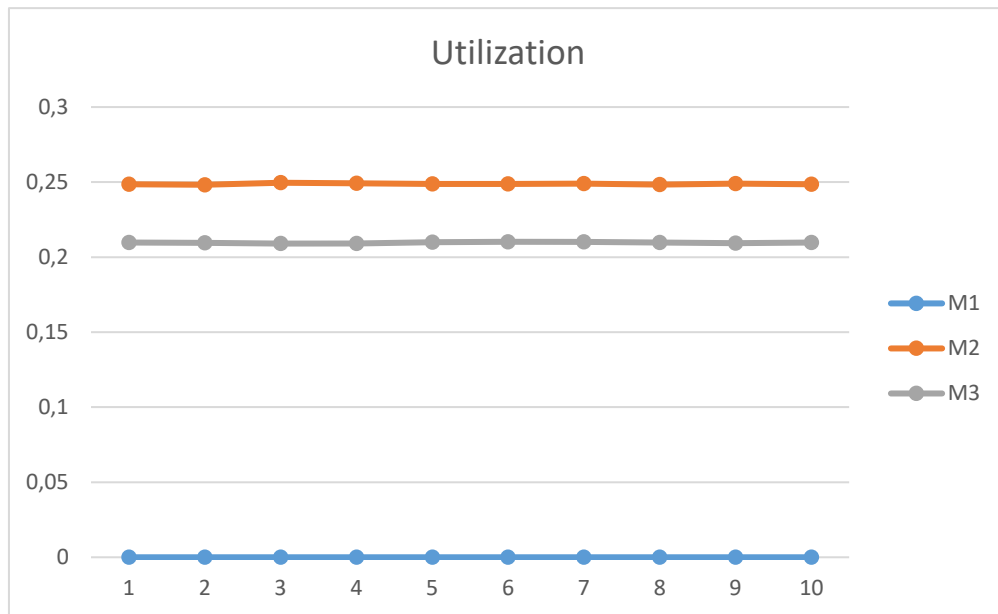
*Table 6.8 Throughput and Time Elapsed over runs (Single pallet)*



Graph 6.1 Throughput Plot

M1	0	0	0	0	0	0	0	0	0	0
M2	0,248	0,248	0,250	0,249	0,249	0,249	0,249	0,248	0,249	0,249
M3	0,210	0,209	0,209	0,209	0,210	0,210	0,210	0,210	0,209	0,210

Table 6.9 Utilization of Machines (Single Pallet)



Graph 6.2 Utilization Plot (Single Pallet)

As clearly visible on graphs, outputs have a low variability over different runs: Utilization is quite constant while Throughput seems oscillating around a mean value. Their mean and variance are shown in Table 6.10.

	TH [job/min]	U(M1)	U(M2)	U(M3)
Mean Value	0,08830369	0	0,249	0,210
Variance	1,877E-06	0	1,692E-07	1,570E-07
St. Dev. %	1,552%	0	0,165%	0,189%

Table 6.10 Mean Statistical Value of Throughput and Utilization (Single Pallet)



Machines' Utilization has a low mean value both for Machine 2 and 3: this is caused by the total absence of queues in the system. Pallets don't waste time in waiting for machining. These two sample values have both a very low percentage of Standard Deviation. This can be attributed to the fact that demand, and so duration of production campaign, is enough high to permit to the pallet to have a distribution on machines over time like the one imposed by probabilistic routing. In simple words, the higher is the number of times the tool simulates the route of the pallet, the higher is the probability that the distribution of pallets over machines follows the probabilistic routing. A provocative example can be done imposing demand equal to 1: each simulation cycle will have a high utilization value for one machine and a zero value on the other.

Throughput swings around its mean value. This is safely attributable to the stochasticity of simulation and it cannot be estimated as an abnormal behavior, as a proof the Standard Deviation is very low. The reliability of the absolute values calculated for Throughput can be analyzed in a simple way: the expected job's cycle time is evaluated using service time and probabilistic routing as described in Eq. 6.5 and then it is compared with Averages Times per Pallet's results applying a simple t Test.

$$Exp\ cycle\ time = 2 \times ([Prob\ routing(1st\ row)] \times [Serv\ Times] + Carrier\ Serv\ Time)$$

*Equation 6.5 Expected Cycle Time*

In this case the Expected Cycle time's result is:

*11,45 minutes*

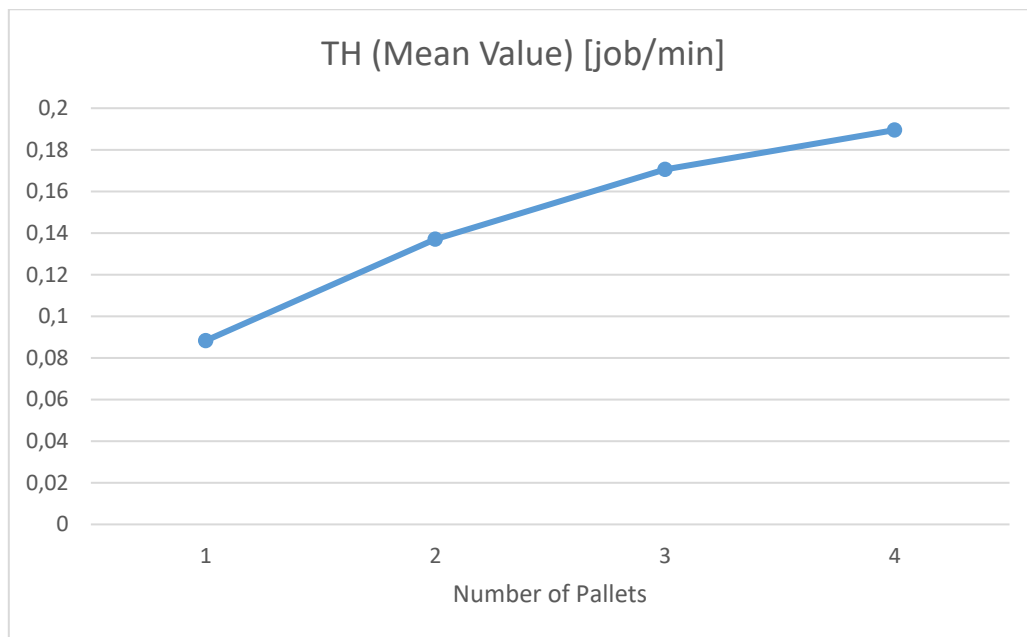
This value is submitted to a T-Test with the values of Average Time per Pallet. The simple T-Test is a statistical test to verify if the average of a set of data differs significantly from a predicted value. The null hypothesis selected is that the mean is equal to 11.45 minutes; the alternative hypothesis states that it is not equal to expected cycle time. Minitab's result of the T-Test is that null hypothesis cannot be rejected; the tool can be considered as reliable.

### 6.2.2 Multiple pallets of the same class

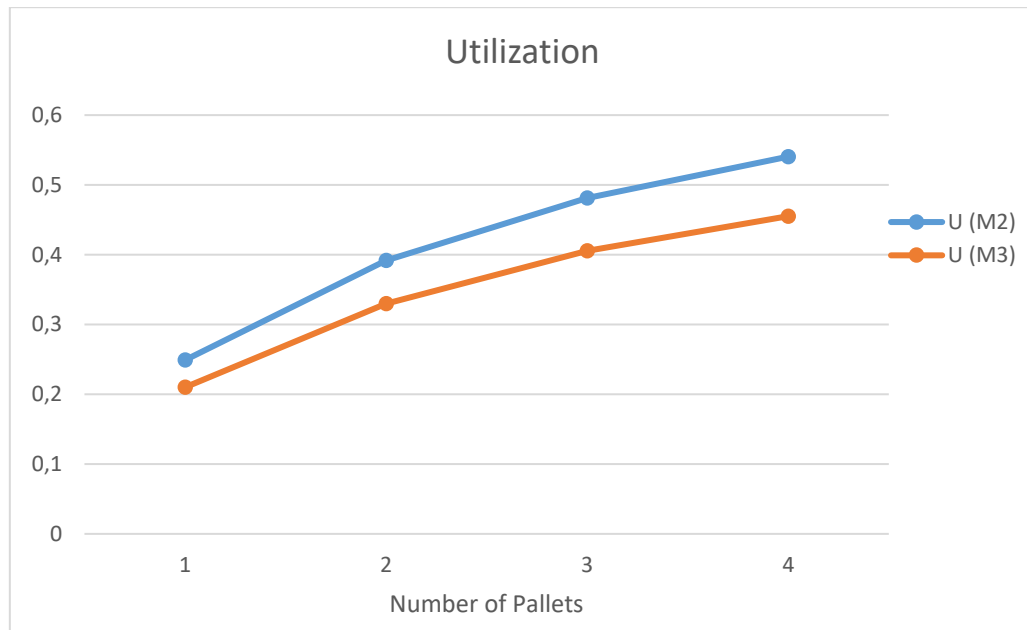
The second experiment is a simple pursuance of the first one: as a sort of What-If analysis, the number of pallets is increased and their effect on performance studied. In Table 6.11 and Graph 6.3 are visible only significant mean values.

	K=2	K=3	K=4
TH (Mean Value) [job/min]	0,13708	0,17059	0,18949
TH (St. Dev. %)	1,830%	2,030%	2,8%
U (M2)	0,3916	0,4813	0,5405
U (M3)	0,3300	0,4055	0,4552

Table 6.11 Mean Statistical Values (Multiple Pallets)



Graph 6.3 Throughput Plot (Multiple Pallets)



Graph 6.4 Utilization of machines (Multiple pallets)

As expected, Throughput rises with the number of pallets. It is important to analyze its trend: it is not linear, but it is a sort of exponential asymptotic behavior. The Throughput does not increase in the same way over steps but the higher is the number of pallets, the lower is the throughput improvement. This is the forecasted behavior of the system, because of waiting time in queues and blocking. These two effects act in different ways: blocking's consequence arises when pallets' quantity exceeds capacity of one or more stations and it increases with the number of jobs. Queues' effect always exists, except for the single pallet case, but its contribution starts to decrease when capacity of queues is approximately fulfilled.

The Utilization trend is similar and it can be explained in the same way. The unique difference is that in this case only blocking effect modifies the performance.

### 6.2.3 Multiple states with single classes

After the validation of the simulation tool, the thesis focuses on the validation of the algorithm, especially from the point of view of the transition analysis. A multiple states experiment is needed. The first one is composed of two states, each one with a single class as shown in Table 6.12.

	State 1	State 2
Class	Class 1	Class 2
Pallets' quantity	4	4
Ratio	1	1

Table 6.12 States compositions (Multiple states with single classes)

This is a very simple case of transition between two states. Significant results are shown in Tables 6.13.

PUT	PUT (%)	No Reconf PUT	No Reconf PUT (%)
120	0,013008	0	0

Table 6.13 Pallets Unused over Time (Multiple States with single classes)

	Period 1	Period 2	Period 3
Throughput [job/min]	0,200569	0	0,189193
St. Dev. % (TH)	1,315%	0,000%	2,568%
Duration [min]	1748,245	30	531,3666
St. Dev. % (D)	1,293%	0,000%	2,487%

Table 6.14 Throughput and Duration over periods (Multiple States with single classes)

	Period 1	Period 2	Period 3	Mean weighted on durations
M1	0,299242	0	0	0,226509
M2	0,606183	0	0,541177	0,583353
M3	0	0	0,45539	0,10477

Table 6.15 Utilization of machines over periods (Multiple States with single classes)

The algorithm divides perfectly the campaign into expected periods. The first is composed by four Class 1 pallets, the second is the reconfiguration one, and it is empty, while the last is characterized by Class 2 with four jobs. In this case, only the reconfiguration step marks the passage between states.

Pallets Unused over Time has a predictable result: the unique loss of pallets' saturation takes place during reconfiguration. The PUT is fixed, due to the fixed time of reconfiguration. Percentage value changes depending on total time behavior. It is trivial to say that No Reconfiguration values are equal to zero.

Utilization's results are like ones evaluated in the precedent test. Each period is characterized by a single class, so utilization's values follows their routing values and their service times. The aggregate value is weighted on period's durations: it is important to underline the true utilization of machines during the whole production campaign.

Throughput analysis is like the one done in the previous validation. First and last periods have similar results, due to the similar composition of states and service times. Reconfiguration period has a throughput equal to zero, but it doesn't really affect the whole productive campaign due to its short duration.

#### 6.2.4 Multiple states with multiple classes

Last validation experiment concerns a two states case, with multiple classes on the first one. Transition becomes more complicated than the one of the previous example. Data of the experiment are described in Table 6.16.

	State 1	State 2
Class	Class 1, Class 2	Class 3
Pallets' quantity	4	4
Ratio	$\frac{1}{2}, \frac{1}{2}$	1

Table 6.16 States composition (Multiple States with multiple classes)

Significant results are shown in Tables 6.17-20.

PUT	PUT (%)	No Reconf PUT	No Reconf PUT (%)
3399,947	0,246691	3279,947	0,24006757

Table 6.17 Pallets Unused Time (Multiple States with multiple classes)

	Period 1	Period 2	Period 3	Period 4
Throughput [job/min]	0,099383	0,150304	0	0,268689
St. Dev. % (TH)	1,319%	1,448%	0,000%	1,067%
Duration [min]	1029,078	1639,973	30	746,2288
St. Dev. % (D)	1,591%	1,250%	0,000%	1,016%

Table 6.18 Throughput and Duration over periods (Multiple States with multiple classes)

	Period 1	Period 2	Period 3	Period 4	Mean weighted on durations
M1	0,15094	0,22002	0	0,22271	0,14981
M2	0,58627	0,44612	0	0,73071	0,38747
M3	0,23564	0	0	0,28073	0,07038

Table 6.19 Utilization of machines (Multiple States with multiple classes)

Period 1	Period 2	Period 3	Period 4
1	1		3
1	1		3
2			3
2			3

Table 6.20 Periods Composition (Multiple States with multiple classes)

Due to the multiple classes of the first state, periods compositions can differ from one cycle to the other, depending on class demand fulfillment. In this case, all the cycles present the same composition described in Table 6.20. In this case the second period is not a reconfiguration one, even if it comes after a class fulfillment. The algorithm must respect the possibility matrix and it can't impose the contemporary production of Class 1 and Class 3, so the system must wait for Class 1 fulfillment before insertion of Class 3. Reconfiguration is postponed to third period.

Results are like the ones of the previous example, except for PUT and Throughput. Two unsaturated periods affect Pallets Unused over Time. In this case the Reconfiguration period provides only a small percentage of the PUT (less than 1%), the main responsible is the second period.

Throughput analysis is different from precedent ones. The first period has a low Throughput value, despite its four pallets composition. This result may be caused by a high value of blocking and waiting time, provoked by probabilistic routing matrix of Class 1 and Class 2. Instead, the last period has a very high Throughput: this may be attributed to the service time of Class 3 in the L/U station which is low in relation with other classes' ones.

### 6.3 Conclusion

All the results obtained are expected and they respect data and values of each test. Both simulation tool and algorithm can be considered a valid solution for performance evaluation of a Flexible Manufacturing System.



# 7 Performance Evaluation

## 7.1 Introduction

The main objective of this research is demonstrating the profitability of the application of a modern pallet with zero points mounted on. The first method used is the comparison between performances: it should be demonstrated whether FMS performances using the new pallet are better or not than ones with a standard pallet.

This analysis provides that both systems work with the same production strategy, which is the one defined by the algorithm, and with the same configuration of stations. The unique difference between these systems is related to reconfiguration duration: the standard pallet needs more time than the modern one to be reconfigured. The statistical analysis has been performed with an ANOVA test on a  $2^k$  factorial plan.

ANOVA results have been compared then with performances of a Flexible Manufacturing System employing standard pallets with a different strategy. This strategy represents the method to obtain best possible performances with standard pallets. This secondary study will comprehend an economic analysis to identify whether and in which conditions the new pallet is preferable than the old one and vice versa.

## 7.2 Performance comparison

Performances of the system have not to be evaluated in a specific case. The aim of the research is showing preferability of the new pallet in general, without any alteration done by composition or features of cases. The solution is the analysis of several production cases, randomly generated, each one with different characteristics: the method chosen to generate an experimental plan with these attributes is the factorial experiment.

The Flexible Manufacturing System considered is composed by identical machines: each piece can be machined by every one of them in the same way and lasting the same service time. Because of this feature, each machining station has the same probability to be reached by each kind of job.

There are some features that are fixed throughout all the cases. This choice has been made to get comparable performance results and to avoid a too complicate experimental plan. These features are: number of machines, minimum and maximum number of classes per state, possibility matrix, service time for Carrier

and L/U, capacity of queues and probabilistic routing matrix. Their values used for experiments are shown in Tables 7.1-5.

Number of machines	Classes' range per state
3 (L/U and Carrier excluded)	2-5

Table 7.1 Fixed data for experiments

	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	C 10
C 1	1	1	1	1	1	1	0	1	1	1
C 2	1	1	1	1	1	0	1	1	1	1
C 3	1	1	1	0	0	1	1	1	1	1
C 4	1	1	0	1	1	1	1	1	1	1
C 5	1	1	0	1	1	1	1	1	0	1
C 6	1	0	1	1	1	1	1	0	1	1
C 7	0	1	1	1	1	1	1	1	1	1
C 8	1	1	1	1	1	0	1	1	1	1
C 9	1	1	1	1	0	1	1	1	1	1
C 10	1	1	1	1	1	1	1	1	1	1

Table 7.2 Fixed Possibility Matrix for experiments

	Service Time (equal for all classes) [min]
Carrier	0,5
Load/Unload Station	1

Table 7.3 Fixed Carrier and L/U Service Times for experiments

Carrier	L/U	M1	M2	M3
1	12	2	2	2

Table 7.4 Fixed Capacity of queues for experiments

	Carrier	L/U	M1	M2	M3
Carrier	0	0,5	0,16667	0,16667	0,16667
L/U	1	0	0	0	0
M1	1	0	0	0	0
M2	1	0	0	0	0
M3	1	0	0	0	0

Table 7.5 Fixed Probabilistic Routing Matrix for experiments

### 7.2.1 Factorial Experiment

The factorial experiment's design consists in two or more factors, each one with a certain number of levels, and it defines a plan of experiments representing all the possible combinations of levels of factors. In this way, the system is tested on different production cases with various conditions. Each experiment can be evaluated on different replicates: they are random cases generated using the same levels of factors, so the same conditions. The factorial design provides the capability to study not only main effects of factors, but also interactions between them.

Six different factors have been chosen for this kind of experiment. The main one is the Reconfiguration Time (TREC), which makes the distinction between modern and old pallets. The remaining factors are Number of States (NS), Number of Pallets (K), Number of Classes (NC), Range of Demand (RD) and Machining Time (TMAC).

In this case, a  $2^k$  factorial experiment has been chosen. It is a factorial experiment with only two levels for each factor. Each factor is studied in two distinct conditions, one high (+) and one low (-). It is a useful tool to simplify the experimental plan when number of factors is quite high, like this analysis. The amount of experiments is equal to  $2^k$  (k is the number of factors): 64 experiments compose this experimental plan as shown in Table 7.6.

NS	K	NC	RD	TREC	TMAC	
-	-	-	-	-	-	1
+	-	-	-	-	-	2
-	+	-	-	-	-	3
+	+	-	-	-	-	4
-	-	+	-	-	-	5
+	-	+	-	-	-	6
-	+	+	-	-	-	7
+	+	+	-	-	-	8
-	-	-	+	-	-	9
+	-	-	+	-	-	10
-	+	-	+	-	-	11
+	+	-	+	-	-	12
-	-	+	+	-	-	13
+	-	+	+	-	-	14
-	+	+	+	-	-	15
+	+	+	+	-	-	16
-	-	-	-	+	-	17
+	-	-	-	+	-	18
-	+	-	-	+	-	19
+	+	-	-	+	-	20
-	-	+	-	+	-	21
+	-	+	-	+	-	22
-	+	+	-	+	-	23
+	+	+	-	+	-	24
-	-	-	+	+	-	25
+	-	-	+	+	-	26
-	+	-	+	+	-	27
+	+	-	+	+	-	28
-	-	+	+	+	-	29
+	-	+	+	+	-	30
-	+	+	+	+	-	31
+	+	+	+	+	-	32
-	-	-	-	-	+	33
+	-	-	-	-	+	34
-	+	-	-	-	+	35
+	+	-	-	-	+	36
-	-	+	-	-	+	37
+	-	+	-	-	+	38
-	+	+	-	-	+	39
+	+	+	-	-	+	40
-	-	-	+	-	+	41
+	-	-	+	-	+	42
-	+	-	+	-	+	43
+	+	-	+	-	+	44
-	-	+	+	-	+	45
+	-	+	+	-	+	46
-	+	+	+	-	+	47
+	+	+	+	-	+	48
-	-	-	-	+	+	49
+	-	-	-	+	+	50
-	+	-	-	+	+	51
+	+	-	-	+	+	52
-	-	+	-	+	+	53
+	-	+	-	+	+	54
-	+	+	-	+	+	55
+	+	+	-	+	+	56
-	-	-	+	+	+	57
+	-	-	+	+	+	58
-	+	-	+	+	+	59
+	+	-	+	+	+	60
-	-	+	+	+	+	61
+	-	+	+	+	+	62
-	+	+	+	+	+	63
+	+	+	+	+	+	64

Table 7.6 2<sup>k</sup> Factorial Plan

## 7.2.2 Factors Description

The aim of this statistical analysis is the estimation of the effects that factors could have on FMS performances. Factors' levels have been chosen to have a high level and a low level; use of levels with similar values is quite useless. Choices are shown in Tables 7.7 and 7.8.

	NS	K	NC	RD	TREC [min]
-	5	7	6	[50 150]	20
+	10	12	10	[200 300]	120

Table 7.7 Factors Levels (Factors NS - K - NC - RD - TREC)

	TMAC [min]
-	[4,34; 4,72; 3,76; 2,42; 2,69; 3,49; 2,93; 4,18; 3,45; 3,88]
+	[43,4; 47,2; 37,6; 24,2; 26,9; 34,9; 29,3; 41,8; 34,5; 38,8]

Table 7.8 Factors Levels (Factor TMAC)

Number of States represents the precise number of predefined states the system must pass through. The low level is fixed to 5, in order to analyze a considerable number of passages between states and not only a few. The high level is double the low one to study a time horizon higher and higher and to increase a lot the quantity of transitions.

Number of Pallets defines the quantity of pallets available and so the maximum number of pallets that the system could machine contemporarily. Levels have been chosen to study different situations of starving and blocking that can happen in the FMS, especially in fractioned periods for starving and in full periods for blocking.

Number of Classes is the factor that describes the production mix of the campaign. It simply defines the number of different classes of pallets are used during production campaign. It is important to analyze whether FMS performances change increasing or decreasing quantity of different classes. Each class has its own machining times and demand.

Range of Demand defines the size of lots used in the production campaign. The low level represents a production campaign with small lots, while the high one

describes a system working with big lots. This factor imposes a sort of threshold to demand: initial demand of each class and any possible future increment must stay within the limits defined by RD interval. The demand is expressed in number of pallets.

Machining Time is the factor that describes modification in service times of machining stations. The low level has been chosen to represent a Flexible Manufacturing System working with pieces that don't need much time to be machined, their range is about 2-5 minutes. The high level has values ten times bigger than low level ones and it should represent a production campaign with parts long to be machined.

Reconfiguration Time is the most important factor studied and its effect is the main target of this factorial plan. It describes how much time operators need to reconfigure pallets just out of the production system. Its two levels make the distinction between the new reconfigurable pallet and the old one. The low level represents the modern pallet and its value has been set to 20 minutes, following results of some practical tests on the physical pallet. It is a very short time compared to 120 minutes fixed for high level, representing the standard pallet. This value has been chosen to cover all the mechanical operations that the standard pallet needs to be reconfigured. It is crucial to study the effect of this factor on FMS performances: the objective is to analyze if they significantly increase when the new pallet is employed.

### 7.2.3 Performance Indicators

The multiplicity of factors makes experiments with conditions sometimes very far one from the other. This fact complicates the statistical analysis, since a comparable performance indicator is needed. KPIs already shown in Chapter 6 are not useful. Total Time depend on demand that is different for each experiment. Throughput is related to machining times and production mix, which are factors of the analysis. Utilization of machines is not suitable for production performance evaluation. PUT can be used only for some minor considerations. Therefore, new performance indicators have been used to compare all the experiments.

The first one is the Adjusted Throughput (THadj): it is a throughput weighted on machining rates of pallets' classes used in the system (machining rate is the inverse of machining time). Since each experiment has its own production mix, different from the others both for classes and for demands, it is required to align throughput to the same reference in terms of machining rate. A situation with a high demand of a class having a long machining time (and so a low machining rate) is disadvantaged against a replicate, maybe of the same experiment, with a low demand of that class. The idea is that Throughputs must be transformed as if

they had the same production mix, so as if they have the same Mean Machining Rate (MMR). The reference for MMR is called RMR (Reference Machining Rate). Values of MMR and RMR should be evaluated before and then applied in the THadj formula. MMR and RMR formulas are shown in Eqs. 7.1-2.

$$RMR = \frac{\sum_{i=1}^{\text{number of classes}} \text{machining rate}(i)}{\text{number of classes}}$$

Equation 7.1 Reference Machining Rate (RMR)

$$MMR = \frac{\sum_{i=1}^{\text{number of classes}} (\text{demand}(i) \times \text{machining rate}(i))}{\sum_{i=1}^{\text{number of classes}} \text{demand}(i)}$$

Equation 7.2 Mean Machining Rate (MMR)

Once evaluated MMR and RMR, THadj can be calculated with formula described in Eq 7.3.

$$TH_{adj} = TH \times \left(1 - \left(\frac{MMR - RMR}{RMR}\right)\right)$$

Equation 7.3 Adjusted Throughput (THadj)

If MMR is higher than RMR, THadj will be lower than Throughput, while an Adjusted Throughput greater than standard one means that  $MMR < RMR$ . The rate of increasing or decreasing is defined by the rate of growth of MMR with respect to RMR. For example, if the Mean Machining Rate is 5 percent higher than Reference Machining Rate, Adjusted Throughput will be evaluated as  $(1-0,05) * TH$ .

Adjusted Throughput is a good indicator for the productivity and speed of the system, but it is limited to situations with the same composition of machining times, or at least with machining times of the same order of magnitude. This



boundary makes this indicator not useful for the totality of experiments, but only for those with the same Machining Time level (TMAC).

The second KPI is called Exploitation Factor (EF). It evaluates how much production time has been exploited for machining. It is a good indicator for the estimation of time wasted on non-value adding processes, such as waiting or moving between stations. As can be seen on its formula in Eq. 7.4, Exploitation Factor is an approximated indicator, since it is based on mean machining times and not on simulated ones.

$$EF = \frac{\sum_{i=1}^{\text{number of classes}} \text{demand}(i) \times \text{machining time}(i)}{\text{Total production time}}$$

Equation 7.4 Exploitation Factor (EF)

The higher is the Exploitation Factor, the lower is the waste of time during production campaign. EF is simply a rate and it can be utilized for any comparison, regardless of conditions and factors.

#### 7.2.4 Experiments Results (Exploitation Factor)

Each experiment represents a defined mix of levels and so a certain condition of the system. Total demand and composition of classes are the unique characteristics that have not been determined a priori. They are randomly generated for each replicate, to get an analysis as free as possible from alterations done by specific composition of cases.

It has been chosen to evaluate three replicates per each experiment: having more than one random case for each experiment is useful to get results free from alterations even within same conditions. Each replicate is composed of 5 repetitions. A repetition is an evaluation of the same replicate: in this case, they are useful to have an accurate result since simulation takes part in every evaluation. Therefore, the result of each replicate is estimated as the mean of results of its five repetitions.

The factorial plan is composed of 64 experiments, each one with three replicates. The indicator chosen for the first statistical test is the Exploitation Factor, since it is the only one with a comparable value on all the factors. Results are shown in Table 7.9. Each replicate is described by its mean value, variance, and range.

EF	Replicate I			Replicate II			Replicate III		
	Mean	Var	Range	Mean	Var	Range	Mean	Var	Range
1	1,6542	0,0032	0,1391	1,5743	0,0013	0,0860	1,4467	0,0020	0,1153
2	1,9484	0,0052	0,1801	1,6037	0,0018	0,1003	1,5318	0,0013	0,0906
3	1,9152	0,0014	0,0896	1,7152	0,0010	0,0826	2,0384	0,0039	0,1601
4	1,9312	0,0113	0,2606	2,2315	0,0010	0,0822	1,9833	0,0007	0,0612
5	1,6506	0,0004	0,0477	1,8623	0,0012	0,0801	1,7720	0,0030	0,1514
6	1,7987	0,0004	0,0516	1,7875	0,0011	0,0883	1,6316	0,0033	0,1441
7	1,6224	0,0008	0,0777	1,5413	0,0010	0,0815	1,7571	0,0023	0,1270
8	1,7773	0,0018	0,1187	1,8723	0,0024	0,1218	1,6855	0,0027	0,1249
9	1,5685	0,0010	0,0791	1,6692	0,0005	0,0566	1,6934	0,0010	0,0835
10	1,9928	0,0015	0,1038	1,5762	0,0004	0,0559	1,7289	0,0007	0,0500
11	1,9175	0,0026	0,1315	1,7151	0,0009	0,0628	2,0814	0,0025	0,1215
12	2,0142	0,0005	0,0572	1,8211	0,0005	0,0535	1,8118	0,0023	0,1215
13	1,6568	0,0016	0,1110	1,6917	0,0023	0,1206	1,5067	0,0010	0,0735
14	1,6564	0,0016	0,1027	1,8199	0,0006	0,0663	1,7378	0,0001	0,0224
15	1,7052	0,0009	0,0747	1,9035	0,0032	0,1314	2,0006	0,0002	0,0334
16	1,9260	0,0004	0,0494	1,9714	0,0018	0,1025	1,8986	0,0006	0,0536
17	1,6722	0,0018	0,0962	1,6373	0,0027	0,1362	1,5131	0,0019	0,0985
18	1,5703	0,0012	0,0852	1,4855	0,0014	0,0895	1,3536	0,0030	0,1332
19	1,5524	0,0009	0,0796	1,4721	0,0002	0,0341	1,7091	0,0008	0,0749
20	1,6207	0,0011	0,0763	1,8086	0,0020	0,1070	1,7043	0,0008	0,0670
21	1,5973	0,0013	0,0764	1,5459	0,0015	0,0978	1,3885	0,0005	0,0491
22	1,6032	0,0008	0,0656	1,6728	0,0012	0,0814	1,4077	0,0005	0,0576
23	1,5024	0,0012	0,0978	1,6148	0,0015	0,0994	1,7131	0,0018	0,1049
24	1,6435	0,0018	0,0963	1,7160	0,0008	0,0674	1,7917	0,0044	0,1622
25	1,4961	0,0003	0,0386	1,4559	0,0007	0,0612	1,5378	0,0016	0,0989
26	1,5326	0,0010	0,0819	1,5698	0,0003	0,0401	1,6583	0,0008	0,0617
27	1,4819	0,0007	0,0761	1,7280	0,0052	0,1616	2,0553	0,0013	0,1005
28	1,8772	0,0041	0,1686	1,6246	0,0002	0,0376	1,8503	0,0005	0,0511
29	1,6585	0,0023	0,1208	1,6723	0,0040	0,1312	1,6193	0,0022	0,1156
30	1,5785	0,0038	0,1327	1,7068	0,0002	0,0360	1,6512	0,0002	0,0378
31	1,8336	0,0004	0,0519	1,6745	0,0010	0,0805	1,7471	0,0001	0,0248
32	1,7392	0,0002	0,0306	1,8746	0,0003	0,0482	1,7805	0,0005	0,0557
33	2,2913	0,0112	0,2708	2,0223	0,0105	0,2699	2,1428	0,0207	0,3505
34	2,1050	0,0075	0,2186	1,8531	0,0019	0,1209	2,1167	0,0041	0,1328
35	2,3944	0,0021	0,1153	2,4063	0,0095	0,2457	2,0314	0,0055	0,2068
36	2,0970	0,0092	0,2224	2,3500	0,0134	0,3192	2,3621	0,0089	0,2473
37	1,9033	0,0144	0,2557	2,0799	0,0052	0,1771	1,8701	0,0039	0,1471
38	2,1439	0,0045	0,1473	2,0305	0,0081	0,2237	2,0061	0,0079	0,2443
39	2,1914	0,0055	0,2026	2,2861	0,0076	0,1961	2,2762	0,0044	0,1860
40	2,5011	0,0089	0,2592	2,2496	0,0053	0,1817	2,2055	0,0019	0,1055
41	1,9947	0,0015	0,0972	2,3074	0,0090	0,2190	2,4305	0,0034	0,1622
42	1,9930	0,0008	0,0689	2,0002	0,0014	0,1045	1,8903	0,0030	0,1302

43	2,2677	0,0050	0,1825	2,3177	0,0021	0,1145	2,1283	0,0036	0,1443
44	2,6185	0,0452	0,4427	2,4104	0,0035	0,1511	2,4835	0,0024	0,1237
45	2,0922	0,0013	0,0936	2,0421	0,0039	0,1604	2,0417	0,0092	0,2518
46	2,0810	0,0009	0,0724	2,0687	0,0044	0,1620	2,1598	0,0003	0,0413
47	2,0745	0,0011	0,0796	2,1815	0,0021	0,1216	2,1975	0,0014	0,0972
48	2,2806	0,0023	0,1203	2,2109	0,0013	0,0862	2,1695	0,0016	0,1033
49	1,9013	0,0009	0,0691	2,0133	0,0113	0,2684	1,8086	0,0164	0,2887
50	1,9434	0,0013	0,1016	1,9435	0,0016	0,1045	2,0352	0,0026	0,1213
51	2,1722	0,0043	0,1659	2,2154	0,0049	0,1755	2,3045	0,0063	0,2107
52	2,4994	0,0005	0,0556	2,7234	0,0035	0,1553	2,4768	0,0026	0,1247
53	2,2599	0,0016	0,1043	2,0404	0,0041	0,1629	2,7253	0,0108	0,2656
54	2,1740	0,0038	0,1421	1,9888	0,0033	0,1247	2,0451	0,0029	0,1216
55	2,1678	0,0033	0,1370	1,9694	0,0031	0,1431	2,2560	0,0052	0,1854
56	2,2216	0,0007	0,0607	2,1856	0,0123	0,2472	2,1341	0,0068	0,2218
57	1,8263	0,0027	0,1327	2,1049	0,0019	0,1187	2,4045	0,0052	0,1819
58	2,0908	0,0005	0,0558	2,1122	0,0019	0,1082	2,2270	0,0014	0,0859
59	2,3747	0,0118	0,2741	2,3502	0,0044	0,1664	2,0339	0,0013	0,0888
60	2,2278	0,0051	0,1920	2,2476	0,0009	0,0710	2,4425	0,0022	0,1189
61	2,0623	0,0036	0,1575	1,9908	0,0062	0,2178	2,1070	0,0013	0,0876
62	2,1231	0,0026	0,1386	2,0393	0,0042	0,1743	2,1618	0,0006	0,0530
63	2,3025	0,0043	0,1390	2,2829	0,0031	0,1524	2,2953	0,0043	0,1559
64	2,3256	0,0030	0,1441	2,1834	0,0029	0,1235	2,3276	0,0032	0,1496

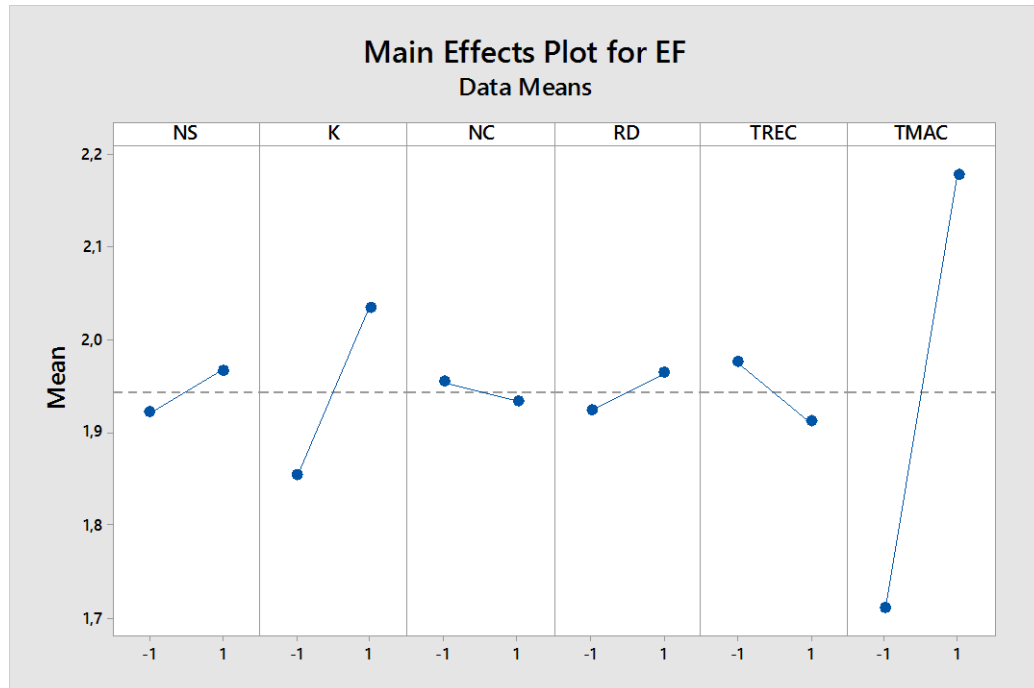
Table 7.9 Experiments Results (Exploitation Factor)

These results have been analyzed to discover possible effects of factors on performances of the system. The test chosen for this analysis is the ANOVA test.

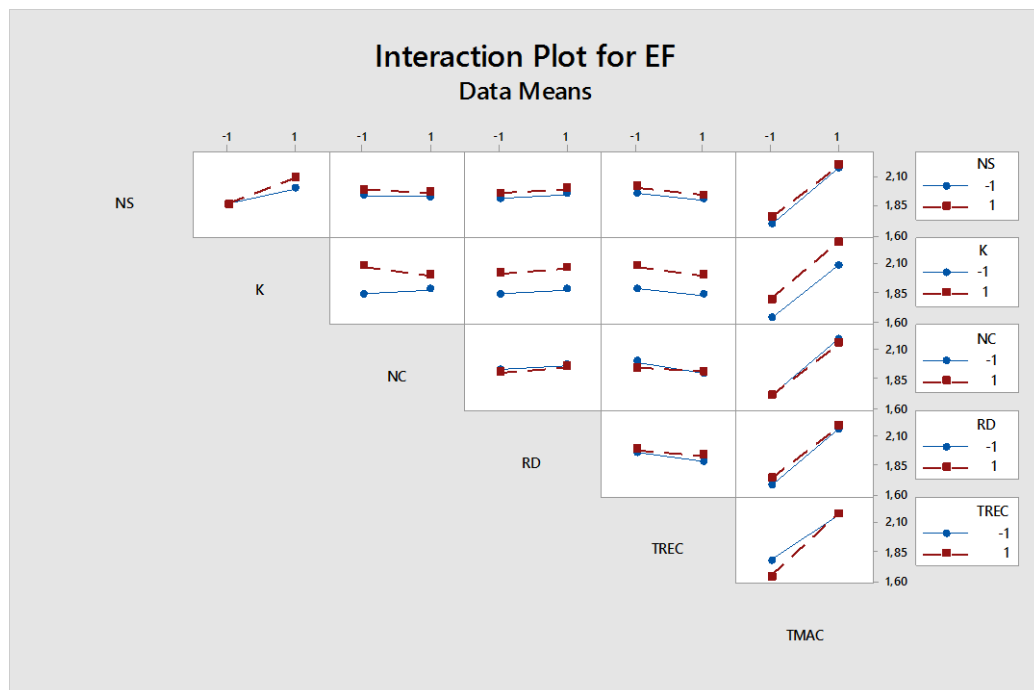
Analysis of Variance (ANOVA) is a statistical test that can identify differences of means of groups of data analyzing their variabilities. Therefore, it can discover whether factors are modifying responses or not. Its method is based on F tests carried out on relationships between variances within groups and variances through groups. It could estimate not only main effects of factors, but also any possible interaction between them. All the effects are used for the creation of a linear model that describes behavior of responses as a function of factors.

Since the number of factors is high, a General Linear Model (GLM) has been used. GLM is the most flexible form of ANOVA, it can model multiple predictor variables, both categorical and continuous. Statistical tests have been developed on Minitab software.

Main effects and interactions plots make a first screening of results: they are built on simple means of data grouped by levels and they can give an idea of possible results of the GLM.



Graph 7.1 Main Effects Plot (Exploitation Factor)



Graph 7.2 Interaction Plot (Exploitation Factor)

In the main effects plot it is clearly visible a possible significant effect of the Machining Time and maybe of the Number of Pallets. The interaction plot seems to give no information, since trends of each couple are quite parallel.

The number of replicates per run gives enough degrees of freedom to apply a complete model for GLM: this means that interactions up to the 6<sup>th</sup> order are included in the linear model.

The main output of this statistical is the ANOVA table, that is shown here:

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	63	14,3935	0,2285	13,48	0,000
Linear	6	12,5246	2,0874	123,14	0,000
NS	1	0,0994	0,0994	5,87	0,017
K	1	1,5818	1,5818	93,31	0,000 ←
NC	1	0,0191	0,0191	1,13	0,291
RD	1	0,0777	0,0777	4,58	0,034
TREC	1	0,1982	0,1982	11,69	0,001 ←
TMAC	1	10,5484	10,5484	622,24	0,000 ←
2-Way Interactions	15	0,6817	0,0454	2,68	0,001
NS*K	1	0,1022	0,1022	6,03	0,015
NS*NC	1	0,0028	0,0028	0,16	0,688
NS*RD	1	0,0007	0,0007	0,04	0,839
NS*TREC	1	0,0020	0,0020	0,12	0,732
NS*TMAC	1	0,0146	0,0146	0,86	0,355
K*NC	1	0,1687	0,1687	9,95	0,002 ←
K*RD	1	0,0014	0,0014	0,08	0,777
K*TREC	1	0,0072	0,0072	0,42	0,516
K*TMAC	1	0,0170	0,0170	1,01	0,318
NC*RD	1	0,0000	0,0000	0,00	0,963
NC*TREC	1	0,0544	0,0544	3,21	0,076
NC*TMAC	1	0,0133	0,0133	0,78	0,377
RD*TREC	1	0,0083	0,0083	0,49	0,484
RD*TMAC	1	0,0177	0,0177	1,05	0,308
TREC*TMAC	1	0,2713	0,2713	16,01	0,000 ←
3-Way Interactions	20	0,3015	0,0151	0,89	0,601
NS*K*NC	1	0,0166	0,0166	0,98	0,325
NS*K*RD	1	0,0348	0,0348	2,05	0,154
NS*K*TREC	1	0,0026	0,0026	0,15	0,696
NS*K*TMAC	1	0,0366	0,0366	2,16	0,144
NS*NC*RD	1	0,0087	0,0087	0,51	0,475
NS*NC*TREC	1	0,0414	0,0414	2,44	0,121
NS*NC*TMAC	1	0,0022	0,0022	0,13	0,717
NS*RD*TREC	1	0,0000	0,0000	0,00	0,960
NS*RD*TMAC	1	0,0006	0,0006	0,03	0,853
NS*TREC*TMAC	1	0,0141	0,0141	0,83	0,364
K*NC*RD	1	0,0688	0,0688	4,06	0,046
K*NC*TREC	1	0,0026	0,0026	0,15	0,695
K*NC*TMAC	1	0,0016	0,0016	0,09	0,759
K*RD*TREC	1	0,0005	0,0005	0,03	0,858
K*RD*TMAC	1	0,0267	0,0267	1,58	0,211
K*TREC*TMAC	1	0,0005	0,0005	0,03	0,865
NC*RD*TREC	1	0,0005	0,0005	0,03	0,865
NC*RD*TMAC	1	0,0311	0,0311	1,84	0,178
NC*TREC*TMAC	1	0,0001	0,0001	0,01	0,932
RD*TREC*TMAC	1	0,0112	0,0112	0,66	0,417
4-Way Interactions	15	0,3104	0,0207	1,22	0,265
NS*K*NC*RD	1	0,0026	0,0026	0,15	0,698
NS*K*NC*TREC	1	0,0045	0,0045	0,27	0,607
NS*K*NC*TMAC	1	0,0328	0,0328	1,94	0,166

NS*K*RD*TREC	1	0,0551	0,0551	3,25	0,074
NS*K*RD*TMAC	1	0,0158	0,0158	0,93	0,336
NS*K*TREC*TMAC	1	0,0089	0,0089	0,52	0,470
NS*NC*RD*TREC	1	0,0032	0,0032	0,19	0,666
NS*NC*RD*TMAC	1	0,0070	0,0070	0,41	0,521
NS*NC*TREC*TMAC	1	0,0795	0,0795	4,69	0,032
NS*RD*TREC*TMAC	1	0,0028	0,0028	0,16	0,687
K*NC*RD*TREC	1	0,0148	0,0148	0,87	0,352
K*NC*RD*TMAC	1	0,0000	0,0000	0,00	0,974
K*NC*TREC*TMAC	1	0,0816	0,0816	4,82	0,030
K*RD*TREC*TMAC	1	0,0002	0,0002	0,01	0,919
NC*RD*TREC*TMAC	1	0,0016	0,0016	0,10	0,758
5-Way Interactions	6	0,5742	0,0957	5,64	0,000
NS*K*NC*RD*TREC	1	0,0167	0,0167	0,99	0,322
NS*K*NC*RD*TMAC	1	0,0288	0,0288	1,70	0,195
NS*K*NC*TREC*TMAC	1	0,0438	0,0438	2,58	0,110
NS*K*RD*TREC*TMAC	1	0,0650	0,0650	3,84	0,052
NS*NC*RD*TREC*TMAC	1	0,0745	0,0745	4,40	0,038
K*NC*RD*TREC*TMAC	1	0,3452	0,3452	20,36	0,000 ←
6-Way Interactions	1	0,0012	0,0012	0,07	0,794
NS*K*NC*RD*TREC*TMAC	1	0,0012	0,0012	0,07	0,794
Error	128	2,1699	0,0170		
Total	191	16,5634			

First column defines degrees of freedom of each factor. Adj SS stays for Adjusted Sum of Squares. The sum of squares represents a measure of variation or deviation from the mean. It is calculated as a summation of the squares of the differences from the mean. The calculation of the total sum of squares considers both the sum of squares from the factors and from randomness or error. It is adjusted because it doesn't depend on factors order. Adj MS is the Adjusted Mean Square, an estimation of population variance evaluated with DF and Adj SS. F-Value column represents values to be used in the F test; it is based on ratio between Adj MS of the effect and the one of the error. The null hypothesis of the F Test is that there is no difference between means: rejecting it signifies that the effect is significant. The last column is the p-value: it is the probability of rejecting the null hypothesis when it is true.

Reliability of ANOVA results must be checked before analyzing them. This is based on normality and equal variances of data with respect to the linear model, since they are preliminary assumptions of the ANOVA. These features can be tested on residuals: they are evaluated as the difference between observed values and ones by the model. Both normality test and test for equal variances carried out on residuals give positive results.

The significance level chosen in this research is 0.05 %: this is the threshold imposed for rejecting null hypothesis in the F Test. This means that if the p-value is under this limit, null hypothesis can be rejected.

Red arrows point out effects and interactions with a p-value less than 0.05%: they can be considered significant effects. These are main effects K, TREC and TMAC and interactions K\*NC, TREC\*TMAC and a fifth order interaction.

The effect of Number of Pallets is intuitive: the higher is the number of pallets the lower is the probability of starving for machining centers. A high value of K involves a better exploitation of machines in value adding activities. Main effects plot quietly predicted this behavior.

The Machining Time effect is largely predictable with the main effects plot. This can be explained with the relationship between machining times and other service and reconfiguration times. If the Machining Time grows up, its ratio with setup times increases: the time fraction spent by each pallet in non-value adding processes, such as moving pallets or loading/unloading, becomes relatively small. Consequently, most of the time is consumed for machining activities.

The fifth order interaction is discarded. It is quite impossible that performances of the system depend on an effect so complicated. The interaction K\*NC is not easy to be explained, a deeper analysis is needed. Pairwise comparisons' test has been used to verify significance of single difference of means related to this interaction. Two different significance level have been considered, 95% and 99%, and the Tukey constant has been chosen. Minitab outputs are shown here:

**Tukey Pairwise Comparisons: Response = EF, Term = K\*NC**

Grouping Information Using the Tukey Method and 95% Confidence

K*NC	N	Mean	Grouping
1 -1	48	2,07339	A
1 1	48	1,99417	B
-1 1	48	1,87192	C
-1 -1	48	1,83258	C

Means that do not share a letter are significantly different.

**Tukey Pairwise Comparisons: Response = EF, Term = K\*NC**

Grouping Information Using the Tukey Method and 99% Confidence

K*NC	N	Mean	Grouping
1 -1	48	2,07339	A
1 1	48	1,99417	A
-1 1	48	1,87192	B
-1 -1	48	1,83258	B

Means that do not share a letter are significantly different.

The main responsible for difference of these means is clearly the effect of Number of Pallets. Its interaction with NC is visible only with a 95% comparison, the effect of

production mix disappears increasing significance level to 99%. The effect of interaction K\*NC can be considered as a secondary effect, a consequence of the main effect Number of Pallets. Its physical explanation can be ascribed to an excessive complication of cases when pallets are several and production mix is wide.

Most important results of this General Linear Model analysis are effects related to Reconfiguration Time. Its main effect is significant, that means that a low reconfiguration time can increase performances of the Flexible Manufacturing System. The physical meaning is associated to reduction of time spent in reconfiguration periods. They are periods working with a fraction, maybe small, of the total number of pallets available; for the same reason of the main effect K, performances decrease during these periods.

A better analysis of Reconfiguration Time effect is done studying its interaction with Machining Time. As for K\*NC, pairwise comparisons have been carried out. Minitab results are shown here:

### **Tukey Pairwise Comparisons: Response = EF, Term = TREC\*TMAC**

Grouping Information Using the Tukey Method and 95% Confidence

TREC*TMAC	N	Mean	Grouping
1 1	48	2,18287	A
-1 1	48	2,17194	A
-1 -1	48	1,77834	B
1 -1	48	1,63890	C

Means that do not share a letter are significantly different

### **Tukey Pairwise Comparisons: Response = EF, Term = TREC\*TMAC**

Grouping Information Using the Tukey Method and 99% Confidence

TREC*TMAC	N	Mean	Grouping
1 1	48	2,18287	A
-1 1	48	2,17194	A
-1 -1	48	1,77834	B
1 -1	48	1,63890	C

Means that do not share a letter are significantly different.

Outputs are the same for both significance levels. There is an important result in this comparison: a couple of means is not significantly different (group A). This is composed by mean (1,1) and mean (-1,1), the ones with the Machining Time at the high level. Even if they have different Reconfiguration Time, there is no difference in responses, while couples with low TMAC level and different TREC level (groups B and C) are discernible.

The information given by the interaction TREC\*TMAC is interesting: Reconfiguration Time effect is significant only for those cases with a low Machining Time. The loss of performances during reconfiguration periods is not



relevant when Machining Time is high, maybe of the same order of magnitude of Reconfiguration Time. In these cases, for both TREC levels, reconfiguration periods are quite infinitesimal with respect to the whole production campaign: their contributes to performances can be easily neglected.

After those considerations, the General Linear Model describing behavior of data is built, simplified with only significant factors:

$$EF = 1,94301 + 0,09077 K - 0,03213 TREC + 0,23439 TMAC - 0,02964 K*NC + 0,03759 TREC*TMAC$$

This function can't be applied for evaluations of the Exploitation Factor, since GLM has been made with a factorial plan and so with high and low levels. Nonetheless, it is a resume of the ANOVA test, showing significant effects, their trends and magnitudes.

Values of R-Squared achieved prove the goodness of fit of the linear model. R-squared is a statistical measure of how close the data are to the fitted regression line; it is the percentage of the response variable variation that is explained by a linear model. It can assume any value between 0 and 1: for example, a R<sup>2</sup> equal to 0,76 means that the model represents the 76% of variability of data around mean. When the number of coefficients of the model increases, the R-squared can grow up without any real improvement in variability prediction: in these cases, the Adjusted R Squared is preferred. Minitab results about these indicators are shown here; both R-Squared and Adjusted R<sup>2</sup> are over 80%.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,130201	86,90%	80,45%	70,52%

Coefficients of the model are not equally divided: Machining Time is the highest one, followed by its interaction with Reconfiguration Time. Reconfiguration Time is significant, but it has been explained that its effect influences performances only for those cases with low TMAC.

This statistical analysis demonstrates that some factors affects performances of the system. The reconfiguration time is one of them: if TREC decreases, performances will increase. However, the ANOVA test reveals that this statement is true only if machining times are low. Therefore, another statistical analysis has been conducted. It is based on experiments with low machining times, in order to study deeply the influence of factors on performances.

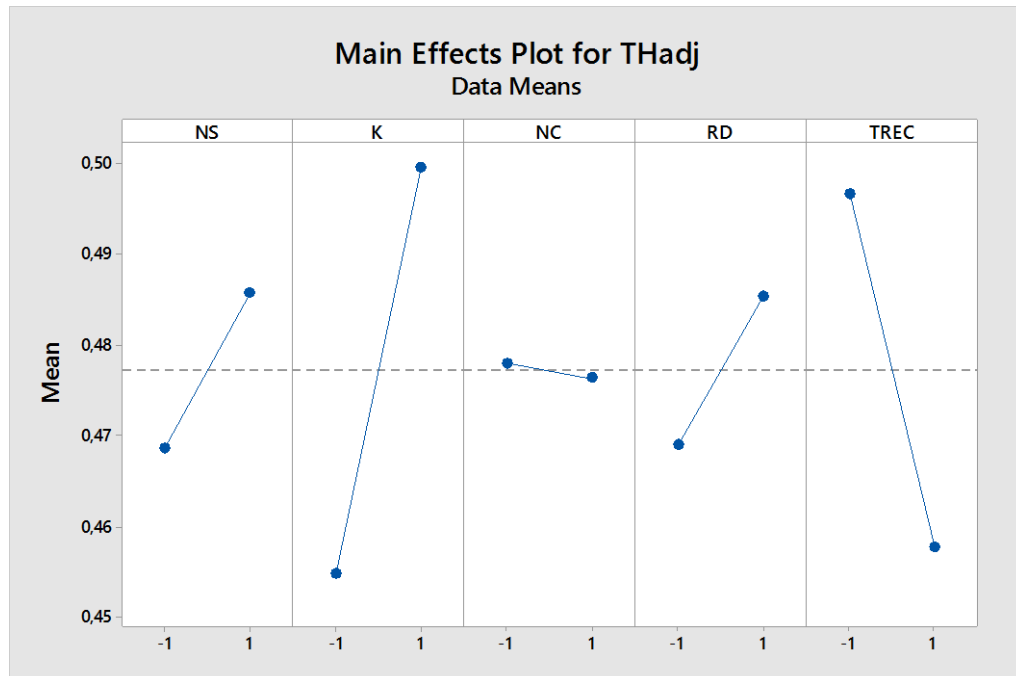
### 7.2.5 Experiments Results (Adjusted Throughput)

The factorial plan used for this consequent results' analysis is half the complete one: only runs from 1 to 32, the ones with a low Machining Time, are utilized. In this case the indicator applied is the Adjusted Throughput, which can be used thanks to fixed Machining Time. It represents performances of the system better than EF: it returns an idea of productivity and speed of the system that cannot be described by Exploitation Factor. Results of tests are visible on Table 7.10.

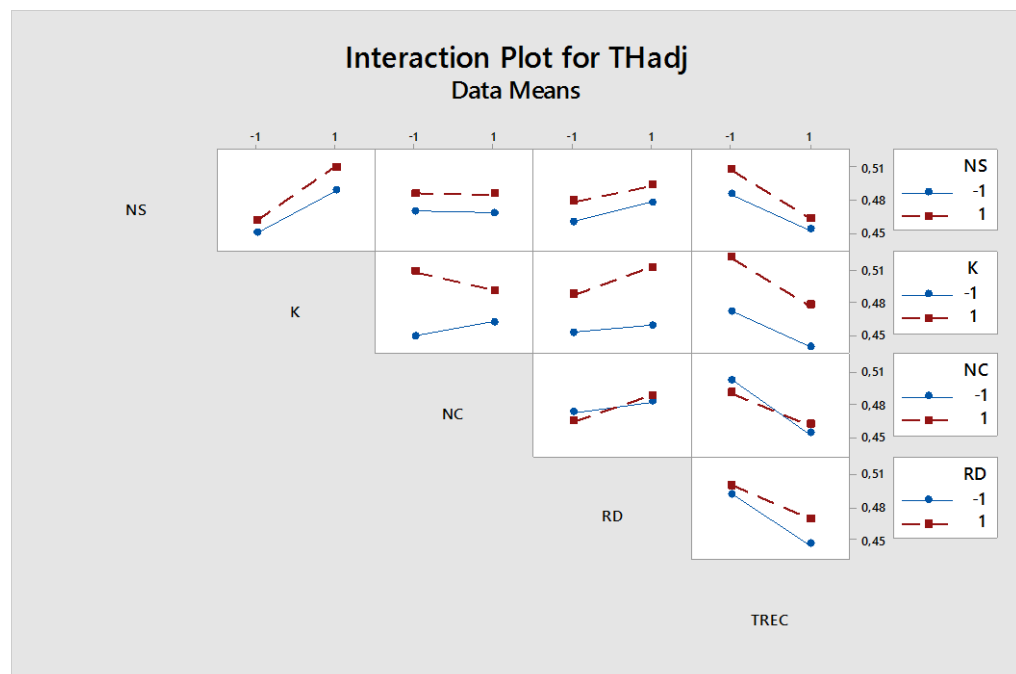
THadj	Replicate I			Replicate II			Replicate III		
	Run	Mean	Var	Range	Mean	Var	Range	Mean	Var
1	0,4701	0,0003	0,0395	0,4450	0,0001	0,0243	0,4087	0,0002	0,0326
2	0,5414	0,0004	0,0501	0,4436	0,0001	0,0277	0,4259	0,0001	0,0252
3	0,5365	0,0001	0,0251	0,4790	0,0001	0,0231	0,5647	0,0003	0,0444
4	0,5395	0,0009	0,0728	0,6264	0,0001	0,0231	0,5545	0,0001	0,0171
5	0,4624	0,0000	0,0134	0,5192	0,0001	0,0223	0,4948	0,0002	0,0423
6	0,5031	0,0000	0,0144	0,4919	0,0001	0,0243	0,4556	0,0003	0,0402
7	0,4518	0,0001	0,0216	0,4273	0,0001	0,0226	0,4941	0,0002	0,0357
8	0,4882	0,0001	0,0326	0,5228	0,0002	0,0340	0,4736	0,0002	0,0351
9	0,4344	0,0001	0,0219	0,4647	0,0000	0,0158	0,4667	0,0001	0,0230
10	0,5584	0,0001	0,0291	0,4424	0,0000	0,0157	0,4818	0,0001	0,0139
11	0,5420	0,0002	0,0372	0,4775	0,0001	0,0175	0,5881	0,0002	0,0343
12	0,5602	0,0000	0,0159	0,5129	0,0000	0,0151	0,5043	0,0002	0,0338
13	0,4619	0,0001	0,0309	0,4731	0,0002	0,0337	0,4232	0,0001	0,0207
14	0,4584	0,0001	0,0284	0,5079	0,0000	0,0185	0,4882	0,0000	0,0063
15	0,4741	0,0001	0,0208	0,5318	0,0003	0,0367	0,5542	0,0000	0,0092
16	0,5370	0,0000	0,0138	0,5537	0,0001	0,0288	0,5306	0,0000	0,0150
17	0,4648	0,0001	0,0268	0,4624	0,0002	0,0385	0,4209	0,0001	0,0274
18	0,4440	0,0001	0,0241	0,4159	0,0001	0,0251	0,3836	0,0002	0,0378
19	0,4394	0,0001	0,0225	0,4104	0,0000	0,0095	0,4719	0,0001	0,0207
20	0,4458	0,0001	0,0210	0,5002	0,0002	0,0296	0,4729	0,0001	0,0186
21	0,4472	0,0001	0,0214	0,4361	0,0001	0,0276	0,3877	0,0000	0,0137
22	0,4509	0,0001	0,0185	0,4732	0,0001	0,0230	0,3923	0,0000	0,0161
23	0,4191	0,0001	0,0273	0,4497	0,0001	0,0277	0,4763	0,0001	0,0292
24	0,4575	0,0001	0,0268	0,4768	0,0001	0,0187	0,5061	0,0003	0,0458
25	0,4162	0,0000	0,0107	0,4068	0,0001	0,0171	0,4264	0,0001	0,0274
26	0,4276	0,0001	0,0228	0,4412	0,0000	0,0113	0,4645	0,0001	0,0173
27	0,4155	0,0001	0,0213	0,4877	0,0004	0,0456	0,5782	0,0001	0,0283
28	0,5242	0,0003	0,0471	0,4523	0,0000	0,0105	0,5135	0,0000	0,0142
29	0,4643	0,0002	0,0338	0,4671	0,0003	0,0367	0,4531	0,0002	0,0323
30	0,4382	0,0003	0,0368	0,4749	0,0000	0,0100	0,4599	0,0000	0,0105
31	0,5064	0,0000	0,0143	0,4670	0,0001	0,0225	0,4857	0,0000	0,0069
32	0,4844	0,0000	0,0085	0,5255	0,0000	0,0135	0,4950	0,0000	0,0155

Table 7.10 Experiments Results (Adjusted Throughput)

As for the precedent results' analysis, a General Linear Model has been chosen to examine data. Main Effects and Interactions plots are visible on Graphs 7.3-4.



Graph 7.3 Main Effects Plot (Adjusted Throughput)



Graph 7.4 Interactions Plot (Adjusted Throughput)

Possible significant effects of K and TREC are predictable looking at Main Effects plot, maybe also Number of States and Range of Demand can be significant factors. Interactions plot doesn't give any possible interpretation of data behavior, only NC interactions seems to have a different trend.

The linear model used is a complete one, with interactions up to fifth order. Minitab's ANOVA table about these data is visible here:

## Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	31	0,135065	0,004357	3,46	0,000
Linear	5	0,097586	0,019517	15,52	0,000
NS	1	0,006967	0,006967	5,54	0,022
K	1	0,047918	0,047918	38,11	0,000
NC	1	0,000066	0,000066	0,05	0,820
RD	1	0,006364	0,006364	5,06	0,028
TREC	1	0,036271	0,036271	28,84	0,000
2-Way Interactions	10	0,015166	0,001517	1,21	0,304
NS*K	1	0,000604	0,000604	0,48	0,491
NS*NC	1	0,000004	0,000004	0,00	0,955
NS*RD	1	0,000054	0,000054	0,04	0,837
NS*TREC	1	0,000914	0,000914	0,73	0,397
K*NC	1	0,005618	0,005618	4,47	0,038
K*RD	1	0,002170	0,002170	1,73	0,194
K*TREC	1	0,000696	0,000696	0,55	0,459
NC*RD	1	0,001177	0,001177	0,94	0,337
NC*TREC	1	0,002574	0,002574	2,05	0,157
RD*TREC	1	0,001355	0,001355	1,08	0,303
3-Way Interactions	10	0,009850	0,000985	0,78	0,644
NS*K*NC	1	0,000322	0,000322	0,26	0,615
NS*K*RD	1	0,004278	0,004278	3,40	0,070
NS*K*TREC	1	0,000529	0,000529	0,42	0,519
NS*NC*RD	1	0,000000	0,000000	0,00	0,986
NS*NC*TREC	1	0,000268	0,000268	0,21	0,646
NS*RD*TREC	1	0,000040	0,000040	0,03	0,859
K*NC*RD	1	0,002021	0,002021	1,61	0,209
K*NC*TREC	1	0,002303	0,002303	1,83	0,181
K*RD*TREC	1	0,000016	0,000016	0,01	0,909
NC*RD*TREC	1	0,000072	0,000072	0,06	0,812
4-Way Interactions	5	0,011775	0,002355	1,87	0,111
NS*K*NC*RD	1	0,001006	0,001006	0,80	0,375
NS*K*NC*TREC	1	0,000486	0,000486	0,39	0,536
NS*K*RD*TREC	1	0,000109	0,000109	0,09	0,769
NS*NC*RD*TREC	1	0,001830	0,001830	1,46	0,232
K*NC*RD*TREC	1	0,008344	0,008344	6,64	0,012
5-Way Interactions	1	0,000689	0,000689	0,55	0,462
NS*K*NC*RD*TREC	1	0,000689	0,000689	0,55	0,462
Error	64	0,080476	0,001257		
Total	95	0,215541			

Results are reliable due to positive results of Normality test and Test for Equal Variances carried out on residuals (p-values  $\gg 0,005$ ). Significance level for rejecting null hypothesis is still fixed to 0.05%.

Red arrows highlight significant effects; they are Number of Pallets and Reconfiguration Time. This result is largely expected and it is a confirmation of results of the precedent analysis.

The Adjusted Throughput follows the same behavior of the Exploitation Factor: it is a corroboration of the fact that both KPIs represent performances of the Flexible Manufacturing System. This is certified by the same kind of analysis carried out on Exploitation Factor, whose ANOVA table's interesting results (only significant factors) are shown here:

K	1	0,63526	0,635261	40,45	0,000
TREC	1	0,46662	0,466621	29,71	0,000

Significant factors are equal and even F-values are very similar, certifying that THadj and EF have analogous behaviors.

Results obtained with THadj explain that it is possible to speed up production of the system increasing number of pallets and using modern pallets with zero points clamps. This result is resumed by the simplified General Linear Model visible here:

$$TH_{adj} = 0,47718 + 0,02234 K - 0,01944 TREC$$

The goodness of this fit is lower than the precedent model's one, but we can consider acceptable these R<sup>2</sup> values:

S	R-sq	R-sq(adj)	R-sq(pred)
0,0354604	62,66%	44,58%	15,99%

Transforming data of the linear model into real values, it is possible to create an approximate model that defines how many pallet per minute can be earned increasing number of pallets and employing zero points. Equation 7.5 describes this model.

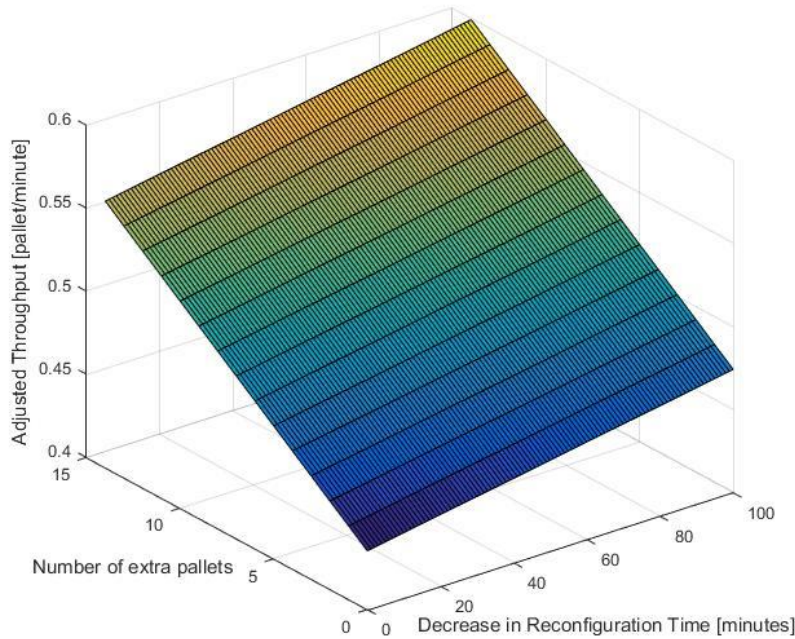
$$TH_{adj}(\Delta k, \Delta minrec) = 0.4354 + 0,008936 * \Delta k + 0,0003888 * \Delta minrec$$

Equation 7.5 Approximated Model for Adjusted Throughput

It is an approximated equation based on data of experiments and created to give a quantitative idea of the possible performance increment. Variables are expressed as differentials since a model with absolute values cannot be extracted from these data. It describes the increment of the Adjusted Throughput from the standard situation of a system with 7 pallets and a reconfiguration time equal to 120

minutes.  $\Delta k$  represents the increment of pallets from the initial situation of 7 jobs, while  $\Delta \text{minrec}$  defines the reduction of minutes applicable to reconfiguration time from the 120 minutes of the standard condition. For example, a condition of  $\Delta k=3$  and  $\Delta \text{minrec}=100$  min means that the system is working with 10 pallets with a reconfiguration time of 20 minutes, so using zero points.

The plan is visible on Graph 7.5 describes the behavior of this model.



Graph 7.5 Approximated Model for Adjusted Throughput

Basing on replicates and on the approximated model's results, mean percentage increment of Throughput caused by the utilization of pallets with zero points instead of standard ones can be assessed to 8 %. This estimation is approximated and may change with different conditions.

### 7.2.6 Experiments Results (Pallets Unused over Time)

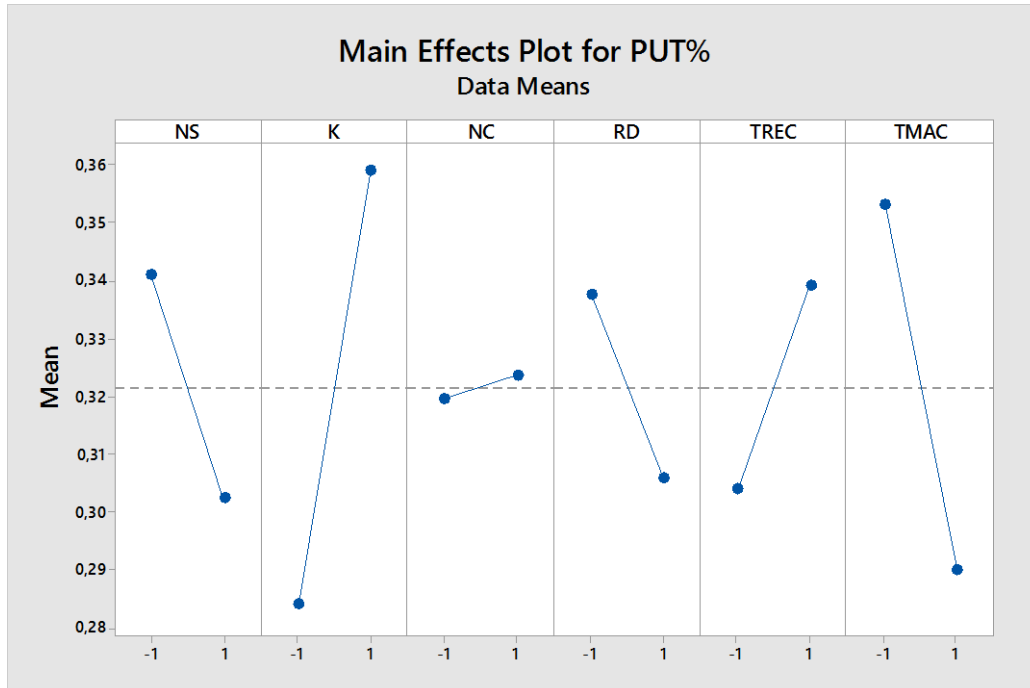
The PUT returns the information about the utilization of available pallets along periods of the production campaign. The higher is the indicator, the higher is the waste of available pallets and then the lower are performances.

The next analysis is finalized to research of possible effects of factors on Pallets Unused over Time. Percentage indicator (PUT%) has been used, since the absolute one can't be compared on different factors' levels. Mean results of replicates are shown in Table 7.11.

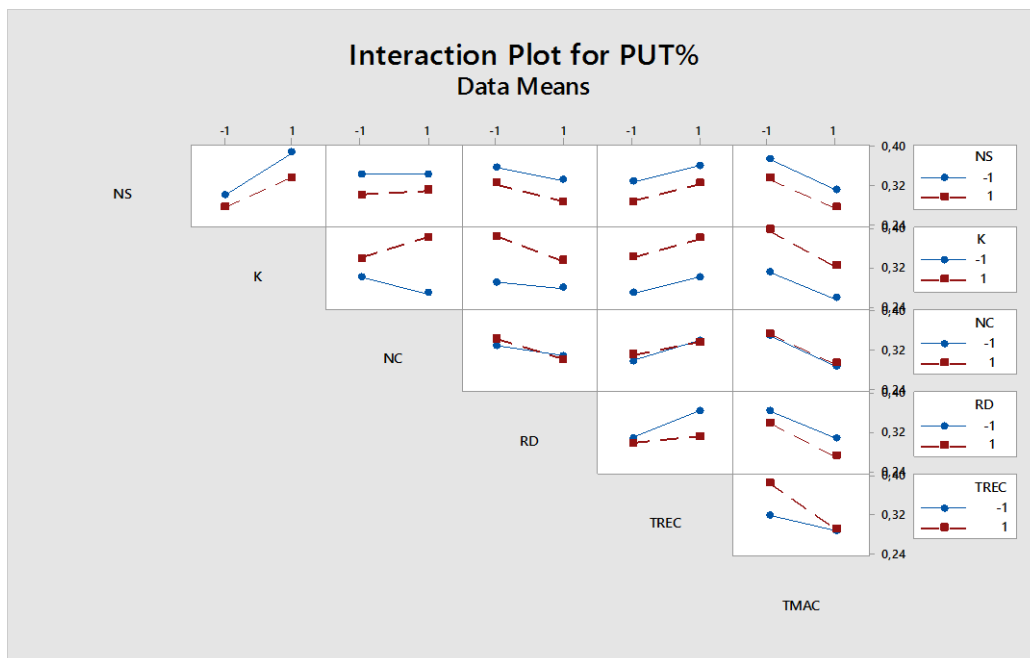
PUT%	Replicate I	Replicate II	Replicate III	PUT%	Replicate I	Replicate II	Replicate III
Run	Mean	Mean	Mean	Run	Mean	Mean	Mean
1	0,280	0,336	0,406	33	0,086	0,268	0,186
2	0,199	0,325	0,333	34	0,193	0,350	0,199
3	0,354	0,468	0,248	35	0,409	0,220	0,521
4	0,273	0,194	0,290	36	0,402	0,212	0,317
5	0,281	0,156	0,233	37	0,333	0,235	0,357
6	0,269	0,179	0,278	38	0,196	0,273	0,322
7	0,534	0,538	0,397	39	0,334	0,352	0,310
8	0,394	0,358	0,425	40	0,346	0,326	0,344
9	0,336	0,274	0,376	41	0,299	0,285	0,371
10	0,182	0,337	0,295	42	0,268	0,274	0,315
11	0,252	0,478	0,245	43	0,229	0,274	0,415
12	0,322	0,360	0,364	44	0,182	0,271	0,217
13	0,300	0,275	0,385	45	0,191	0,220	0,275
14	0,282	0,179	0,257	46	0,193	0,253	0,163
15	0,425	0,386	0,319	47	0,411	0,354	0,348
16	0,336	0,330	0,309	48	0,281	0,360	0,293
17	0,247	0,321	0,372	49	0,370	0,297	0,430
18	0,333	0,376	0,471	50	0,279	0,341	0,286
19	0,528	0,559	0,429	51	0,354	0,389	0,341
20	0,461	0,374	0,397	52	0,341	0,244	0,234
21	0,336	0,364	0,427	53	0,127	0,279	0,248
22	0,342	0,288	0,423	54	0,183	0,273	0,249
23	0,546	0,474	0,450	55	0,398	0,479	0,402
24	0,477	0,428	0,397	56	0,353	0,425	0,419
25	0,370	0,397	0,334	57	0,375	0,215	0,287
26	0,360	0,340	0,268	58	0,187	0,143	0,275
27	0,544	0,408	0,364	59	0,217	0,187	0,431
28	0,323	0,447	0,333	60	0,276	0,247	0,295
29	0,291	0,310	0,312	61	0,277	0,304	0,233
30	0,317	0,244	0,322	62	0,180	0,262	0,153
31	0,339	0,505	0,424	63	0,244	0,285	0,352
32	0,428	0,374	0,379	64	0,255	0,364	0,234

Table 7.11 Experiments Results (PUT %)

The procedure is the same applied on precedent analyses. Main effects and interactions plots are visible on Graphs 7.6-7.



Graph 7.6 Main Effects Plot (PUT %)



Graph 7.7 Interaction Plot (PUT %)



Interaction Plot doesn't show anything interesting, while in the Main Effects plot all the effects, except Number of Classes, may be significant. The ANOVA table is shown here:

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	63	1,04132	0,016529	3,91	0,000
Linear	6	0,64225	0,107042	25,33	0,000
NS	1	0,07179	0,071787	16,99	0,000 ←
K	1	0,27052	0,270515	64,02	0,000 ←
NC	1	0,00076	0,000760	0,18	0,672
RD	1	0,04830	0,048301	11,43	0,001 ←
TREC	1	0,05981	0,059808	14,15	0,000 ←
TMAC	1	0,19108	0,191081	45,22	0,000 ←
2-Way Interactions	15	0,18147	0,012098	2,86	0,001
NS*K	1	0,00752	0,007516	1,78	0,185
NS*NC	1	0,00098	0,000984	0,23	0,630
NS*RD	1	0,00121	0,001214	0,29	0,593
NS*TREC	1	0,00014	0,000142	0,03	0,855
NS*TMAC	1	0,00023	0,000228	0,05	0,817
K*NC	1	0,06802	0,068021	16,10	0,000 ←
K*RD	1	0,01790	0,017903	4,24	0,042
K*TREC	1	0,00036	0,000363	0,09	0,770
K*TMAC	1	0,00448	0,004475	1,06	0,305
NC*RD	1	0,00571	0,005715	1,35	0,247
NC*TREC	1	0,00360	0,003604	0,85	0,357
NC*TMAC	1	0,00006	0,000055	0,01	0,909
RD*TREC	1	0,02207	0,022071	5,22	0,024
RD*TMAC	1	0,00170	0,001699	0,40	0,527
TREC*TMAC	1	0,04748	0,047484	11,24	0,001 ←
3-Way Interactions	20	0,03873	0,001936	0,46	0,977
NS*K*NC	1	0,00186	0,001857	0,44	0,509
NS*K*RD	1	0,02042	0,020417	4,83	0,030
NS*K*TREC	1	0,00015	0,000149	0,04	0,851
NS*K*TMAC	1	0,00214	0,002145	0,51	0,477
NS*NC*RD	1	0,00049	0,000491	0,12	0,734
NS*NC*TREC	1	0,00163	0,001629	0,39	0,536
NS*NC*TMAC	1	0,00121	0,001211	0,29	0,593
NS*RD*TREC	1	0,00000	0,000005	0,00	0,973
NS*RD*TMAC	1	0,00166	0,001655	0,39	0,533
NS*TREC*TMAC	1	0,00297	0,002970	0,70	0,403
K*NC*RD	1	0,00061	0,000609	0,14	0,705
K*NC*TREC	1	0,00061	0,000613	0,14	0,704
K*NC*TMAC	1	0,00002	0,000021	0,00	0,944
K*RD*TREC	1	0,00073	0,000730	0,17	0,678
K*RD*TMAC	1	0,00054	0,000537	0,13	0,722
K*TREC*TMAC	1	0,00124	0,001241	0,29	0,589
NC*RD*TREC	1	0,00159	0,001590	0,38	0,541
NC*RD*TMAC	1	0,00067	0,000668	0,16	0,692
NC*TREC*TMAC	1	0,00004	0,000043	0,01	0,920
RD*TREC*TMAC	1	0,00015	0,000149	0,04	0,851
4-Way Interactions	15	0,06099	0,004066	0,96	0,499
NS*K*NC*RD	1	0,00416	0,004165	0,99	0,323
NS*K*NC*TREC	1	0,00002	0,000018	0,00	0,948
NS*K*NC*TMAC	1	0,00088	0,000877	0,21	0,649
NS*K*RD*TREC	1	0,00045	0,000446	0,11	0,746

NS*K*RD*TMAC	1	0,00212	0,002120	0,50	0,480
NS*K*TREC*TMAC	1	0,00944	0,009440	2,23	0,137
NS*NC*RD*TREC	1	0,00081	0,000808	0,19	0,663
NS*NC*RD*TMAC	1	0,00004	0,000039	0,01	0,924
NS*NC*TREC*TMAC	1	0,00080	0,000800	0,19	0,664
NS*RD*TREC*TMAC	1	0,00345	0,003454	0,82	0,368
K*NC*RD*TREC	1	0,00636	0,006357	1,50	0,222
K*NC*RD*TMAC	1	0,00713	0,007134	1,69	0,196
K*NC*TREC*TMAC	1	0,02381	0,023809	5,63	0,019
K*RD*TREC*TMAC	1	0,00043	0,000430	0,10	0,750
NC*RD*TREC*TMAC	1	0,00110	0,001098	0,26	0,611
5-Way Interactions	6	0,11287	0,018812	4,45	0,000
NS*K*NC*RD*TREC	1	0,00002	0,000024	0,01	0,940
NS*K*NC*RD*TMAC	1	0,00015	0,000150	0,04	0,851
NS*K*NC*TREC*TMAC	1	0,01261	0,012609	2,98	0,087
NS*K*RD*TREC*TMAC	1	0,00511	0,005114	1,21	0,273
NS*NC*RD*TREC*TMAC	1	0,01231	0,012309	2,91	0,090
K*NC*RD*TREC*TMAC	1	0,08267	0,082667	19,56	0,000 ←
6-Way Interactions	1	0,00500	0,004996	1,18	0,279
NS*K*NC*RD*TREC*TMAC	1	0,00500	0,004996	1,18	0,279
Error	128	0,54090	0,004226		
Total	191	1,58222			

Reliability has been tested with Normality and Equal Variances tests on residuals. Results are very similar to ones obtained with Exploitation Factor: this is a further confirmation of those results and it supports the idea that performances depend mainly on the minimization of pallets' waste along periods.

There are only two results different from EF ones: the Number of States is significant and the Number of Pallets' effect is inverse, then EF and PUT % grow up in the same way increasing K.

The NS effect should be attributed to the compulsory waste of pallets of last periods of the campaign. Once reached the last state, the system stops to insert pallets in the system: last periods are always unsaturated from the point of view of jobs. Since PUT % is a percentage made over the time horizon, these last unsaturated periods are heavy when the number of states is low.

The effect of the Number of Pallets can be explained similarly: occasional periods with very few pallets in the system, caused by incompatibilities or unbalanced ratios, have a big impact on PUT % indicator when K is high.

This statistical analysis reveals that some factors affect the waste of available pallets. Results are compatible with those ones related to Adjusted Throughput, except for the Number of Pallets. This incompatibility can be accepted, since PUT doesn't represent performances of the system in terms of productivity, but only the utilization of available pallets.

### 7.3 Economic Analysis

ANOVA tests prove that utilization of modern tombstones increases performances of the system. This assumption is valid under these conditions: the system produces pieces with low machining times with respect to reconfiguration ones and follows the reconfiguration strategy developed in the algorithm model. The first condition can't be overtaken, but the second one may be a limit to potential performances of the FMS with standard pallets. A different reconfiguration strategy could imply performances higher than ones evaluated with the algorithm's production strategy.

A new production strategy has been designed to maximize performances achievable with standard pallets. This procedure aims at verifying whether the employment of modern pallets is profitable. Therefore, an economic comparison between the utilization of zero points' pallets and the application of standard pallets reaching best possible performances has been done.

#### 7.3.1 Zero Reconfiguration Time Strategy

The precedent analysis demonstrates that reconfiguration periods are a sort of wasted time, since their performances are lower than ones of other periods. A good solution to maximize performances of the system could be removing these types of periods from the campaign.

This new strategy is based on a reconfiguration time equal to zero minutes. The algorithm for succession of periods is the same, but reconfiguration periods' duration becomes null. This is not an approximated value, which it is not reachable by modern pallets much less by standard ones. It is a fictitious value that simulates a redesigned management of pallets and reconfigurations.

The maximum number of pallets machined together in the system is lower than the number of available pallets. Some tombstones remain outside the productive system and they are configured and ready to be inserted in the system. As for the standard algorithm, when the demand of a class in the system is fulfilled, pallets of that class are extracted from the FMS for reconfiguration. With the application of this new management of pallets, the system should not wait for reconfiguration of pallets just extracted from the system, since there are other pallets ready to be machined. Reconfiguration process is transformed into a switch: 'finished' pallets are substituted by other ones, without reconfiguration periods or losses of time.

Once extracted from the system, pallets will be reconfigured to be ready for the next substitution. Therefore, reconfiguration doesn't disappear, but it is conducted outside the system on additional pallets. A simple example of that new strategy is visible on Figure 7.1.

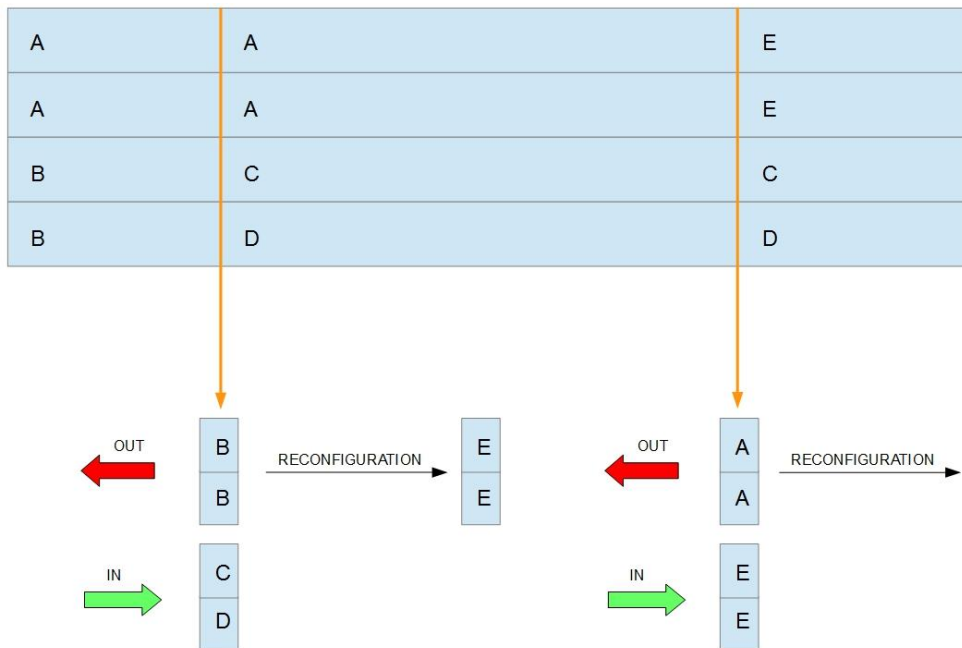


Figure 7.1 Example of Zero Reconfiguration Time Strategy

In the example, it is represented a production campaign with 4 pallets in the system, half of class A and half of class B. Outside the production system there are other 2 pallets, already configured with class C and D. When demand of class B is fulfilled, class B pallets are switched with tombstones C and D. FMS' activities continue with these new pallets, without any reconfiguration period, while pallets of class B, just extracted from the system, are being reconfigured as pallets of class E outside the system. In the same way, pallets A will be switched with class E ones, when demand of class A will be fulfilled.

This strategy could be applied easily to the performance evaluation tool: the algorithm is the same, the unique change is the reconfiguration time equal to zero. There are two approximations: reconfiguration time of pallets outside the system should be lower than productive period, unless they will not be ready for the next switch, and classes needed for the next substitution should be predicted.

### 7.3.2 Performance Comparison

Applying this method, it is possible to calculate best performances achievable with standard pallets. Next step is verifying whether they are better or not than ones obtained with zero points' pallets. The indicator chosen for this analysis is the Adjusted Throughput.

The test chosen for this comparison is the Paired T-Test. It is a statistical test that it is used to compare two population means when samples are correlated. Each observation of a population is paired with the one correlated of the other population. The null hypothesis is that the difference of means is equal to a certain defined value. The alternative hypothesis can have three forms: difference is not equal to the hypothesized difference, it is higher or it is lower. In this analysis, hypothesized mean is set to zero and alternative hypothesis is difference inequality.

In this case, a random set of experiments has been chosen from the first quarter of the Factorial Plan described in Table 7.6; for each of them a performance evaluation with Zero Reconfiguration Time has been conducted. Each observation is a replicate like the one of the ANOVA test: randomly generated case evaluated with 5 repetitions. Then each sample has been paired with its correlated replicate with 20 minutes of reconfiguration time, which have been already calculated in the precedent analysis. The 33 couples of samples selected are visible in Table 7.12.

<b>THadj</b>	TREC = 20	TREC = 0
1	0,540837	0,494219
2	0,443366	0,465833
3	0,425692	0,399007
4	0,536341	0,483175
5	0,478814	0,534259
6	0,564295	0,628622
7	0,538302	0,527364
8	0,626334	0,553706
9	0,554464	0,500690
10	0,462351	0,478833
11	0,519092	0,470501
12	0,494394	0,449140
13	0,541663	0,593597
14	0,477337	0,481237
15	0,587871	0,483631
16	0,536937	0,522975
17	0,553504	0,533461
18	0,530560	0,505187
19	0,558214	0,485689
20	0,442368	0,437784
21	0,481727	0,439838
22	0,560179	0,495845
23	0,512856	0,505420
24	0,504006	0,589046
25	0,503009	0,480256
26	0,491764	0,460357
27	0,455112	0,489845
28	0,451720	0,513232
29	0,427192	0,543747
30	0,493783	0,501130
31	0,461653	0,451304
32	0,472833	0,497604
33	0,423030	0,471518

*Table 7.12 Couples of Performance Samples with 20 and 0 minutes of TREC (Adjusted Throughput)*

The Paired T-Test has been conducted with Minitab software. Minitab results of the Paired T-Test are shown here:

Paired T for 20 - 0

	N	Mean	StDev	SE Mean
20	33	0,50459	0,05052	0,00880
0	33	0,49903	0,04710	0,00820
Difference	33	0,00556	0,05058	0,00880

95% CI for mean difference: (-0,01237; 0,02350)

T-Test of mean difference = 0 (vs  $\neq$  0): T-Value = 0,63 P-Value = 0,532

Since p-value is equal to 0.532, there is no evidence to reject null hypothesis. It is possible to state that there is no difference between performances with modern pallets and best performances obtainable with standard pallets, under low machining time condition. Production speed reached with zero points' clamps can be achieved even using standard tombstones.

The Zero Reconfiguration Time strategy could maximize performances of the system but a higher number of pallets is needed. It requires some more pallets outside the system ready to be inserted in. Since performances are not different, it should be estimated which is the best approach from an economical point of view between modern pallets with standard reconfiguration strategy and standard pallets with Zero Reconfiguration Time.

### 7.3.3 Comparison of costs of different production strategies

This comparison of costs resumes the economic analysis. It should be assessed which production strategy is the most profitable one.

The situation considered is a green field one: the productive system should be built without any preexisting infrastructure. Only differential costs are examined. Flexible Manufacturing System is the same for both strategies, then no costs related are included in the comparison; same consideration is done for overhead costs. Direct Manpower costs are not differential: they are approximated as equal for both approaches and an eventual involvement in the analysis would make it too complicated and linked to specific situations. Costs related to pallets are differential: not only the number of pallets is different between these two approaches, but also the specific price of tombstones.

The system of equations, shown in Eq. 7.6, resumes the cost analysis (each equation is expressed in Euros or any other monetary value).

$$ZRT \text{ cost } (K, SC, \Delta K\%) = K \times (1 + \Delta K\%) \times SC$$

$$ZPP \text{ cost } (K, MC) = K \times MC$$

$$\text{Differential Cost } (K, SC, MC, \Delta K\%) = ZRT \text{ cost } (K, SC, \Delta K\%) - ZPP \text{ cost } (K, MC)$$

*Equation 7.6 System of Equations for Cost Analysis*

The first equation represents the cost of application of standard pallets with Zero Reconfiguration Time (ZRT) strategy. It is a function of the number of pallets (K) and the price of a standard pallet (SC). The term  $\Delta K\%$  expresses the percentage of extra pallets that must be acquired to make possible the use of the ZRT strategy; it is defined as a percentage of the number of pallets used in the system (K). This term has been evaluated using replicates of the Paired T-test: for each of them, the maximum number of pallets switched has been calculated. Results expressed in percentage are visible on Table 7.13 (for each replicate it is showed the minimum value between repetitions), their descriptive statistics are shown in Table 7.14.

	$\Delta K\%$
1	1,00
2	1,00
3	1,00
4	0,92
5	1,00
6	0,66
7	1,00
8	0,92
9	1,00
10	1,00
11	1,00
12	0,92
13	0,86
14	0,86
15	1,00
16	1,00
17	1,00

	$\Delta K\%$
18	1,00
19	1,00
20	1,00
21	1,00
22	1,00
23	0,75
24	0,92
25	0,86
26	0,86
27	0,86
28	0,92
29	0,66
30	0,85
31	1,00
32	0,71
33	0,86

*Table 7.13 Extra Pallets percentages of replicates*



Mean	Variance	Minimum	Maximum
0,920909	0,0107335	0,66	1

Table 7.14 Descriptive Statistics of  $\Delta K\%$

Since  $\Delta K\%$  depends on the composition of each case, an exact value will not be chosen. It is a variable of the system of equations.

The second equation defines the cost of the approach with zero points clamps (ZPP): it is the product between the variable number of pallets (K) and the unitary cost of a modern pallet (MC).

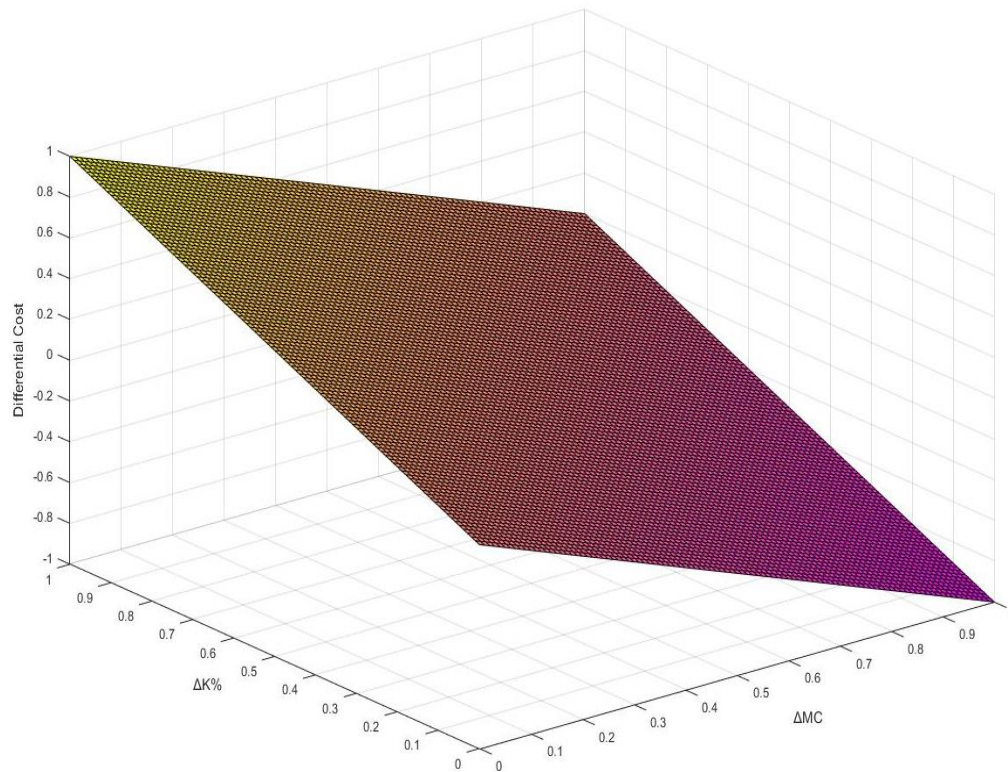
The big issue of this system of equations is the determination of specific costs of pallets. Standard pallet's cost (SC) and modern pallet's cost (MC) are considered as variables of equations, but the Differential Cost equation will be too complicated and uneasy to be interpreted. The marketplace of pallets, tombstones, and clamps is wide and variegated; therefore, it is difficult to choose fixed costs for the standard pallet and for the modern pallet that are not related to a specific situation. The solution to this controversy is based on the composition of MC as a linear combination of SC; it is evident that the cost of a tombstone with zero points clamping is higher than the one of a standard pallet. Modern pallet's cost is defined as  $SC \cdot (1 + \Delta MC)$ , with the percentage  $\Delta MC$  that describes the increment of cost with respect to standard pallet's one. The application of this linear combination in the system of equations gives the chance to simplify Differential Cost: SC and MC are no longer needed for profitability evaluation, only the variable  $\Delta MC$  is used. Since the Number of Pallets is a common multiplier of both ZRT and ZPP costs, also K can be removed. The new complete equation for Differential Cost has only two variables:  $\Delta MC$  and  $\Delta K\%$ . It is shown in Eq. 7.7.

$$Differential\ Cost\ (\Delta K\%, \Delta MC) = (1 + \Delta K\%) - (1 + \Delta MC)$$

Equation 7.7 Differential Cost equation for Cost Analysis

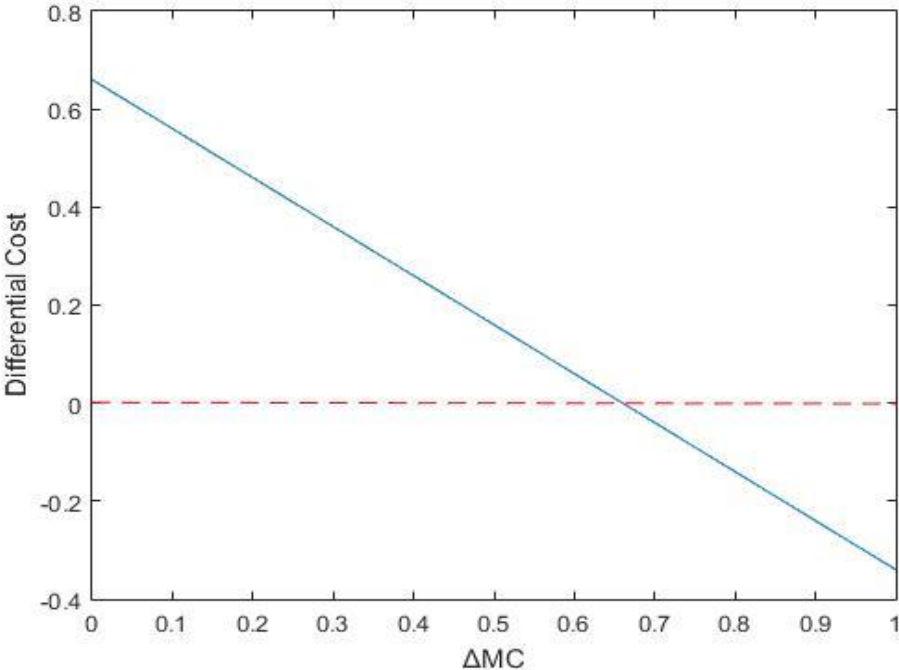
The function is no longer expressed in Euros, but it is dimensionless: multiplying it by SC and by the Number of Pallets will make it in monetary value. The increment of cost of the modern pallet ( $\Delta MC$ ) is not fixed to cover multiple possible situations. The equation can be interpreted easily: if the Differential Cost is higher than zero, the application of zero points clamping is more profitable than

producing with standard pallets. The behavior of this equation is visible on Graph 7.8.

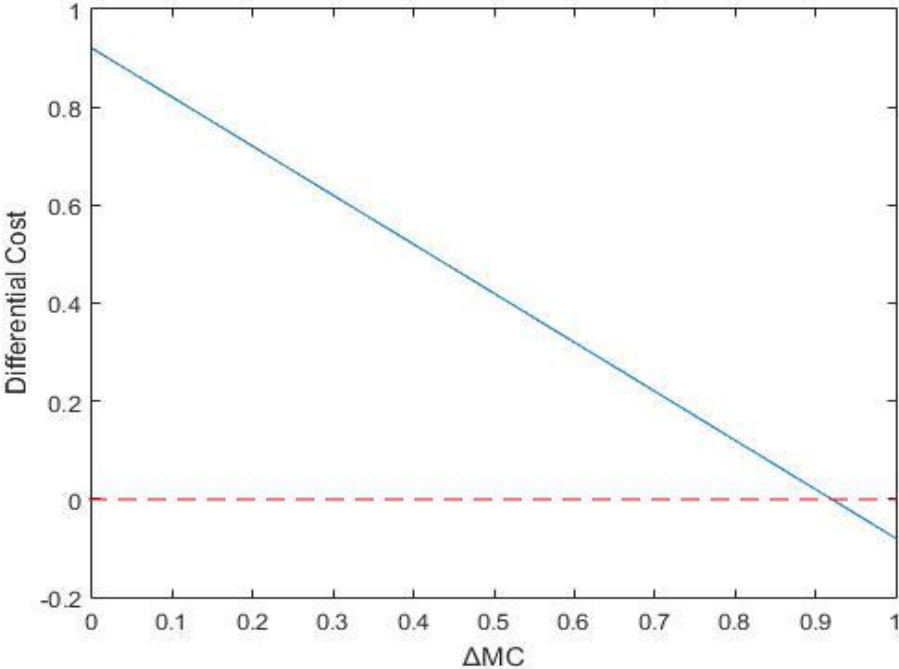


Graph 7.8 Differential Cost

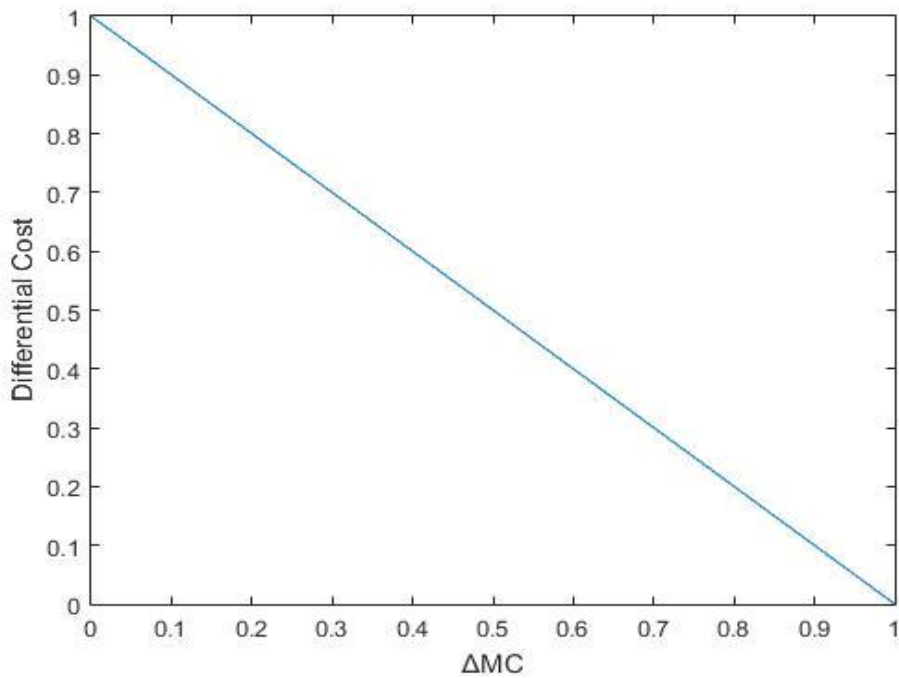
The Differential Cost function is now very simple: it is positive when  $\Delta MC$  is lower than  $\Delta K\%$ . Its trend can be better analyzed with 2D graphs, obtained imposing  $\Delta K\%$  values taken from descriptive statistics shown in Table 7.14 (Mean, Minimum, Maximum). These graphs are showed in Graphs 7.9-11.



Graph 7.9 Differential Cost Plot ( $\Delta K\% \text{ min} = 0.66$ )

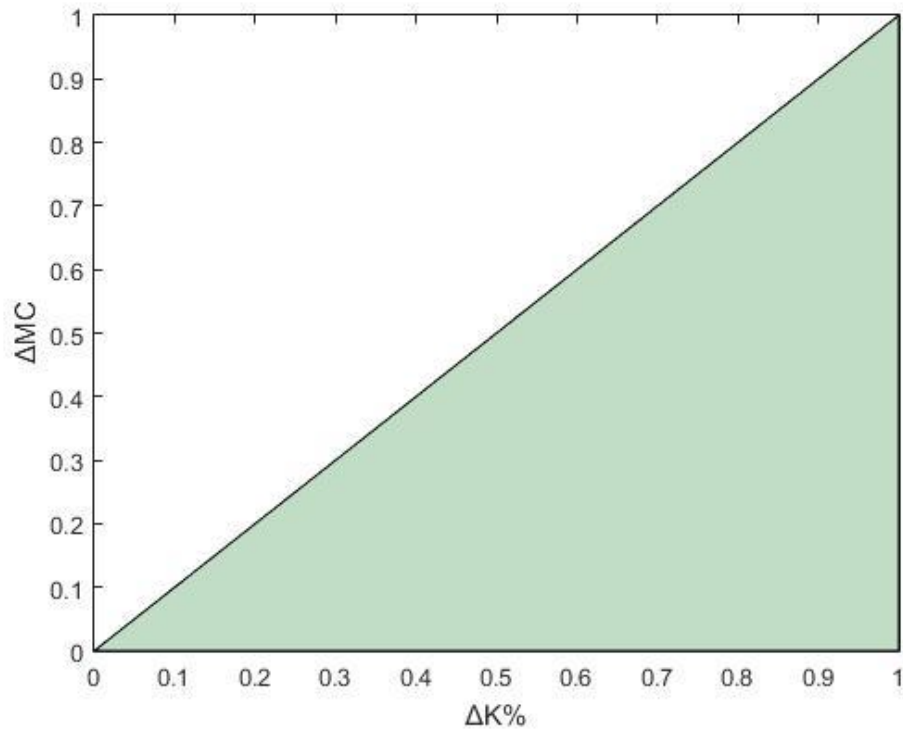


Graph 7.10 Differential Cost Plot ( $\Delta K\% \text{ mean} = 0.92$ )



Graph 7.11 Differential Cost Plot ( $\Delta K\%$  max = 1.00)

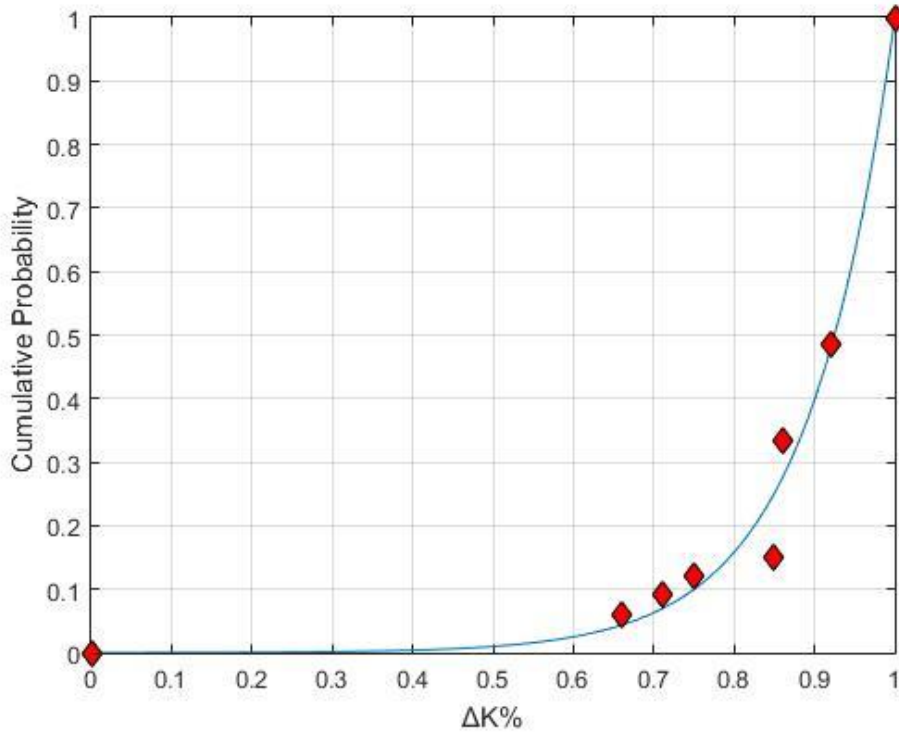
The behavior of the cost function is linear. It is visible on these graphs that the modern pallets' utilization is preferable when the cost increment ( $\Delta K\%$ ) is lower than the percentage of additional pallets to be acquired. This fact means that it is possible to identify a region where zero points clamping application is profitable: this is the domain of cases with  $\Delta MC \leq \Delta K\%$ . This area is visible on Graph 7.12 (the region of profitability is the green area).



Graph 7.12 Region of Profitability of Zero Points Clamping

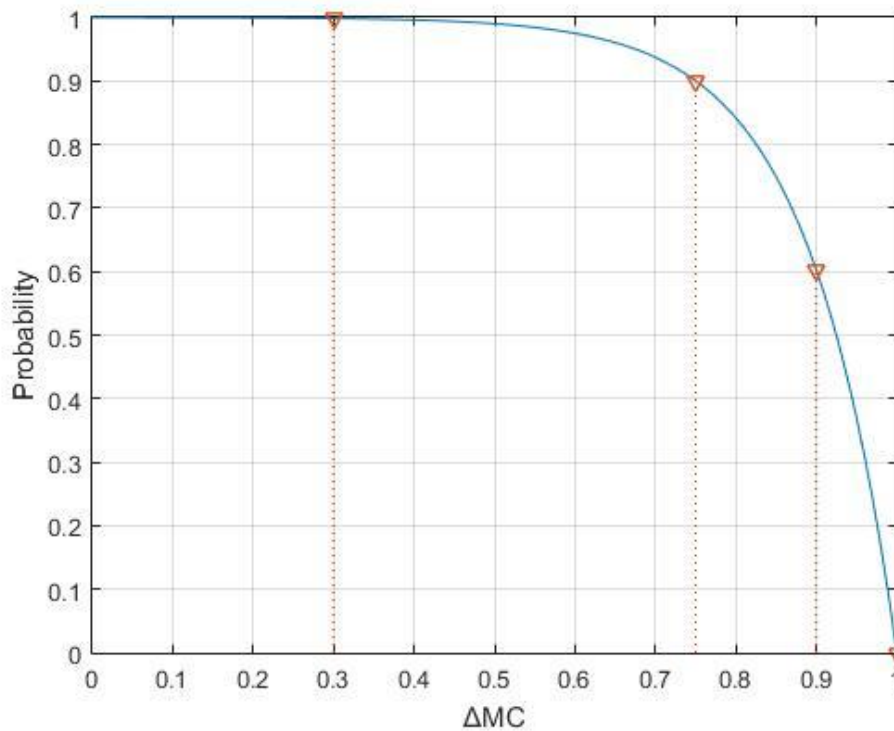
This graph returns the composition of the cases where zero points clamping is better than standard pallets, but it gives no information about possible real values of  $\Delta MC$  and  $\Delta K\%$ . The cost increment brought by modern pallets is strictly linked to singular cases and it can't be predicted, while the percentage of additional pallets can be studied using data of experiments (Table 7.13).

An approximated cumulative probability function has been fitted from those data using an exponential trend. Its curve is visible on Graph 7.13; the blue line represents the fitted curve, while red diamonds correspond to frequencies of data.



Graph 7.13 Cumulative Probability Plot of  $\Delta K\%$

From this exponential function and the one describing the differential cost, it is possible to build the curve of probability of being in the region of profitability as a function of  $\Delta MC$ . This is simply the probability of having a  $\Delta K\%$  higher than  $\Delta MC$ . The curve is shown on Graph 7.14: three possible values of  $\Delta MC$  have been chosen and their probabilities are displayed on the curve. Then exact probability values of each  $\Delta MC$  value selected are visible in the Table 7.15.



Graph 7.14 Probability that zero points are the best choice, in function of  $\Delta MC$

$\Delta MC$	0,3	0,75	0,9	1
Probability	0,99842	0,90021	0,60257	0

Table 7.15 Exact Probabilities for  $\Delta MC$  values chosen

The curve reveals that zero points clamping have a high probability of being chosen. If  $\Delta MC$  is lower than 0.75, modern pallets are the reasonable choice in 90 % of cases. The probability is low only for very high values of cost increment for zero points clamping.

### 7.3.4 Conclusion

Statistical analyses prove that the application of reconfigurable pallets increases performances of the Flexible Manufacturing System, under low machining time boundary. The profitability of their utilization has been demonstrated: it is not always preferable but it has a lower cost than standard pallet's in many probable cases.





## Conclusion

This thesis has been oriented to prove the possibility of increasing performances of a Flexible Manufacturing System employing a new kind of pallet. This assessment could be useful for those entrepreneurs willing to build a new FMS or to increase productivity of an existing one. Since results cover a wide range of conditions, they can suit several industrial cases.

The performance evaluation tool created follows a predefined reconfiguration strategy, appropriate for pallets with zero clamps. It could be helpful for those companies that are working with this new type of pallet: it releases important information not only about performances of the system but also related to future developments of the production campaign. The speed of the tool in evaluating performances is higher than 5 simulated minutes per each second, depending on the complexity of the case: it is fast enough to be used by companies on production sites.

It is a tool widely improvable. The management and utilization of baseplates has not been discussed but it may be included in the algorithm, giving a physical meaning to the compatibility matrix. Their introduction could also change the way demand is managed: the tool's unit for the demand is the pallet, but each tombstone can hold pieces with different demands. The utilization of the baseplate as the unit for the demand could better represent real industrial applications of the system. The simulation phase has been conducted with Java Modelling Tools, a simulation software based on Queueing Networks: this is the arrival point of a research started from analytical methods. Therefore, this method can be changed: a good choice could be a simulation software more accurate and able to design a model closer to real production system. A possible future research could be the application of the tool together with loading decision-making: features of loading may be adjusted to maximize performances of the system. Joining these industrial phases could bring several advantages to companies.

The core of the thesis is the employment of a tombstone with zero points clamps fixed on its faces. This feature has been generically studied, then the object of the analysis is not a specific pallet but any kind of tombstone set in that way. The attribute investigated is the reduction in reconfiguration time: the duration of processes needed to substitute baseplates and to set the pallet to hold different parts can be shortened by 80-90 %. Absolute values of reconfiguration time for both types of pallets are estimated basing on data of pallets' maker and sensible tests. They don't depend on the number of pallets needing reconfiguration; this approximation is plausible thanks to the employment of several operators.

The gain produced by quick reconfiguration could be useful for those production systems aiming at the flexibility as a key feature. The mix flexibility of the system

can be increased through the decrement of the time required for preparing production of a new part. It is also advantageous for unexpected requests: for example, new urgent parts' production may be put in the system without losing too much time.

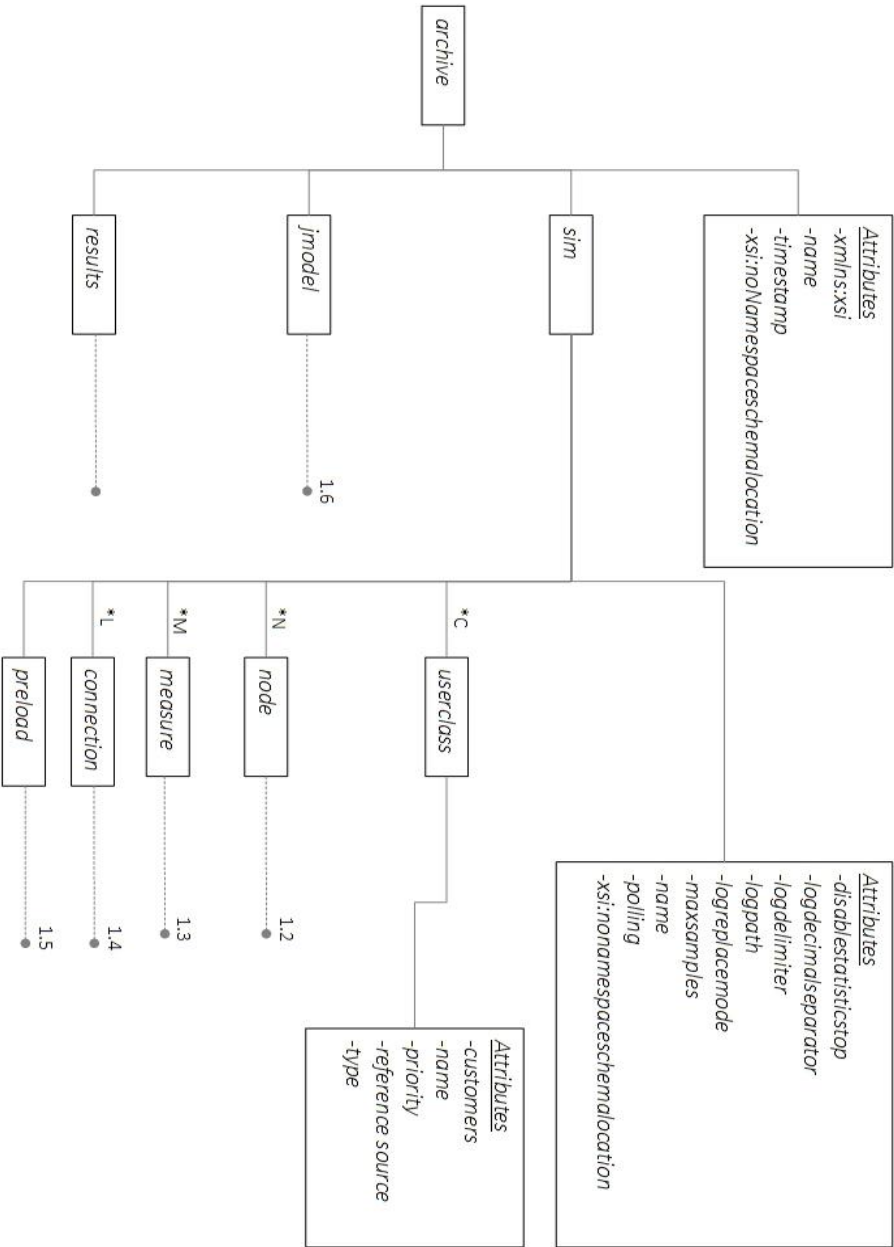
The new kind of pallet is better than a standard one from the point of view of performances. Its application provides higher throughput and lower time wasted in non-value adding procedures. This is proved on several conditions of the system, such as number of pallets, demands and number of classes. There are only two restrictions: the demonstration has been done using the production strategy described by the algorithm and it is true only for those parts with low machining times. The first limitation is related to the approach employed in this thesis, linked to a production strategy suited for zero points tombstones. Its applicability with another strategy may be the starting point of a future research. The second boundary is mandatory and it is linked to relative durations. If machining times are high with respect to reconfiguration ones, the gain in wasted time will be relatively low. This is a crucial information: companies working on parts with high machining times cannot benefit from the application of zero points clamps.

The quantitative increment in throughput can be helpful for the estimation of the economic benefit brought by the installation of a FMS working with reconfigurable pallets. Since this estimation depends on several attributes related to each specific industrial case, different companies will have different cost savings by applying this new technology. Depending on the cost reduction estimated, each entrepreneur can do its own investment appraisal considering that a tombstone with zero points clamps is more expensive than a standard one.

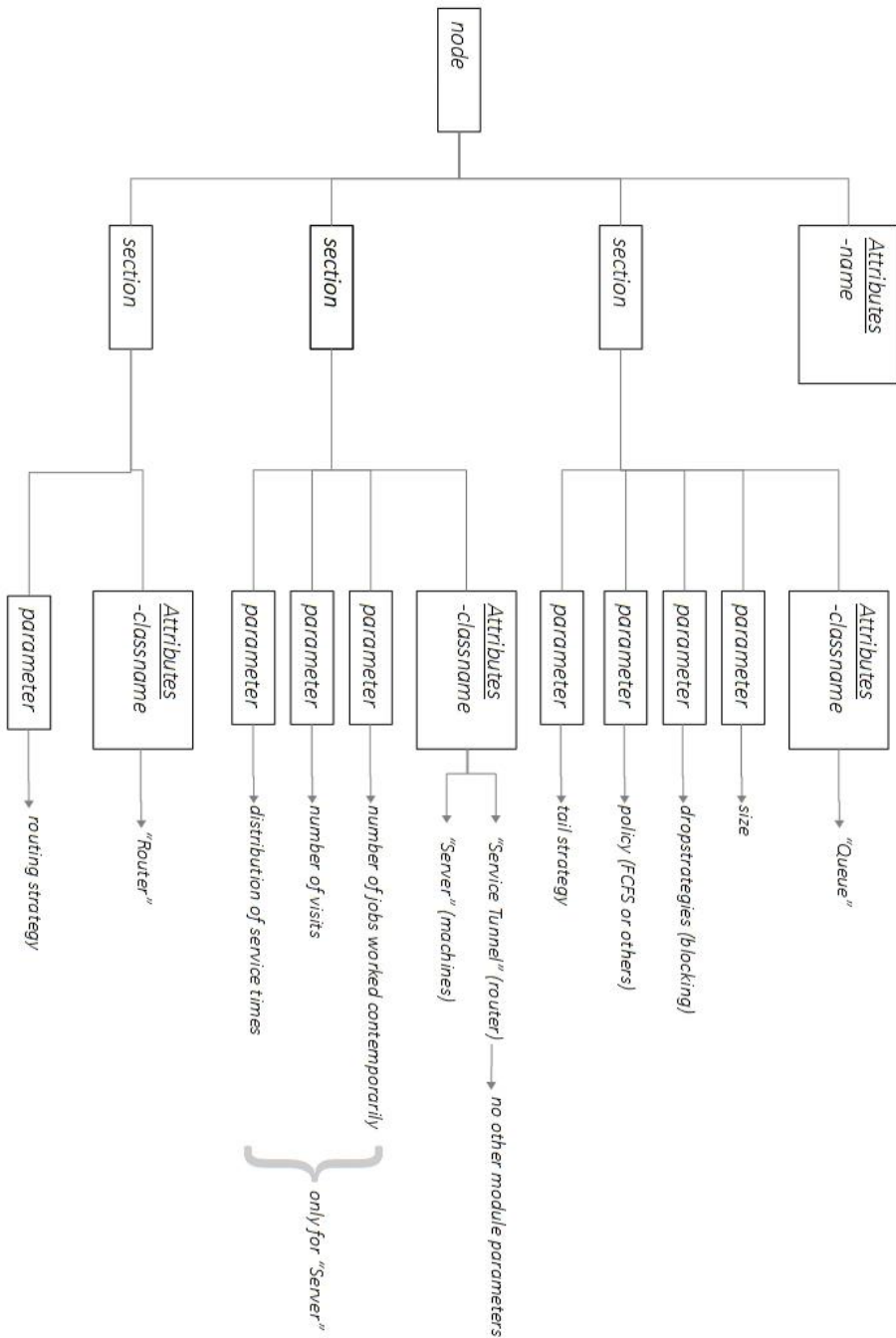
Since the increment of throughput has been evaluated comparing pallets with the same production strategy, then an extra analysis has been conducted. This one compares performances with zero points clamps with those highest reachable with standard tombstones. They can be reached with a different production strategy that needs more pallets than the algorithm's one. It has been proved that there is no difference between performances in this comparison, then an economic analysis has been conducted to estimate the most profitable method to achieve them. The modern pallet is often preferable under moderate conditions.

This research demonstrates that the employment of zero points clamps is an advantage not only from the point of view of performances but also from the economic one.

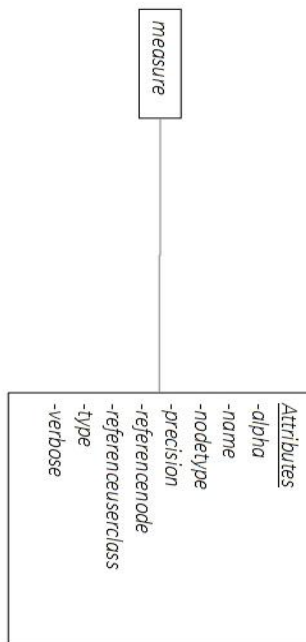
# Appendix



Appendix 1.1 XML structure (archive)



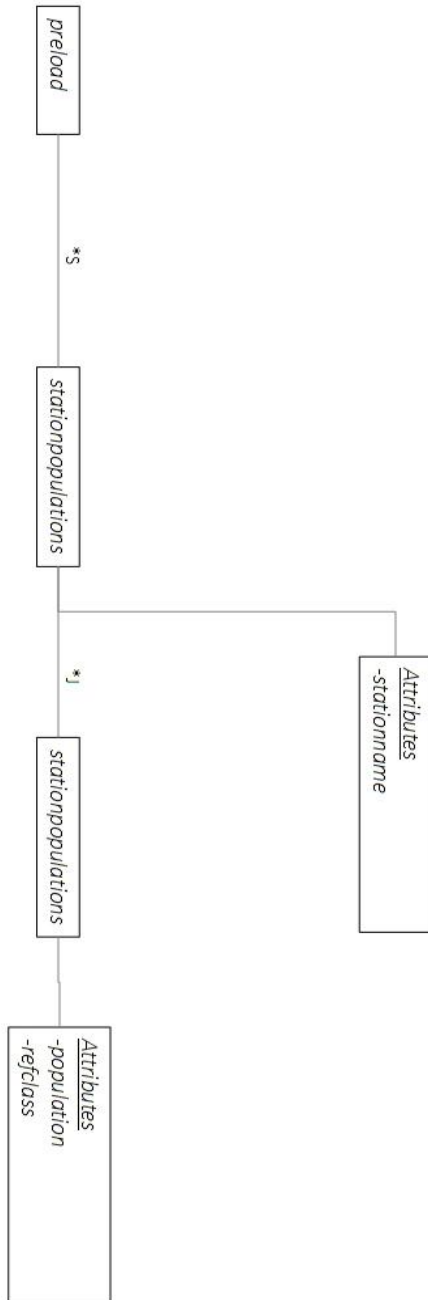
Appendix 1.2 XML structure (node)



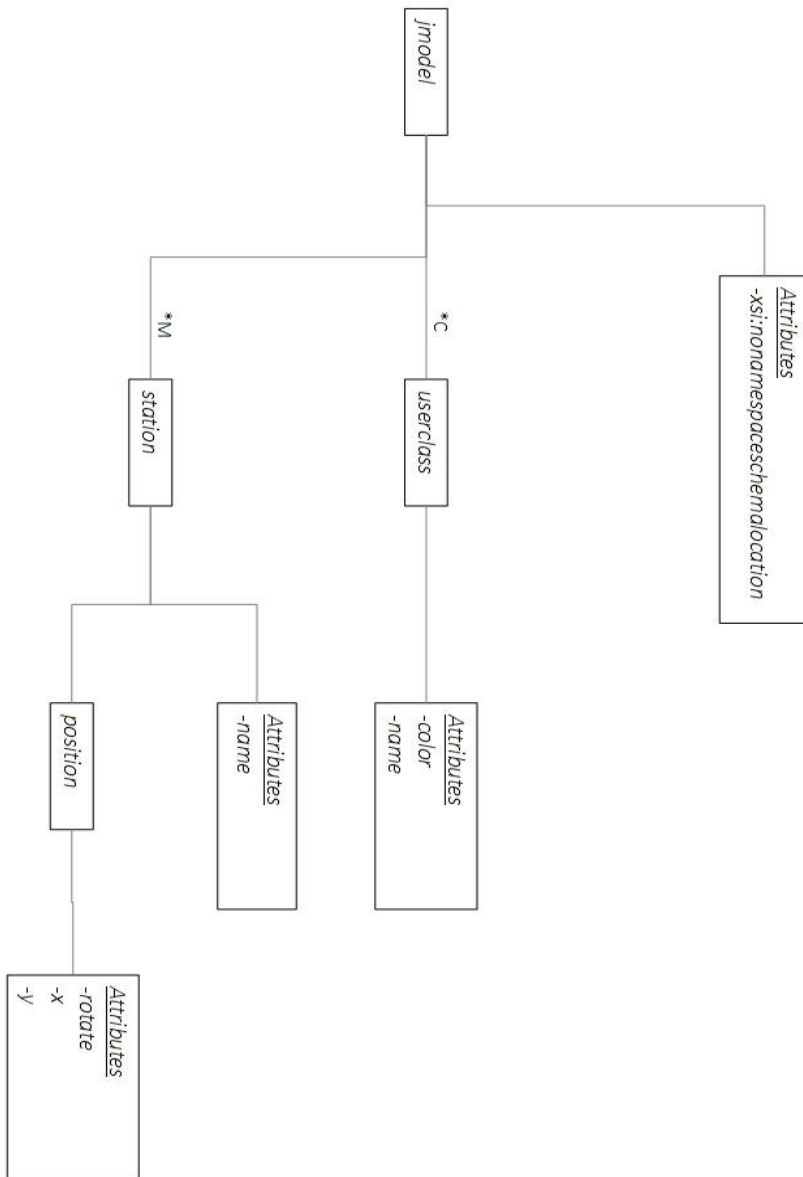
Appendix 1.3 XML structure (measure)



Appendix 1.4 XML structure (connection)



Appendix 1.5 XML structure (preload)



Appendix 1.6 XML structure (jmodel)



Appendix 1.1: It is the external structure of the xml file. It defines general characteristics of the file. The sim module refers to simulation issues. The userclass module fixes the classes introduced in the system. (C stays for number of classes, N for number of nodes, M for number of measures required, L for number of links between nodes)

Appendix 1.2: This module explains all the features of each node of the Queueing Network. Every parameter can have one or more subparameters depending on type of parameter and choice done.

Appendix 1.3: It determines characteristics required for each measure.

Appendix 1.4: A simple description of each connection.

Appendix 1.5: This module concerns the initial quantity of jobs in each node for each class. If there are no jobs in a node, its stationpopulations module does not exist (S stays for number of nodes with at least one job, J for number of classes with at least one job in the node).

Appendix 1.6: It affects the graphical representation of Queueing Network and of simulation results.



# Bibliography

- [1] J. Browne, D. Dubois, K. Rathmill, S. P. Sethi and K. E. Stecke, "Classification of flexible manufacturing systems," January 1984.
- [2] A. Grieco, Q. Semeraro e T. Tollio, «A Review of Different Approaches to the FMS Loading Problem,» *The International Journal of Flexible Manufacturing Systems*, pp. 361-384, 2001.
- [3] J. R. Jackson, «Jobshop-Like Queueing Systems,» *Management Science*, vol. 10, pp. 131-142, 1963.
- [4] W. J. Gordon e G. F. Newell, «Closed Queueing Systems with Exponential Servers,» *Operations Research*, vol. 15, n. 2, p. 254, 1967.
- [5] F. Baskett, K. M. Chandy, R. R. Muntz e F. G. Palacios, «Open, Closed, and Mixed Networks of Queues with Different Classes of Customers,» *Journal of the Association for Computing Machinery*, vol. 22, n. 2, pp. 248-260, 1975.
- [6] S. S. Lavenberg e M. Reiser, «"Stationary State Probabilities at Arrival Instants for Closed Queueing Networks with multiple Types of Customers,» *Journal of Applied Prob.*, vol. 17, pp. 1048-1061, 1980.
- [7] I. F. Akyildiz, «On the Exact and Approximate Throughput Analysis of Closed Queueing Networks with Blocking,» *IEEE Transactions On Software Engineering*, vol. 14, n. 1, 1988.
- [8] S. Balsamo e M. C. Clò, «A convolution algorithm for product-form queueing networks with blocking,» *Annals of Operations Research*, vol. 79, pp. 97-117, 1998.
- [9] S. Balsamo e A. Rainero, «Closed Queueing Networks With Finite Capacity Queues: Approximate Analysis,» in *Proceedings of the ESM 2000, SCS European Simulation Multiconference*, Ghent, Belgium, 2000.
- [10] R. O. Onvural e H. G. Perros, «Throughput analysis in cyclic queueing networks with blocking,» *IEEE Trans. on Software Eng.*, vol. 15, pp. 800-808, 1989.
- [11] Y. Frein e Y. Dallery, «Analysis of cyclic queueing networks with finite buffers and blocking before service,» *Performance Evaluation*, n. 10, pp. 197-210, 1989.

- [12] R. Suri e G. W. Diehl, «A variable buffer size model and its use in analytical closed queueing networks with blocking,» *Management Science*, vol. 2, n. 32, pp. 206-225, 1986.
- [13] I. F. Akyildiz, «Mean Value Analysis of blocking queueing networks,» *IEEE Trans. on Soft. Eng.*, n. 14, pp. 418-429, 1988.
- [14] D. Kouvatsos e N. P. Xenios, «MEM for arbitrary queueing networks with multiple general server and repetitive-service blocking,» *Performance Evaluation*, vol. 3, n. 10, 1989.
- [15] M. Bertoli, G. Casale e G. Serazzi, «JMT: Performance Engineering Tools for system modeling,» *SIGMETRICS Performance Evaluation Review*, vol. 4, n. 36, pp. 10-15, 2009.
- [16] J. A. Buzacott, "The Fundamental Principles of Flexibility in Manufacturing Systems," in *Proceedings of the 1st International Conference on Flexible Manufacturing Systems*, Brighton, 1982.
- [17] D. Gerwin, «Do's and Don'ts of Computerized Manufacturing,» in *Harvard Business Review*, 1982, pp. 107-116.
- [18] G. Fliedner e R. J. Vokurka, «Agility: Competitive Weapon of the 1990s and Beyond,» *Production and Inventory Management Journal* 38, n.3, pp. 19-24, 1997.
- [19] S. Balsamo, V. De Nitto Persone e P. Inverardi, «A review on queueing network models with finite capacity queues for software architecture performance prediction,» *Performance Evaluation*, pp. 269-288, 2003.
- [20] S. Balsamo, A. Marin e G. Dei Rossi, «Applying BCMP multi-class queueing networks for the performance evaluation of hierarchical and modular software systems,» *International Journal of Computer Aided Engineering and Technology*, January 2015.
- [21] A. Seidmann, P. J. Schweitzer e S. Shalev-Oren, «Computerized closed queueing network models of flexible manufacturing systems: A comparative evaluation,» *Large Scale Systems*, pp. 91-107, 1987.
- [22] H. K. Shivanad, M. M. Benal e V. Koti, «Chapter 1: FMS Introduction and Description,» in *Flexible Manufacturing System*, New Delhi, New Age International, 2006, pp. 1-17.

- [23] M. Bertoli, G. Casale e G. Serazzi, Java Modelling Tools user manual, 2016.
- [24] S. Balsamo, «Queueing Networks with Blocking: Analysis, Solution Algorithms and Properties,» in *Network Performance Engineering*, Berlin, Springer, 2011, pp. 233-257.
- [25] M. Jain, S. Maheshwari e K. S. Baghel, «Queueing network modelling of flexible manufacturing system using mean value analysis,» *Applied Mathematical Modelling*, pp. 700-711, 2008.
- [26] H. Tempelmeier e K. Heinrich, *Flexible Manufacturing Systems: Decision Support for Design and Operation*, Braunschweig: John Wiley and Sons, 1993.