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Manufacturing Dynamics and Performance Evaluation

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Abstract

Manufacturing companies are striving to remain competitive in the market and maintain their economic growth and productivity. Uncertainties regarding the changes in product demand, workpiece material, product design, and technological advancement, have imposed pressure on manufacturing systems. Market uncertainties force manufacturing companies to be flexible and responsive in producing different parts, by adapting the existing system without the need for a substantial investments. The market is characterized by time variations in product quantities and varieties while manufacturing systems remain inherently fixed. To sustain competitive manufacturing, a company has to adopt to new production requirements and be responsive to market changes quickly. Conscious decisions have to be made for a system to respond to market fluctuations. In order to respond to the dynamic changes, there is a need for developing methodologies that analyse, evaluate and control performance of manufacturing system at the system and/or process levels.

The primary focus of the thesis is to develop a novel generic framework for modelling and controlling manufacturing systems intending for improvement of the performance of manufacturing and make companies more competitive. The framework incorporates the complex interrelations between the process and system parameters, i.e., the dynamics of the system. Thus, provides a quantitative and qualitative analysis for performance evaluation and for optimizing performance of manufacturing system. The generic framework can further be adapted for studying specific manufacturing systems in discrete manufacturing. Three case studies are presented. The case studies are performed in an automotive company where the effect of various levels of control is investigated in manufacturing systems configured as transfer line or as a flexible manufacturing system.

Two aspects of the dynamic nature of manufacturing system are investigated in this thesis: (1) The engineering nature of the system, i.e., the selection of appropriate process parameters to manufacture a product according to the design specification, and (2) The business nature of the system, i.e., the selection of system parameters with respect to the way the product is manufactured. At the process level, the parameters are controlled within the process capability limits to adapt to the changes of the system parameters in response to the market dynamics. At the system level, operational parameters are controlled to satisfy performance criteria.

A case study for resource use analysis during primary processes has also been investigated and presented. The critical operations and the operations that have the highest energy consumptions and the potential for energy savings have been identified.

The methodology developed for analysing the performance of the dynamic manufacturing system is based on a system dynamics modelling approach. Results obtained from different modelling approaches are presented and compared based on the selected performance metrics.

Keywords: Manufacturing system and strategy; performance evaluation; manufacturing dynamics; decision-making; system dynamics; sustainable and energy efficient manufacturing

Sammanfattning

Tillverkande företag strävar efter att förbli konkurrenskraftiga på marknaden och behålla sina ekonomiska tillväxt och produktivitet. Marknadsosäkerhet, såsom förändringar i produktbehov, arbetsmaterial, produktdesign och teknikutveckling, sätter tryck på tillverkningssystem för att reagera till dessa förändringar. Medan marknaden kännetecknas av tidsvariationer i produktkvantiteter och sorter, förblir tillverkningssystemen oförändrade. Osäkerheten på marknaden tvingar tillverkningsföretagen att vara flexibla för att producera specifika komponenter genom att anpassa det befintliga systemet till externa variationer. För att upprätthålla den konkurrenskraftiga tillverkningen måste ett företag snabbt anpassa nya produktionskrav och vara mottagligt till marknadsförändringar. Medvetna beslut måste fattas för att ett system ska kunna reagera på marknadsvariationer. För att omvandla ett tillverkningssystem från ett fast till ett dynamiskt system finns det behov av metoder för att analysera, utvärdera och kontrollera prestanda hos tillverkningssystem på process och/eller systemnivå som svar på marknadsförändringar. Att beskriva de komplexa relationerna mellan process och systemparametrarna, dvs studera systemets dynamik, är ett av huvudmålen för denna avhandling.

Därför är huvudarbetet i avhandlingen att utveckla en ny generisk ram för modellering och kontroll av tillverkningssystem, med syfte till att förbättra tillverkningsekonomin och göra företagen konkurrenskraftigare. Metoden skapar en kvantitativ och kvalitativ analysstruktur för optimering och för att undersöka prestanda hos tillverkningssystemen med hänsyn till den komplexa interaktionen mellan processparametrarna och tillverkningssystemets operativa parametrar.

När det gäller det dynamiska tillverkningssystemet finns det två aspekter som studerades i denna avhandling: (1) Systemets tekniska karaktär, det vill säga valet av lämpliga processparametrar för att tillverka en produkt enligt designspecifikationen och (2) Systemets affärsart, det vill säga valet av systemparametrar med avseende hur produkten tillverkas. På processnivå styrs parametrarna inom processens duglighetsgränser för att anpassa sig till förändringar av systemparametrarna vilka styrs av marknadsdynamiken. På systemnivå är det operativa parametrar som styrs för att uppfylla prestandakriterier. Den generiska ramen kan vidare anpassas för att studera specifika tillverkningssystem inom komponenttillverkning. Flera fallstudier presenteras där effekten av olika kontrollnivåer undersöks i tillverkningssystem med olika komfgurationer.

En fallstudie för resursanvändningsanalys inom primära processer har också undersökts och presenterats. De kritiska operationerna och de operationer som har högsta energiförbrukning och de potentiella energibesparingsområdena har identifierats.

Metoden som utvecklats för att analysera prestanda i det dynamiska tillverkningssystemet är baserat på systemdynamikmodellering. Stella/iThink - simuleringsplattform har använts i modellering. Resultat som erhållits från olika modelleringsmetoder presenteras och jämförs baserat på de valda prestandamått.

Nyckelord: tillverkningssystem och strategi; utvärdering av prestanda; tillverkningsdynamik; beslutsfattande; systemdynamik; hållbar och energieffektiv tillverkning.

Preface

The research presented in this doctoral thesis has been conducted at the Department of Production Engineering, KTH - Royal Institute of Technology, Stockholm, Sweden since 2013. This work would not have been possible without the guidance of people who encouraged me and who were faithful to support me through to its completion. I am deeply thankful to all the people who made this work possible.

I would like to express my sincere gratitude to my supervisor Professor Mihai Nicolescu, who offered me the opportunity to undertake this research and to work with him started from my Master thesis. He always supported, guided and encouraged me with all of his knowledge, motivation, and patience. I would not be able to finish any steps of my PhD studies without his support. He cares for every matter, more than a simple supervisor, he has been a father and mentor. I have learnt a lot from him and developed personally and professionally. Many thanks Mihai and God bless you.

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My sincere thanks also go to all dear colleagues, PhD students, researchers and staffs at IIP for the valuable discussions, for their support and all the friendly working environment.

A very special and foremost thank to Almighty God for His endless help, grace and unconditional love. Also, I would like to thank all my fathers, brothers and sisters in Christ at the parishes of Ethiopian Orthodox Tewahedo Church in Stockholm, especially to MK Sweden members, for their prayers, unforgettable moments and love.

Finally, I would like to express my heartfelt gratitude to my family, my parents, brothers, sisters, and all extended families for their unconditional love, unfailing encouragement, positive models and support. My dearest Berisha I am always grateful and blessed having you by my side, many thanks and stay blessed. I am dedicating this dissertation to my parents. Thank you for your prayerful encouragement, for teaching me the principle of being positive, and ''everything happens for a reason and is for good". I owe a very special thanks to all dear friends in Ethiopia, Sweden and all over the world.

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This project would be impossible without the cooperation and support of the following people from SCANIA CV AB, Sweden. Acknowledgement to Rolf Johansson, Mats Boström, Tomas Persson, and Anders Johansson for the discussion, guidance, for the plant tour, training, and made me familiar with the process, for the facilities, etc.

Tigist Fetene Adane
Stockholm, May 2018

“እግዚአብሔርንም ለሚወዱት
እንደ አሳቡም ለተጠሩት
ነገር ሁሉ ለበጎ እንዲደረግ እናውቃለን።”

“And we know that in all things God works for the good of those who love him, who have been called according to his purpose”

Romans 8:28

God indeed is my savior

The evidence of my existence

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List of Figures

[1] Near net shape casting concept in this thesis is used to explore possibilities to produce parts with better tolerance and accurate geometrical dimension, in order to decrease the machining efforts.

List of Tables

List of Publications

The papers appended in this dissertation are listed below in the order of their appearance:

1. Adane T. F. and Nicolescu M. (2014) 'System dynamics analysis of energy usage: case studies in automotive manufacturing', *International Journal of Manufacturing Research*, Vol. 9, No. 2, pp.131-156.

2. Adane T. F. and Nicolescu M. 'Towards a Generic Framework for the Performance Evaluation of Manufacturing Strategy: An Innovative Approach'. *J. Manuf. Mater.* Process. 2018, 2, 23.

3. Adane T. F., Bianchi M.F., Archenti A. and Nicolescu M. (2015). 'Performance evaluation of machining strategy for engine-block manufacturing'. *Journal of Machine Engineering*, 15/4, 81-102

4. Adane T. F. and Nicolescu M. (2016). 'System dynamics as a decision support system for machine tool selection'. *Journal of Machine Engineering*, 16/3.

5. Adane T. F., Bianchi M. F., Archenti A. and Nicolescu M. (2018). 'A decision support system for analysis of performance of manufacturing systems'. Journal of Manufacturing Systems: under review.

Other publications:

6. Tigist F. Adane, Mariam Nafisi, Farazee M. A. Asif, Daniel T. Semere, Mihai Nicolescu, 'Modeling industrial processes using system dynamics', *The 5th Swedish Production Symposium*, Oct 2012, ISBN 978-91-7519-752-4

7. Adane, T. F.; Nicolescu, M.; Archenti, A. (2018). 'Machining strategy for future engine-block manufacturing: case study'. TRITA-ITM-RP 2018:1

Abbreviations

ABS	Agent based simulation
AHP	Analytical hierarchy process
ANOVA	Analysis of variance
CLD	Causal loop diagram
CNC	Computer numerical control
DEA	Data envelopment analysis
DES	Discrete event simulation
DMS	Dedicated manufacturing system
DSS	Decision support system
FM/FMC	Flexible Machine tool
FMS	Flexible manufacturing system
GPM	General purpose machine tool
MCDM	Multi criteria decision making
MRR	Material removal rate
MS	Manufacturing system
MTBF	Meantime between failure
MTTR	Meantime to repair
NNSP	Near-net shape production
RQ	Research question
SD	System dynamics
SPMs	Special purpose machines

Chapter 1

Introduction

In this chapter, the background and motivation of the performed thesis work are described. The performance evaluation of a Manufacturing System (MS) in the automotive industry is outlined. Current research gaps and the challenges are detailed, followed by research scope, objectives, and research questions. Finally, author contributions and thesis outline with reference to the appended papers are described.

1.1 Research background and thesis motivation

Among all economic groups, manufacturing is of high importance to the world economy, with a huge potential to generate wealth, jobs and a better quality of life. Particularly the automotive industry, which is the largest manufacturing investor in R&D, plays a crucial role in this aspect accounting for 25% of total R&D annual spending. It also generates €839 billion turnover, which represents 6.9% of EU GDP. The manufacturing of engine components is vital to automotive and other vehicle manufacturing, companies. The European vehicle manufacturers are the largest private investors in R&D in Europe, with annual spending of €20 billion in R&D, or 4 % of their turnover [4]. In addition, 5.3% of the EU workforce is employed in this sector [62]. Almost 3 million of the world's jobs in the automotive industry represent 10% of Europe's manufacturing employment [1]. Figure 1.1 shows the global remarkable increase in automotive production and demand fluctuations from 2000 to 2016. The sales and demand are expected to increase by 7.7% in 2017 [5].

In a competitive manufacturing environment, companies are continually looking for ways to improve and update the performance of their manufacturing systems. The development of new manufacturing systems, as well as the improvement of existing systems, requires an understanding of external/internal variations. Moreover, in today's unpredictable business environment, manufacturing enterprises face

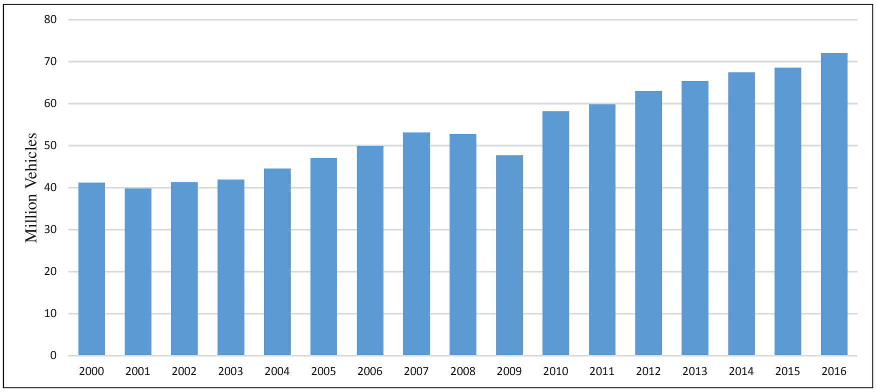


Figure 1.1: World automotive production from 2000-2016.

a multitude of challenges to meet ever-increasing customer desires and demands to provide new and more customized products at the most cost-effective price. In particular, automotive companies are under high pressure to introduce structural and operational innovations for better product quality, availability and cost. Manufacturing companies in this sector have to be quick in adapting their operations and systems to fulfil the functionality gap from customers, e.g., demand fluctuations. Moreover, automotive manufacturers must renew their methodologies more quickly to adapt to changes in fashion and to create new trends.

Due to the wavering of market demands, companies realize the need for a comprehensive manufacturing strategy and decision support system to control the existing system and to address future needs and challenges. As a consequence, it will be mandatory to consider methodologies/strategies to meet such requirements. The automotive company has a sound track record of innovative and affordable solutions and will maintain its efforts to make the future engine components manufacturing sustainable in such a way that their operations lead to better performance of the systems, i.e., to be more efficient, productive, economical and safe.

Analysing the performance of the manufacturing system and the complex interaction between the system's parameters has been of interest to manufacturing companies. In most cases, researchers and practitioners follow experimental analysis to investigate the performance of manufacturing systems without taking into consideration their relationships with process parameters. It is also realized that manufacturing companies are adopting the traditional manufacturing paradigms and, through acquiring experience to analyse the performance of their manufacturing system.

One of the limitations of the conventional performance measurement systems used today for the evaluation of manufacturing systems is that they do not take into consideration technology-based performance measures, which are essential to fully optimize a manufacturing system. The primary issue is the lack of a systematic approaches for such case to be followed. It is also essential to have a methodology deployed for studying the possible effect of variations on the performance of manufacturing systems.

1.2 Research scope

The need to evaluate the factors, influencing the performance of manufacturing systems has led to the development of analytical as well as simulation models that are used in the design and operation of manufacturing systems. There are a number of specialized analytical models, which are based on some mathematical techniques that have solutions only for simple systems. Overwhelmingly, simulation models are used in the analysis of the performance of manufacturing systems.

Technical areas of interest in the simulation of manufacturing systems include the following functions and are accomplish with the aid of industry 4.0, cyber-physical systems, computer-aided, communication-based and internet-based procedures and processes.

i. Models of manufacturing tasks in production, with the objective of designing workstations, cells and production lines, quality assurance and maintenance.

ii. Models of manufacturing processes aimed at the design of procedures for process and production planning and control, activity scheduling, inventory management and logistics.

iii. Models of supply systems targeting the design, planning and control of production and logistics system .

The primary objective addressed in this thesis is to develop a generic framework for the performance analysis of the dynamics of manufacturing systems. The research focuses in general on sustainable component manufacturing, and in particular, attention is focused on the manufacturing process of engine blocks through developing a concept for the performance evaluation of a manufacturing system. The scope of the research presented in this thesis is described in Figure 1.2.

The preliminary investigation started with the analysis of the energy use of a primary process, e.g., casting, and then the performance analysis and evaluation of a secondary process, i.e., the machining process. The generic framework is designed based on the actual case in an automotive company, and such a concept can also be adapted to any similar component manufacturing system. This concept, at process level, is to analyse the performance at station level in the manufacturing system. Whereas, at system level, the sequence of operations at stations are taken into consideration to evaluate the performance of the manufacturing system.

Finally, by adapting, editing and re-using blocks of the generic model, three case studies are performed. An approach for the performance analysis of different manufacturing systems' configurations is developed. Consequently, the methodology can

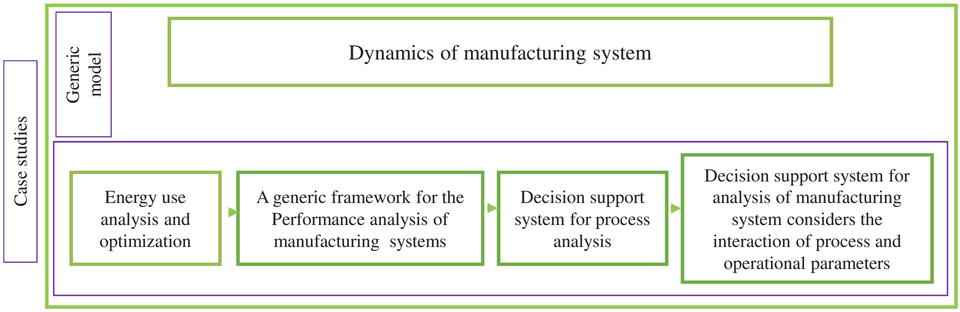


Figure 1.2: A schematic representation of the scope of the research included in the thesis.

be used as a decision support system for the comparison of different processes and manufacturing system configurations.

1.3 Scientific concept and research methodology

Scientific method is essential to provide scientists with a systematic tool for investigating the research problem by collecting and analysing information that can lead to the validation of new research facts or conclusions. Research is, by its nature, characterized by cyclical or, more exactly, helical evolution [72]. In the search for enhanced knowledge, in this thesis, a cyclic research approach is followed by systematically collecting, analysing, and interpreting information (data) to increase understanding of a phenomenon in which there is an interest.

One of the significant steps in scientific work is the identification of the research problem and formulation of research questions. Finally, it ends with the resolution of the problem or attempts to provide answers to the questions. At this point, one or many problems or questions may emerge that need to be solved. As mentioned, this thesis' research problem deals with developing models for analysing and control performance of complex manufacturing system which includes the technological and business performance evaluation methodology. This is the broad scope of the thesis, however, to address the problem, the different sub-problems are defined and solved following their own cyclic process. The overview of the cyclic research process (steps) driving the presented work is shown in Figure 1.3.

A descriptive and analytical approach is followed to understand the current state-of-the-art technology. Data have been collected to analyse the proposed approach (see Figure 1.3) and to suggest a policy that can improve the existing system. A systematic literature review is carried out based on the published articles from Google Scholar, Web of Science, Scopus, etc. Analysis of the main performance parameters (metrics), process parameters and the relationships between these parameters are identified. In conducting this research, in order to understand the

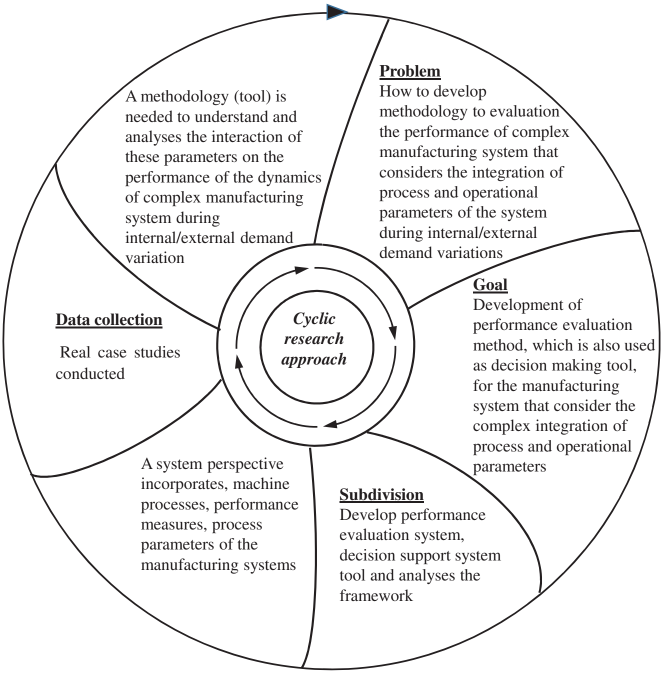


Figure 1.3: Cyclic research approach driving the machining process of manufacturing system (adapted from [72]).

current production system, a comprehensive study of the company's manufacturing systems and the methodology to be deployed has been carried out. A detailed investigation of the manufacturing environment, such as type of manufacturing systems configuration, the machining processes, the type of operations, the control factors, and possible external variations has been completed. The company's manufacturing systems - both flexible system and dedicated system (transfer line) are investigated. The critical stations in each manufacturing system are identified and studied. The critical stations are selected, followed by identification of the critical features and operation parameters and their mathematical relationships. For data collection, historical documents of the investigated system have been assessed, discussions with the production managers and production operators have been conducted, interviews and questionnaires have been prepared. Measurements of some data during production are also performed (direct measurement of some data on the shop floor during production has made; historical data and design specification values have investigated). Through the process of investigating the system, the current manufacturing strategy used, and its management mechanisms, is studied.

Quantitative and qualitative approaches were deployed to develop the framework, which consider different aspects of the performance analysis and/or decision process [29]. The system dynamics approach was selected and followed to structure the process of an engine block and to design an effective policy for managing the complex manufacturing system. Stella/iThink platform has been used to build, simulate and analyse the system dynamics model presented in this thesis. It provides a flexible way of building simulation models based on a causal loop or stock and flow diagrams. Studying the dynamics of manufacturing system, a causal loop diagram (conceptual model) that shows the structure of the system's main parameters, their interaction, influences and the feedback of the system, is developed based on a qualitative approach. Regarding the quantitative approach, the relationship of the parameters is mathematically represented in the model built in environment. A method for the performance evaluation of the manufacturing systems and a decision support tool for the comparison of processes and manufacturing systems for the current production configuration are developed. A new strategy to improve the existing manufacturing conditions is proposed. The model is run, simulated and analysed with the given data collected. The research work presented follows the detailed description of the steps shown in Figure 1.4.

1.4 Problem statement, objectives and research questions

Understanding the complex interaction between the process and operational parameters of a manufacturing system in response to disturbances in the systems' inputs (e.g., volume of products, change in workpiece material) is the primary research objective. Consequently, this allows for a better understanding of the performance of the manufacturing system, and enables control of the process parameters for a more competitive and sustainable manufacturing environment. Subsequently, as previously mentioned, it can be used as a decision support system for the comparison of different scenarios such as process selection, and different configurations of manufacturing systems. The capability of the manufacturing system varies with time, conditions of operational parameters and working environment.

However, as mentioned, there is a lack of a systematic approach for understanding the performance of the manufacturing system that considers the complex interaction of process and operational parameters, and how to manage and control variations in the system's inputs. For example, when there is a change, due to, e.g., a fluctuation in demand or workpiece material, an important issue is how the manufacturing system responds to these changes and how the different system parameters interact to manage these variations and achieve production goals. This is essential for evaluating the productivity, and cost of the current production system if any internal and/or disturbance.

As previously mentioned, one of the primary objectives is to develop a generic simulation modelling concept for the performance evaluation of manufacturing systems based on defined performance metrics (e.g., productivity, cost, and quality). Which will allow decision-makers to assess and plan the current and future behaviour of the manufacturing system and provide solution that can improve the

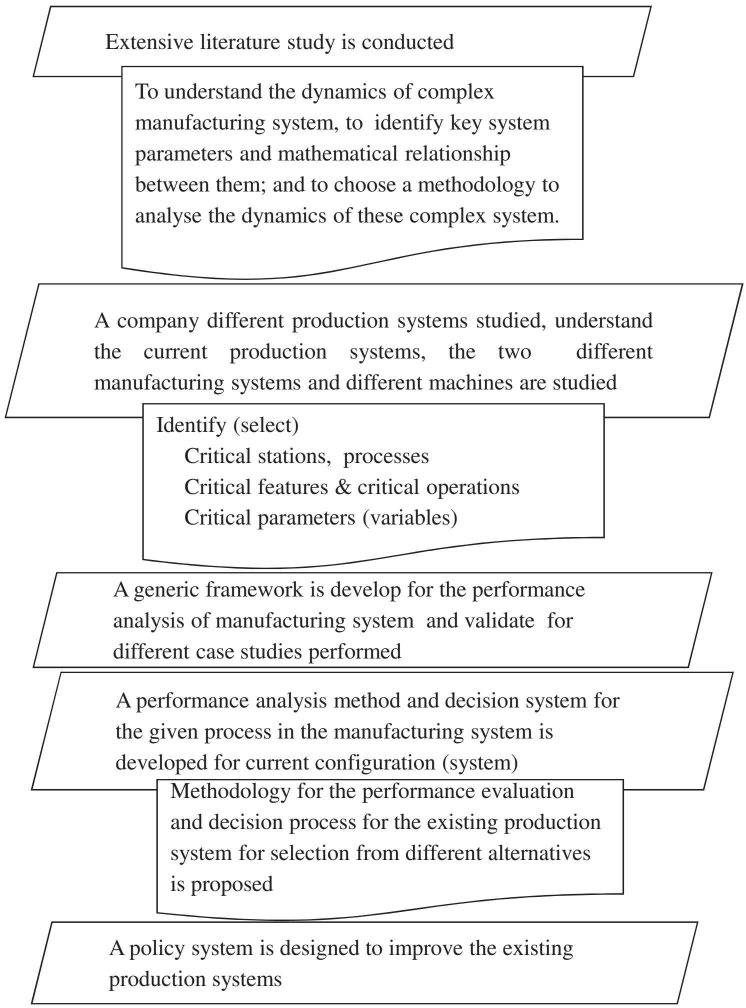


Figure 1.4: Overview of the steps that is driving to developing the framework.

performance. To address the problem described and to achieve the given objectives, the main investigation activities in this research adopted the following research questions:

RQ 1: How can the complex interactions and dynamics of process and operational parameters be captured for performance analysis of a manufacturing system?

RQ 1.1 Which process and operational parameters are critical to represent the dynamics and performance of MS?

RQ 1.2 Given the complexity and non-linearity of the dynamics, how efficiently/proficiently can these be modelled for analysis?

RQ 1.3 Can the findings be generalized into a framework applicable to other manufacturing systems?

1.5 Thesis structure

The thesis consists of five chapters including the introduction section.

Chapter 1 In this chapter, the background and motivation of the performed thesis work are described. The performance evaluation of a manufacturing system in the automotive industry is outlined. Current research gaps and challenges are detailed, followed by research scope, objectives, and research questions. Finally, author contributions and thesis outline with reference to the appended papers are described.

Chapter 2 This chapter presents the dynamics of manufacturing systems. The manufacturing system parameters and performance measures are described. The different levels of manufacturing system analysis are described. The manufacturing system controlling strategies are defined and the results of the papers related to the control methods applied are summarized. Then, the control of the machining process conditions is discussed. Finally, the basic elements of the manufacturing strategy framework are presented.

Chapter 3 This chapter describes the modelling techniques of a complex manufacturing system. The different approaches used in the analysis of complex manufacturing system are illustrated. The two most widely used approaches, SD and DES, are compared. Then the method relevant to the specific case under study for this work is specified and selected. The underlying reasons for the use of SD for the analysis of complex dynamic systems are presented. The study is based on the literature review of the different articles describing the use and applications of SD and DES in general and in manufacturing industries in particular.

Chapter 4 This chapter discusses the results of the significant research contributions posed in Section 1.4 in relation to the appended papers. The analysis of energy use of a primary process, i.e., casting, and the performance analysis, and evaluation of the manufacturing systems of a secondary process, i.e., the machining process, in the application of SD modelling and simulation of a complex manufacturing process are presented.

Chapter 5 This chapter presents conclusions, answers the research questions, and addresses industrial implications and future research directions.

1.6 Appended papers and author contributions

Paper A Adane T. F. and Nicolescu M. (2014),'System dynamics analysis of energy usage: case studies in automotive manufacturing', I*nternational Journal of Manufacturing Research*, Vol. 9, No. 2, pp.131-156.

This paper is a revised and expanded version of a paper entitled 'System dynamics analysis of energy usage: case studies in automotive manufacturing' presented at The 5th International Swedish Production Symposium, SPS12, Linköping, Sweden, November 2012.

In **Paper A**, the author contributed in developing the concept to the first case study, i.e. the primary process of casting and wrote the expanded version under the supervision of the co-author.

Paper B Adane T. F.and Nicolescu, M. Towards,'A Generic Framework for the Performance Evaluation of Manufacturing Strategy: An Innovative Approach'. *J. Manuf. Mater. Process.* 2018, 2, 23.

Paper C Adane T. F., Bianchi M. F., Archenti A. and Nicolescu M. (2015). 'Performance evaluation of machining strategy for engine-block manufacturing'. *Journal of Machine Engineering*, 15/4, 81-102.

Paper D Adane T. F. and Nicolescu M. (2016). 'System dynamics as a decision support system for machine tool selection'. Journal of Machine Engineering, 16/3.

Paper E Adane T. F., Bianchi M. F., Archenti A. and Nicolescu M. (2018). 'A decision support system for analysis of performance of manufacturing systems'. Journal of Manufacturing Systems: under review.

Paper B, **Paper C**, **Paper D** and **Paper E**, the author contributed in developing the concept and performed the model and writing the paper with the co-author/s.

1.7 Thesis relation to appended papers

Figure 1.5 shows the publications roadmap and how the different papers are interrelated.

In **Paper A**, the research work shows the energy use analysis of a casting process in automotive manufacturing companies. The critical operations, and the operation that has the highest (intensive) energy consumption in the process are identified, and a decision support system that can improve and minimize energy consumption is presented.

Paper B presents the generic framework for performance evaluation of the manufacturing system of an engine block. The framework is enabled as a decision support system and performance analysis of manufacturing systems that considers the complex dynamics interrelationships among process and operational parameters. In **Paper C**, the performance of the process in a flexible manufacturing system, and policies that improve the existing manufacturing condition, are described. **Paper D** shows a comparative analysis of the performance of the process using two special purpose machines, of the case study have different configuration, but operate with similar function, in the transfer (dedicated) and flexible manufacturing systems, respectively.

Finally, **Paper E** presents the identification of the main parameters and the performance analysis of a MS. The interrelationships among the process and operational parameters are considered in the analysis. It also contributes to the comparison of the flexible and dedicated manufacturing systems, considering these integrations with respect to the performance criteria. The primary research contributions of this thesis are focused on a primary process of casting and secondary process of machining. Therefore this dissertation doesn't cover the assembly process, which is marked with blue dotted lines in Figure 1.5.

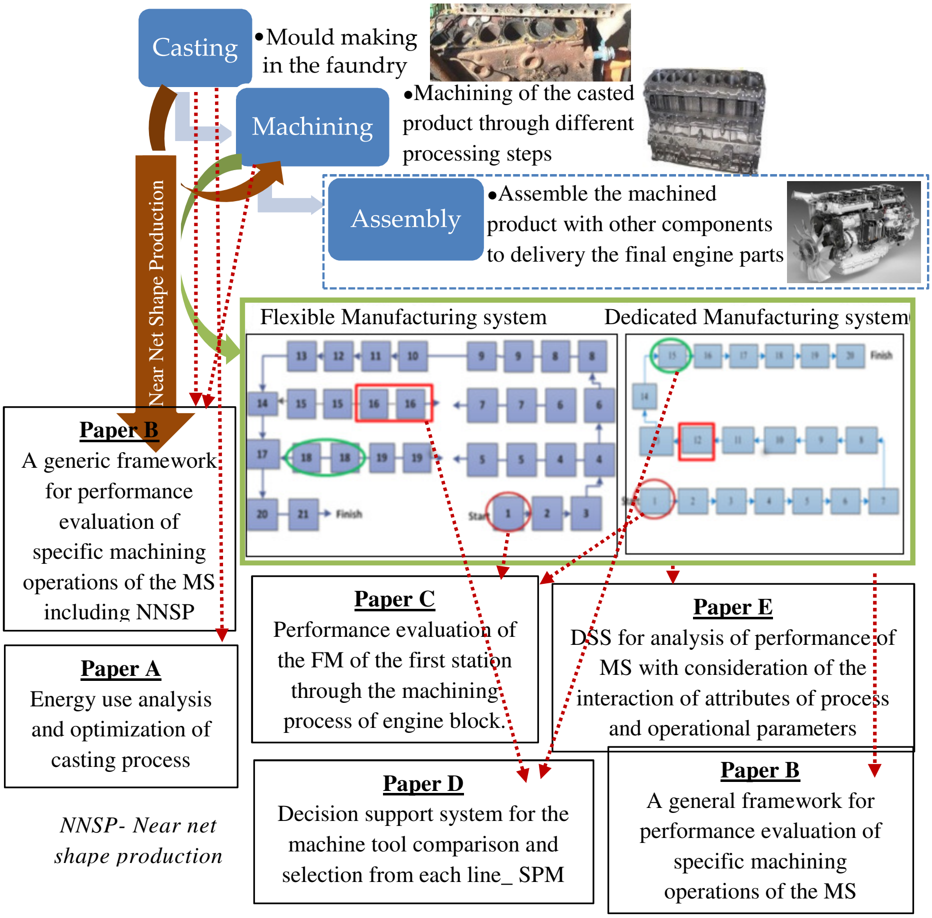


Figure 1.5: Publication roadmap steps for research process.

Chapter 2

Dynamics of manufacturing systems

This chapter presents the dynamics of manufacturing systems. The manufacturing system parameters and performance measures are described. The different levels of manufacturing system analysis are described. The manufacturing system controlling strategies are defined and the results of the papers related to the control methods applied are summarized. Then, the control of the machining process conditions is discussed. Finally, the basic elements of the manufacturing strategy framework are presented.

2.1 Background

A system is a collection of objects and their interconnections; be they physical, engineering, economic, financial, demographic or social. A manufacturing system embraces all procedures and facilities to transform raw materials into final products [2]. Groover defined a manufacturing system as a part of a production system. It is a complex arrangement of integrated equipment i.e., physical elements characterized or controlled by measurable system parameters and human resources, whose function is to perform one or more processing and/or assembly operations [44]. The physical elements include machines, cutting tools, material handling, fixtures, etc.; the measurable parameters are production rate, takt time (cycle time), total production time, capacity, unit cost, etc. The human resources are direct labour and indirect labour (including maintenance and repair personnel).

A dynamical system is one that evolves with time [8]. In the case of manufacturing systems, to respond to external or internal time variations, they have to be flexible. In order to develop flexible manufacturing systems able to operate in a variable economic environment, companies need a consistent manufacturing strategy to decide how to coordinate manufacturing systems. A manufacturing strategy is "a pattern of decisions, both structural and infrastructural, which determine the capability of a manufacturing system and specify how it will operate" [78]. Slack defined a manufacturing strategy as a set of coordinated tasks and decisions that need to be taken in order to achieve the company's required competitive performance objectives [85]. McGrath and Bequillard stated that a manufacturing strategy is the overall plan a company employs to manufacture products on a worldwide basis to achieve customer needs [64]. A business-oriented manufacturing strategy requires a decision framework to support markets [20]. The alignment (linking) of manufacturing and business strategies aids the development and deployment of manufacturing capabilities that can enhance the company's strategies to achieve a better performance [79, 82, 88, 27, 96, 97, 45].

Production decision making as part of the manufacturing strategy has to meet market challenges. Manufacturing strategy concerns two major issues: (i) the process choice in terms of alternative processes, inventory and capacity, and (ii) the infrastructure in terms of manufacturing system engineering, planning and control system and quality assurance.

Investments in manufacturing processes and infrastructure are considerable. Inappropriate investment always has detrimental implications on the company's market position. The most critical issue is the link between market demand and production capacity, which determines the volumes that could be produced [28]. This is a main reason that give the dynamic dimension to a manufacturing system way to operate. The concept of capacity and production volumes is strongly linked to that of flexibility. The ability of a manufacturing system to produce the volumes demanded at a reasonable of cost is one fundamental reason for studying the dynamics of manufacturing systems.

The link between the market demand for a product and the organization and operation of a manufacturing system is fundamental in studying and modelling the dynamics of the manufacturing system. Particularly, the models that are developed in this thesis have the purpose of investigating the capability of a manufacturing system in terms of volume limits (max-min) within which it is still reasonable to operate a certain system (to maintain) without the need for costly investments. Except market fluctuations, there are also internal influences that give a dynamic character to a manufacturing system. These can be changes in the design, workpiece material, variation between batches, etc.

A mathematical model of a dynamic system is a collection of quantities (variables and parameters) and their interrelationships (usually equations), which describe how the system behaves. An effective mathematical model is one which not only explains the system's behaviour to date but that can also be used to predict the future behaviour of the system; the ability to predict a system's behaviour is the first step in controlling it.

Thus, variables are quantities that vary significantly during the time period over which the system is observed, while parameters are quantities that are constant or whose variation is small and irrelevant in comparison to that of the variables (which makes it possible to model this type of parameter as a constant) over the same time period. Because of the large number of parameters/variables of manufacturing systems, they are listed in this thesis in groups, as illustrated in Figure 2.2. As the perturbations act at the input of the system, in order to keep the manufacturing system stable, the variables and parameters have to be controlled. The controlling of the system can be achieved at several levels, process level and/or operational level, structural level or organizational level (see Figure 2.1). The structural level considers the number and arrangement of workstations, machines, buffers or storages necessary to describe the manufacturing process.

Figure 2.1 describes the structure and dynamics of manufacturing systems considered in this thesis. The manufacturing system comprises the different inputs, outputs and sequence of operations (processes), that transform a work material from one state of completion to a more advanced state that is closer to the final desired product. It adds or creates value to a product by changing the geometry, properties, appearance and complexity of the starting material. The sequence of production machines forms a manufacturing system configuration – which is either a transfer line or a flexible systems – comprising of different machines at each station, material handling system, the manufacturing process, etc. The manufacturing process represents the machining process conditions of each machine at each station

During the manufacturing of a part, a variety of processes are needed to remove excess of material (the main machining processes of milling, drilling and turning are used as means of removal). A machining process involves many interrelated parameters [81]. The complex interactions of these parameters through time, directly or indirectly, influences the metal removal rate and the output of the part produced. The machining system is represented by a closed-loop system comprising a machine tool elastic structure and the cutting process [7]. These two subsystems are related to, and interact with, each other. The machine tool elastic structure includes machine, cutting tool, workpiece, and clamping system [59] whereas the cutting process includes, for example, cutting parameters (depth of cut, feed rate, cutting speed, spindle speed, etc.), tool material, cutting process operations (milling, boring, turning, drilling, etc.) and cutting tool geometry [19, 71].

During manufacturing, process parameters can be controlled in a limited range, determined by the process capability and other technological constraints, that directly or indirectly influence the sequence of the operations, see Figure 2.1. Nevertheless, in many cases the true relationship between these parameters is not fully understood. Expressing the interaction of the different process parameters is very complex, because of the nonlinear phenomena incorporated in the process. The manufacturing process is influenced by a number of input and output variables. The process input variables are the process independent variables and the output variables are the process dependent variables. Some of the parameters that influence the process are cutting conditions - cutting speed, feed rate, spindle speed, depth of cut; cutting tool - material type, coating, tool geometry, etc.; machine - rigidity, capacity, accuracy, etc.; workpiece material - type, hardness, tensile strength, thermal conductivity, etc.; cutting fluid properties and characteristics, etc.

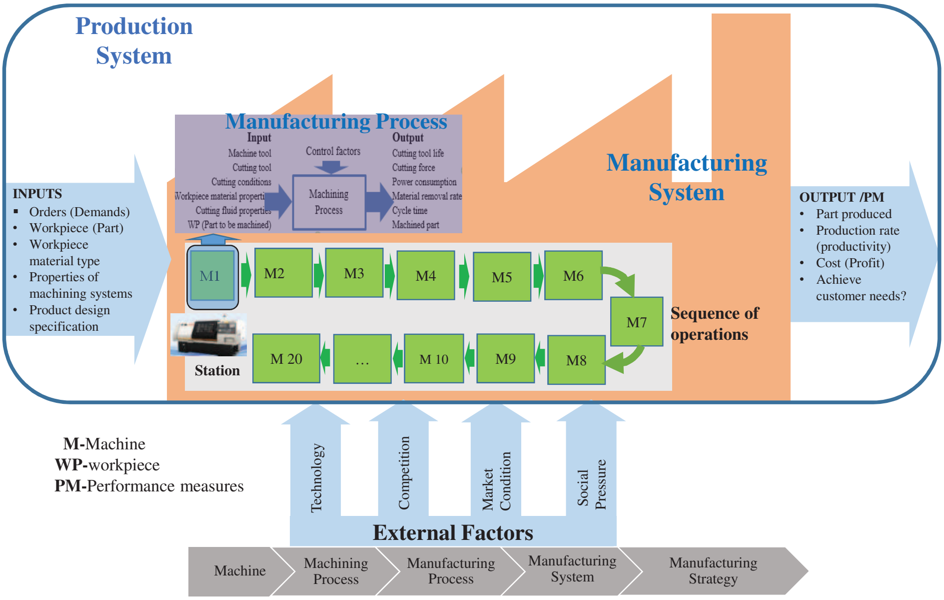


Figure 2.1: Dynamics of manufacturing systems.

The process is controlled by adjusting parameters within certain limits. Of all of these process parameters, feed, speed and depth of cut are among the most important [81]. A precise understanding of these critical parameters will improve the performance of the manufacturing system (reduce cost, improve productivity). Thus, the change of these parameters' complex interaction through time directly or indirectly influences the metal removal rate and the output of the part produced. The change in manufacturing process in turn affects the performance of operations (processes), and influences the whole manufacturing system. Since the parameters in the system interact with one another and everything is connected to everything else, many parameters change simultaneously. The dynamic complexity of the system arises from the interaction among parameters over time.

The relationship among the parameters determines how well the system can process or be controlled to accomplish the manufacturing task. The control of the manufacturing process in relation to the system objectives refers to the entire manufacturing system. The control of the individual station plays a large role in the success of the whole manufacturing system, Figure 2.1. The entire manufacturing system must be managed in order to schedule and control individual processes, part quality, takt time, production rates, cost, inventory level, etc. How well its working conditions are performed is measured by the performance metrics.

Manufacturing companies are operating in an uncertain and constantly changing environment driven by changes in customer demands, product design and processing technology [31]. Uncertainty in manufacturing systems also increases complexity, which is seen as a main challenge in many fields [57, 33, 32]. The manufacturing system's working conditions can be influenced by internal variations, like workpiece material type and/or external variations e.g., market requirement (demand changes), technology advancement, competition, etc. Complex systems' behaviour is intrinsically difficult to understand due to the dependencies, relationships, or interactions among their parameters or between a given system and its environment. These dynamic interactions increase the system complexity and make its behaviour nonlinear. Systems that are complex have distinct properties that arise from these relationships. Therefore, it is critical to understand these relationships, the manufacturing system's working conditions, and the strategy in order to evaluate and manage the production of optimal output.

2.2 Manufacturing system parameters

In this thesis, the relevant input source of variations and performance parameters are identified through extensive literature survey, case study, experience, and expertise knowledge. The effect of these input parameters' variations on the manufacturing systems is evaluated in relation to the performance criteria. As has been mentioned, the possible variations could be volume of demand, workpiece material type change, or some design changes of the product. Moreover, the performance that a manufacturing system is expected to accomplish is evaluated through performance metrics including cost, productivity, quality, capacity, flexibility etc. The principal manufacturing system parameters deployed are presented in Figure 2.2 [36, 40, 55, 69, 17] and described in **Paper B**, **Paper C**, **Paper D** and **Paper E**. For ease of clarification and to understand the effect of the different parameters on the system process, they are categorised into groups (later on it will help us to interrelate each factors together).

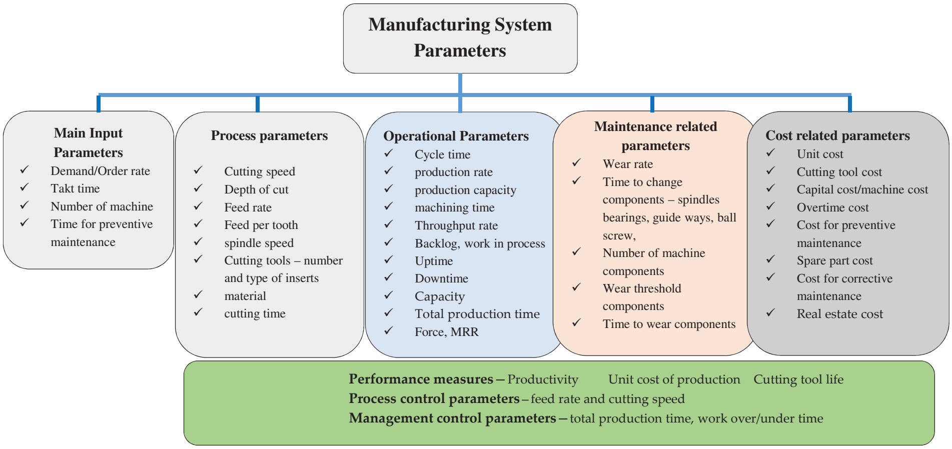


Figure 2.2: Main manufacturing system parameters .

Manufacturing systems parameters comprise machining process, operational, cost and maintenance related and others parameters.

2.2.1 *Machining process parameters*

Machining process parameters are also called structural parameters and include: material removal rate, cutting speed, feed rate, depth of cut/cutting depth, spindle speed, workpiece diameter, cutting time/machining time/period of engagement, length of workpiece/machined length, power, force, machine tool, and so on.

2.2.2 *Performance metrics*

Performance measures are metrics used to 'quantify the efficiency and/or effectiveness' [16] of manufacturing systems. Performance metrics are also called operational parameters or key performance measures. Key dimensions of manufacturing's performance can be described in terms of cost, quality, price (cost), productivity, and flexibility , e.g., [50, 82, 39, 95, 98, 83, 46].

Production rate - produce the right amount of product within the given time Productivity is one of the most important performance indicators adopted to evaluate the performance of manufacturing systems. The specific factors incorporated to determine productivity are, for instance, feed rate, cutting speed, machining time, tool change time, load, and unload time, set-up time, pre-maintenance time, time for failures, etc. Machining time is one of the most crucial factors.

Cost – price, cost per part, total cost. The costs of production are the performance metrics that consider the different cost components that are related to manufacturing processes. The cost per part is the main factor considered. Thus, the higher the throughput is, the better the cost performance for the manufacturing system will be. Relevant input sources of parameters related to total cost per part are, principally:

- *Maintenance cost per part*: the cost spent performing maintenance activities such as preventive maintenance, corrective maintenance and external maintenance workers performing maintenance activities. This depends on time spent for preventive maintenance, corrective maintenance and scheduled overhaul for the components.
- *Machine tool cost*: the capital investment cost, which includes the cost of the machine tool including education, and the number of required machine tools.
- *Cutting tool cost*: includes the tools for different operations.
- *Overhead cost*: includes only operator's overtime cost. It doesn't include costs, staff wages, heating, lighting, and so on.
- *Capital cost per part*: depends on the machine tool type used - in this case SPM or FMC (GPM).
- *Tool cost per part*: depends on the tool life and therefore on cutting process parameters.
- *Spare part cost*: determined by calculating the cost of replacing worn out machine components and operator's overtime cost - it is the cost the operator spends performing maintenance activities.
- *Real estate cost*: the factory adaption cost and the floor area used by the specific machine type.

Quality - fit for purpose and aesthetics, the process parameters should be within the design specification limit to keep the quality of the part produced and to deliver the required specification of output. That means although the quality aspect is a fundamental requirement and performance indicator for part production, in this thesis, the machining system capability is to be considered as a constraint and not as a parameter to be monitored.

Capacity - The ability of a manufacturing system to fulfil market demand is primarily determined by its production capacity. Thus, in order to be responsive to fluctuations in demand there is a highly recognized need for capacity scalability i.e., increasing or decreasing number of machines, working hours, as well as working shifts, etc.

Flexibility - the ability of the production line to be agile and to adjust (customize) the different aspects to produce the desired products, for example lower and higher demand, change in workpiece material, new feature introduction, how the system accommodates the arrangement of the line, the total production time available, how to adjust the different process parameters, etc.

The mathematical expressions for some of the major time and cost factors accounted in the thesis are described below:

1. Time factor

- Machining time (T_m): the time the tool is engaged in machining a given part during the cycle on a given machine tool type, and required operation(s) (boring, milling, reaming, etc.). The cutting time is determined by the operation type:

$$T_m = \sum T_m(r, sf, f) \tag{2.1}$$

  where, $T_m(r, sf, f)$ - time for roughing,semi finishing and finishing operation.

- Part handling time (T_h): the time spent loading and unloading the part.
- Cycle time (T_c): total machining time, set up time, loading/unloading time and more.

$$T_c = \frac{\sum T_m(r, sf, f) + T_i + T_h + T_o}{n_m} \tag{2.2}$$

  where, T_c - cycle time, T_h - part handling time(loading and unloading time), T_i - idle time, T_o - time for others, $T_m(r, sf, f)$ - time for roughing,semi finishing and finishing and n_m - number of machine.

- Takt time: the rate at which parts can be produced to meet the required demand. For example if a manufacturing system has a takt of T minutes that means that every T minutes there is an output (a produced part). This is estimated by net available time and expected demand.
- Total production time: is influenced by takt time, the system efficiency and the level of demand
- Downtime and uptime: the period of time when the machine is not being utilized due to technical failure, corrective maintenance, preventive (planned) maintenance, or tool change time and so on.
- Tool change time: the time spent changing the tool at the end of the tool life. The tool change time per part is determined by the tool change time and the number of part cuts during the tool life.

$$T_p = \frac{T_t}{n_p} \tag{2.3}$$

  where, n_p - number of part cut in one tool life, T_t - tool change time and T_p - tool change time per part.

2. Cost factor: considers only the type of costs that are different with respect to the different manufacturing system configurations. For example, material cost is not influenced by the type of machine tools or the manufacturing system's configuration. The unit cost (cost per part) is estimated based on the cost described above.

$$C_p = \frac{C_c + C_m + C_t + C_o + C_{sp}}{P_r} \quad (2.4)$$

where, C_p - unit cost (cost per part produced), C_c - capital cost, C_m - maintenance cost, C_t - tool cost, C_O - overtime cost, C_{sp} - spare part cost and P_r - production rate(throughput rate).

3. Overall equipment efficiency: evaluates and measures manufacturing operations.

4. Capacity: the capacity of the manufacturing system to produce; determined by the uptime and cycle time.

2.3 Process and system level analysis

2.3.1 System level analysis

In system level analysis, all sequences of operations in the manufacturing line are hidden inside black boxes, see Figure 2.3. The strategy for this level of analysis ignores the internal mechanism (process) of each station and focuses solely on the output of parts in response to selected inputs and execution conditions. As input parameters, only the workpiece property specifications from the primary process and the control factors from the external environment are considered. In general, this level of analysis is not concerned with how the detailed inner process of each station is tuned/adjusted to achieve the desired output.

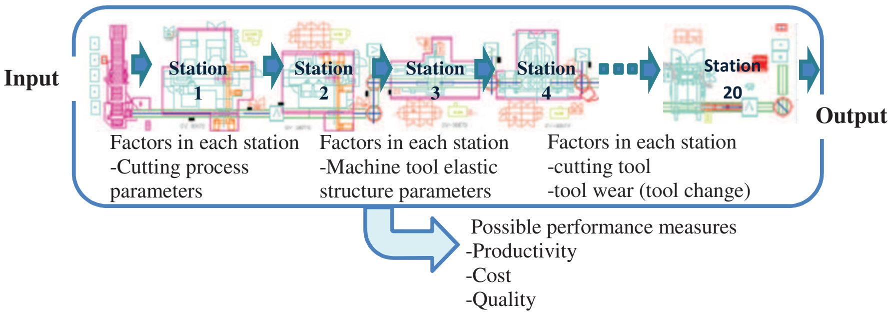


Figure 2.3: Sequence of stations for an engine block machining line-system level analysis.

2.3.2 Process level analysis

In process level analysis, each station in the manufacturing system is accounted for independently, unlike in the system level analysis. A detailed process level analysis considers almost all of the factors at each station. To analyse the output of the part produced, each station's input parameters, the control factors, the interaction of process parameters and other activities are taken into consideration (see Figure 2.4). Figure 2.4 describes the machining process of some features at a station (station 1 from Figure 2.3 is taken as an example). The parallel machines in this given station, which are identical and function in exactly similar operations, indicate the possibility of adding a machine in order to cut the cycle time by half.

To evaluate the entire manufacturing system, the working conditions of each station are analysed independently, like in process level analysis, consequently combining and placing them in a green box.

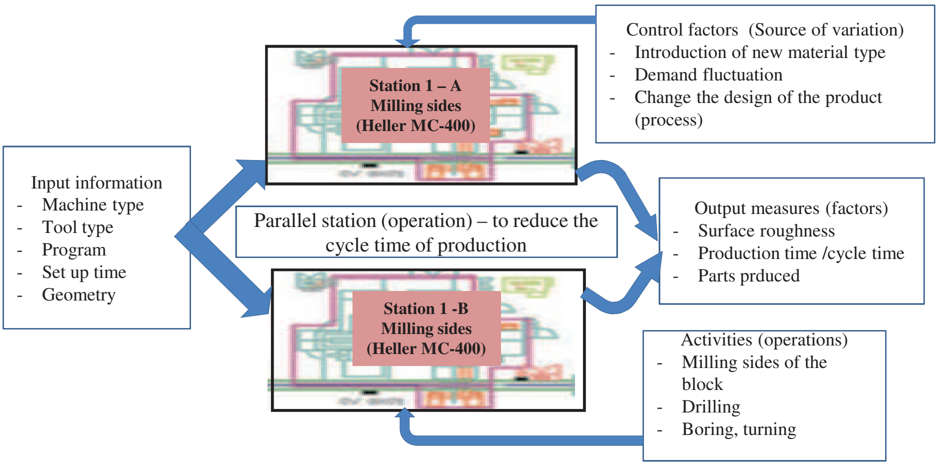


Figure 2.4: Machining processes of features at a station with identical parallel machines—process level analysis.

2.4 Manufacturing control strategy

There are two main aspects that have to be discussed when selecting the manufacturing system configuration. One is the technological aspect, i.e., process capability, which is related to the selection of the processes able to produce a part to the required design specification and the other is the business aspect that is the system capability and refers to selecting the way the product is made. The business aspect concerns the product volumes and varieties a system can produce. Product variety refers here to the different product designs or types that are produced by the system.

There are two types of production facilities considered for analysis and simulation in this thesis: (1) flow-line production or transfer lines with dedicated workstations arranged in a sequence and (2) Flexible Manufacturing Systems (FMS) possessing multiple automated stations and is capable of variable routings among stations. FMS flexibility allows it to adapt to soft product variety.

The two production facilities differ from technological and mainly, from a business perspective. While the transfer line provides low manufacturing costs for the production of a limited range of products in high quantities, the FMS is economically justified for the mid volume requirements of family of parts, i.e., product varieties.

The main objective of the modelling is to investigate and compare the limits of the process capabilities of these two manufacturing system types to match the system capability levels in response to the input fluctuations that can be determined by changing in the quantities, varieties, design, and work material properties.
The dynamics of a machining system is defined by two conditions:

1) The time variation of the input in the system. The variation can be originated by the external perturbations caused by market demand changes or internal variations determined by the design or workpiece material.

2) Control of a system's parameters to respond to the variation at the input.

Without satisfying both conditions a manufacturing system cannot be considered a dynamic system. For example, if the demand is decreasing, the system has to respond to this input by decreasing the production rate. Otherwise, if the system continues to produce at the same rate, the inventory will increase, while the cost of production will exceed the revenue, which will make the system unstable.

Hill points out that the "markets are inherently dynamic while manufacturing is inherently fixed" [49]. Whereas market fluctuation is a time dependent phenomenon, manufacturing will remain fixed unless conscious control decisions are made. Market requirements are critical to manufacturing strategy [74], because a criterion qualifying of an order wins orders from customers [48].

The controlling strategies followed to improve the performance of manufacturing systems can be:

1) Process or production control: in which the critical process parameters are controlled i.e., feed rate, cutting speed, depth of cut.

   At the process control, the parameters are controlled within the capability of the system. This means that the process parameters can be controlled only within a range that still ensures the specified quality of the part (the operational parameters are evaluated at the system level). For each manufacturing system there is a limited range for controlling the process parameters. If the limits are reached, then other forms of control could be implemented.

2) System control also called management control, this considers

- the control of operators working hours and shifts i.e., control of the number of shifts, number of working hours (extra working hours, work over the weekend /over or under time) and control of total production time.
- the control of number and arrangement of work stations, machines, buffers or storages. This type of control requires investments.

The following table, Table 2.1, summarizes the controlling factors considered in order to analyse the performance of the manufacturing systems in the published papers.

Table 2.1: Summary of control strategies followed by each paper

	Manufacturing system performance controlling factors	
	Process control	**System control**
PaperC	feed rate, cutting speed are controlled to speed up and slow down production to manage the capacity during increase and decrease demand variations respectively	◇ in the flexible manufacturing system a machine that performs a similar parallel operation was added to cut down the cycle time and achieve the desired demand, ◇ the total production time was taken into consideration to see the different alternatives
PaperD	process level control was tried to be performed but it was robust to make the changes due to the properties of the system of the case study (dedicated machine and dedicated manufacturing system)	◇ the total production time was accounted to work on the demand requested
PaperE	control of the variation of process parameters, feed rate and speed are controlled to speed up and slow down production, during a decrease, increase and cyclic demand variation	◇ a machine was added for the flexible manufacturing system to reduce the cycle time of a station, ◇ the production time was varied to manage the demand requested

2.5 Machining process control

Control of the dynamics of manufacturing systems within capability limits is performed in a top-down approach. The primary interest of the controlling is to maximize productivity, to reduce the cost per part, and to control the capacity of production during internal/external demand variations. In response to the input variations, new operational parameters are calculated and if necessary the system is balanced. Then, the process parameters are controlled to new values and the performance of the system is evaluated with respect to the performance measures.

The strategy of machining process control is the machining method and process conditions in accordance with the machining status. It can also be referred to as the machining system procedures (conditions) determined by all the decisions taken with the objective of producing the desired part output to optimize the system with respect to the desired output and related targets, as shown in Figure 2.5.

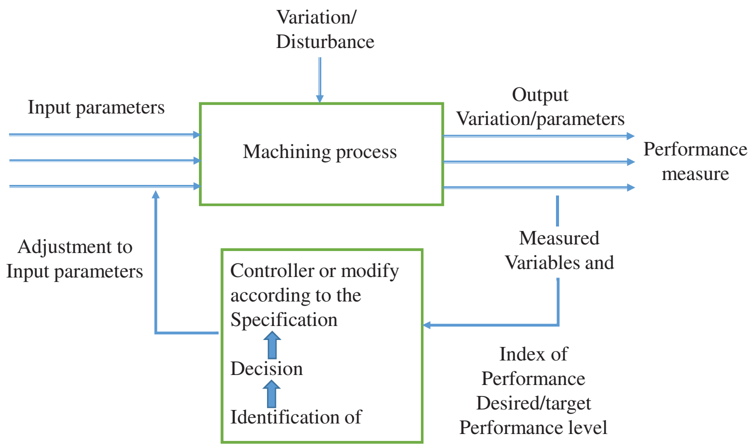


Figure 2.5: Machining strategy the control on the machining process.

At the process stage, there are two levels of control: (i) soft control and (ii) hard control. The soft control is performed with the help of the main cutting parameters, i.e., depth of cut, feed rate and cutting speed, while the hard control concerns other conditions such as tool geometry, tool material, cutting fluid, fixturing etc.

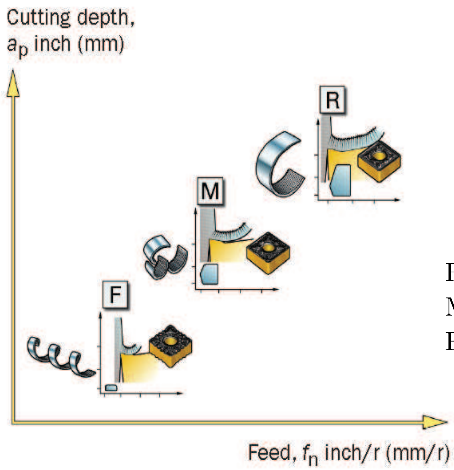
The main cutting parameters in a machining operation are depth of cut, feed rate and cutting speed. Depth of cut is often predetermined by workpiece geometry and operation sequence. Consequently, feed rate and cutting speed are first choice control parameters. The feed rate determines the cutting force level and the power consumption, while cutting speed determines the heat generated and consequently the tool life. Therefore, the feed rate and cutting speed can only be controlled in a limited region. The feed rate and depth of cut have an influence on the cutting forces and temperature; therefore, they strongly affect the cutting speed permitted by the tool. The change in feed rate changes the cutting speed. Therefore, determining the appropriate feed rate for a given machining operation depends on the tool used (type, material), the type of operations (roughing, or finishing), and surface roughness in the finishing operation.

Feed rate control has to be performed by taking into consideration the surface roughness in the finishing operation. To predict the ideal average roughness for a surface produced by a single-point tool, the effects of nose radius and feed can be combined in an equation, Eq.2.5. In the equation, it is assumed that the nose radius is not zero, and that the feed rate and nose radius are the principal factors to determine the geometry of the surface finish [15, 42]. The equation applies to estimating the ideal surface finish in face milling with insert tooling:

$$R_i = \frac{f^2}{32N_R} \tag{2.5}$$

where, R_i - theoretical arithmetic average surface roughness, f - feed per tooth and N_R - nose radius.

The other factor to be accounted for when controlling the process is the chip control. Many processes require a series of roughing operations (R and M shown in Figure 2.6) followed by a final finishing operation (F). In the roughing operations, R, there is maximum material removal, depth of cut is made as large as possible within the constraints of available power, machine tool and structural rigidity, and strength of the cutting tool. Thus, the large cutting depth and feed rate combination, can result in high cutting forces. Consequently, this causes higher MRR, small chip, results in harder chip break, as shown in Figure 2.6, and less time in cut. Medium roughing machining, M, is most general purpose application with wide range of cutting depth and feed rate combination. Finally, in the finishing operation, F, depth is set to achieve the final dimensions for the part. There is a small depth of cut and low feed rates, which results in low cutting forces. Consequently, this forms longer and thinner chips, and longer cutting time.



R rough machining
M medium machining
F finishing

Figure 2.6: Effect of feed rate on chip formation, courtesy of Sandvik Coromant [3].

An increase in cutting speed will rise the temperature, which results in undesirable effects for a cutting process. Temperature rise is a very important factor that limits the cutting speed because of its major adverse effects [54]. The possible detrimental effects of high cutting temperature on cutting tool:

- lowers the strength, hardness, stiffness, and wear resistance
- may undergo plastic deformation of the cutting edge if the tool material is not sufficiently hot-hard and hot-strong, thus altering the tool shape
- causes dimensional inaccuracy and uneven dimensional changes in the part being machined, depending on the physical properties of the material, thus making it difficult to control its dimensional accuracy and tolerances
- can induce surface damage, metallurgical changes in the machined surface, adversely affecting its properties

As a consequence, the control limits of cutting speed values must be carefully determined. If these limits are exceeded, then other parameters must be considered for control, e.g., cutting tool material and geometry.

When cutting speed increases, tool life reduced rapidly. On the other hand, if the cutting speed is low, tool life is long, but the rate at which material is removed is also low. Thus, there is an optimum cutting speed, based on economic or production considerations, where the tool life is long and production speeds are reasonably high. It is important, for controlling the machining process, to target this optimum value when using cutting speed as a control parameter. Control of cutting speed is based on making the best use of the cutting tool, which normally means choosing a speed that provides a high metal removal rate yet suitably long tool life. Mathematical formulas have been derived to determine optimal cutting speed for a machining operation, given that the numerous time and cost components of the operation are known. The formulas allow the optimal cutting speed to be calculated for either of two objectives: (1) maximum production rate (Figure 2.7), or (2) minimum unit cost (Figure 2.8). Both objectives seek to achieve a balance between material removal rate and tool life. The formulas are based on a known Taylor tool life equation for the tool used in the operation. Accordingly, feed, depth of cut, and work material have already been set.

Figure 2.7 describes the time elements in a machining cycle, which are plotted as a function of cutting speed. To maximize production rate, the speed that minimizes the total cycle time per part produced is determined. This is the speed for maximum production rate.

Figure 2.8 presents the different cost components that determine the total cost of producing a part during a given operation. Total cost per part is minimized at a certain value of cutting speed. For minimum cost per part, the speed that minimizes production cost per part for the given operation is determined. This is the speed for minimum cost per part that optimizes the system.

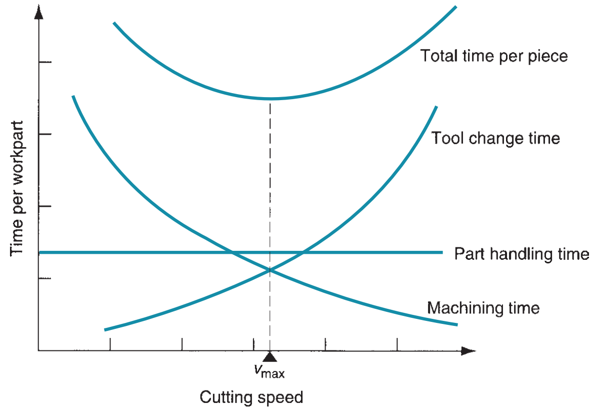


Figure 2.7: Elements of time in a machining cycle as a function of cutting speed [43].

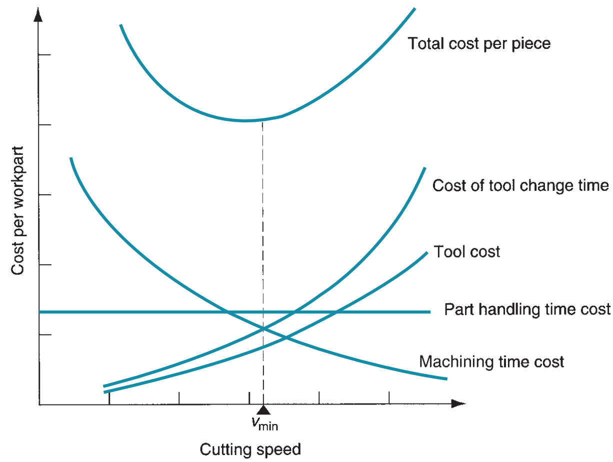


Figure 2.8: Cost components in a machining operation as a function of cutting speed [43].

2.6 A framework for manufacturing strategy

A manufacturing strategy framework is a methodology for a set of activities and a pattern of decisions that can be adapted according to a given company's manufacturing conditions. The strategy should be designed to accommodate the particularities of a given manufacturing system.

While controlling the manufacturing process, for example, how to manage the productive performance to a fluctuation in demand over the given time horizon is one of the manufacturing strategy activities to be managed. The different alternatives designed could be to adjust the cutting process variables (to speed up or slow down the production process), increase/decrease total production time i.e., work (schedule) overtime or under time, or increase/decrease number of shifts. Due to the fluctuations of factors like demand, workpiece material, design specification, etc. the input parameters values for the machining process could vary, which influences the performance of the process, and in turn the system capability, as shown in Figure 2.9. The basic elements of a manufacturing strategy framework includes:

1. Structure: the major decisions that are linked to the manufacturing functions
    - Facilities: type of manufacturing systems' configuration/layout (arrangement of production system), number of stations/machines, type of machines
    - Production process, production equipment
    - Integration between different aspects
2. Infrastructure: system performance measures
    - Production rate, throughput analysis
    - Cost - total cost, cost per part (unit cost)
    - Quality - to keep the quality of the part, the cutting process parameters are set within the design or working specification limit.
    - Production capacity
    - Flexibility (change in product design, response to demand volume, new feature introduction, change in product design specification, etc.)

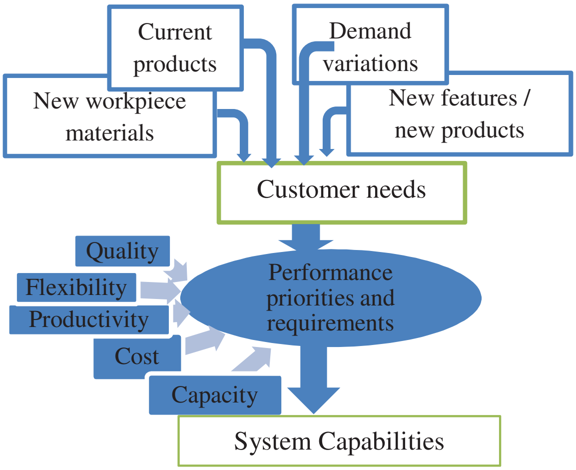


Figure 2.9: System variations in relation to system performance .

Chapter 3

Modelling of Complex Systems

This chapter describes the modelling techniques of a complex manufacturing system. The different approaches used in the analysis of complex manufacturing system are illustrated. The two most widely used approaches, SD and DES, are compared. Then the method relevant to the specific case under study for this work is specified and selected. The underlying reasons for the use of SD for analysis of complex dynamic systems are presented. The study is based on the literature review of the different articles describing the use and applications of SD and DES in general and in manufacturing industries in particular.

3.1 Modelling of manufacturing systems

In the context of a manufacturing system, the dynamic interaction between the process and operational parameters under the influence of input disturbances forms a complex system. Thus, the external and/or internal variations introduced into a manufacturing system determine the behaviour of the system's conditions, which in turn affect the system capability. For example, if the external variation is a change in demand, then these fluctuations determine the manufacturing system's operational parameters, which in turn affect the production process and the system performance. These dynamic interactions increase the system complexity and make its behaviour nonlinear.

When the complexity of a system makes analytical methods impractical for evaluating the performance and improving the ongoing system, simulation based tools with a rigorous experimental design and statistical output analysis can be used [92]. Many researchers have discussed different aspects of simulation and modelling techniques in their publications and have been using these as an aid in their decision-making process and for performance evaluation. It is possible to perceive in a model how a real-world activity performs under various conditions and to test various hypotheses/scenarios at a fraction of the cost of performing the actual activity.

The main advantages of simulation over experimental analysis arise from the better understanding of interactions and identification of potential difficulties, allowing for the evaluation of different alternatives and therefore, reducing the number of changes in the final system [73]. It also has an advantage in its flexibility, ability to deal with variability and uncertainty, and its use of graphical interfaces to facilitate communication with users or customers, and comprehension by analysist.

Application of simulation and modelling has played a significant role in evaluating the performance of design and operation of manufacturing systems [70, 35, 12]. Literature on simulation that has been conducted during the recent decades has witnessed the diversification of phenomena in terms of manufacturing system techniques and applications [101]. It is commonly applied in the areas of supply chain management, business process engineering, scheduling, organizational theory and modelling, manufacturing system design and operation, operations management in various industries at global, business and operation levels. Various simulation paradigms are available to date, each one with its own benefits and drawbacks. Some of the major techniques available in the manufacturing and business areas include discrete event simulation (DES) [25, 86, 24, 23], system dynamics (SD) [47, 30, 9, 99, 93, 75, 21], agent based simulation (ABS), mathematical programming models, multi criteria decision making (MCDM) models [94, 10], analytical hierarchy process (AHP) [51], Data envelopment analysis (DEA), petri net models [61, 22, 68], Monte Carlo, Taguchi's methods along with analysis of variance (ANOVA), design of experiments and so on [101]. Some of these simulation and modelling techniques in manufacturing and business areas are described in **Paper B**, **Paper D** and **Paper E**.

A review by Jahangirian et al. found that DES is the first most widely used technique followed by SD, which are the second most widely used in manufacturing and business areas [52]. A crucial point in this regard for companies is to decide which simulation approach fits their system best. More specifically, which modelling techniques to use for the specific application under study is one of the research questions to be addressed in this context. Therefore, appropriate simulation tool must be selected based on the types of models to be constructed for the given problem and area of interest [65]. The choice of a suitable modelling techniques is influenced by the problem definition and/or purpose of the model [18], and object (the real world context under investigation) of the model. Therefore it is essential to integrate these characteristics (selection principles), usually ignored by analyst, modeller, and researcher, in the early stage of the modelling process.

In general, the relevant questions expected of the model to answer and the expected outputs of the problem will be identified and defined first. In addition, key criteria for a comparison of various methodologies should be identified in regard to the problem defined for the specific application under study.

Authors have tried to compare DES and SD methodologies and suggest a procedure (through guidelines) to select the most suitable one for the given problem.

Finding a definite procedure was impossible, nevertheless, a general guideline for selection can be drawn. Lorenz and Jost proposed a concept to select a suitable method for a particular area [63]. The link among the three dimensions: problem (purpose), object (the real world characteristics under investigation) and methodology are the key factors considered by the above authors. Accordingly, the link between purpose and object determines the methodology that suits the specific area of interest, as shown by the structure in Figure 3.1.

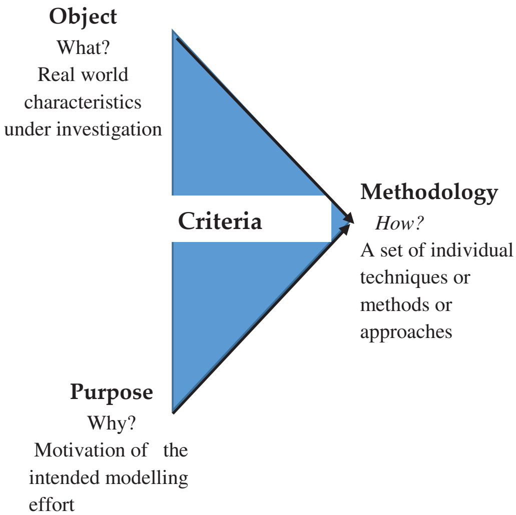


Figure 3.1: The link between purpose and object that fit with adequate methodology.

Consequently, modelling of complex systems in this thesis starts by defining the problems that address the issues of interest followed by the purpose of the model. Once the purpose is defined, the system being modelled, the object under study and time frame (horizon) in which the behaviour of the system is analysed are set. Then, the methodology that is best suited to and that aligns within the characteristics or perspectives based on the defined criteria (as shown in Table 3.1) is chosen.

3.2 Problem definition

The main limitation of the customary performance measurement systems used in today's evaluation of manufacturing systems is that they do not consider the technological performance measures. Those measures are essentially to control and fully optimize a production system. This limitation is reflected in the existing simulation models that do not consider the adaption of the process parameters to the change in the operational conditions. To evaluate and control the performance of such manufacturing systems there is a need for a methodology that addresses this limitation. In addition, a technique to analyse the dynamic interrelationships among different factors of the manufacturing systems is also missing.

3.3 Identifying model purpose

The purpose of the model refers to the motivation of the intended modelling effort, which includes:

- Understanding the system as a whole (aggregate level).
- Understanding interaction between system parameters.
- Understanding feedback, delay and nonlinear relationships. For e.g., how the manufacturing systems are managed if there are fluctuations due to the dynamic nature of the manufacturing environment.
- Investigate the disturbance in the manufacturing environment.
- Analysing the system behaviour when modifications in the production are required: Developing different scenarios and understanding the system behaviour under different conditions. Understanding different causes, possible long-term consequences, forecast of the production system etc.
- Evaluation of the existing system and proposal of policies/strategies that can improve the existing manufacturing conditions.
- Possibility to use qualitative and quantitative data for simulation.

Identifying objects under investigation

The object relates to the real world characteristics of the problem under investigation. Characteristics such as:

- Number of entities: in this thesis there are large numbers of parameters considered in the manufacturing system.
- Uncertainty of getting a complete set of data - some data are guessed and obtained from experience or as a graphical function based on historical data. That is, it is impossible to get the exact values of some data.
- Causal relationships among factors of the manufacturing system.
- Modification and change of manufacturing condition: This is not an effect within a matter of hours but rather weeks, months or years. Accounting the different variations that will impact the factors interrelated in the system in a nonlinear fashion, which needs time.

3.4 Comparison of SD and DES for modelling manufacturing systems

SD and DES are the two established simulation approaches that model the behaviour of systems through time. Both approaches were emerged almost simultaneously with the advent of computers. Despite the fact that, each methodology is more suitable for some specific type of system applications (problems), [76]. Each follows different approaches, different perspectives, and both can be used to analyse real case system applications (problems) from different points of view. They have been used in different areas of application and as described in [89, 58, 18, 66], stated that there exists very little communication between SD and DES.

Discrete event simulation (DES) is the most popular approach for simulation models of manufacturing systems [25]. It has been employed to understand and assess the impact of decisions made on the production system, including its various functional areas. DES support the engineer and decision maker to analyze each individual operation and evaluate and improve manufacturing processes and to make decisions at an early stage of implementation [67]. Kibira et al. stated that, typically, DES is done to address a particular set of problems, and it does some 'what if' analyses, in which the effect of different options can be investigated [56]. Smith reviewed the literature on the use of DES for manufacturing system design and operation problems [86]. Caggiano, A., and Teti, R. applied DES to analyze the different manufacturing cell production strategies [24]. DES was also employed to improve the performance of manufacturing systems in terms of throughput time, productivity, energy efficiency and resource utilization [24, 23].

Helo presented a SD model for strategic scenarios analysis and polices for the supply chain operations in manufacturing systems [47]. Oyarbide et al. investigated the application of SD in the transfer line modelling task [73]. Deif and ElMaraghy analyzed the concept of capacity management of the different performance measures of the manufacturing system using a SD approach under conditions of unanticipated demand fluctuations [30]. Shooshtarian and Jones used SD simulation modelling for the analysis of production line systems for the continuous model of transfer lines with unreliable machines and finite buffer stock in the system [84].

There is limited literature available on the comprehensive comparison between SD and DES. The existing comparisons mainly tend to be biased by either SD or DES analysts [66], or authors personal opinion on their area of expertise, or the way they perceive the system they use, or the practice of model development, or the modelling philosophy, etc. This is due to the fact that some people are more comfortable with, and stick to, what they know best. In addition, the system being modelled is given less attention than the purpose of the model.

Because of the flexibility of the modelling process, along with its ability to combine both qualitative and quantitative information, SD has been applied in many different fields of study. SD allows qualitative factors to be considered in the system whereas in DES quantitative data is important that is either accurate historical data or estimates of future performance.

In a SD problem, the dynamics of the problem are usually associated with the operations of the internal structure of a given system. In this sense, the interactions between subsystems and/or variables are important. Therefore, SD simplifies the analysis of complex systems where a large number of interrelations between variables exist and in which cognition is not sufficient in the decision process. Referring to DES, in some application it can sometimes be unnecessarily complex. General comparison of SD and DES is described in **Paper B** and **Paper E**.

3.5 Criteria for comparison

As already mentioned, a structured approach is necessary in order to precisely select suitable simulation and modelling techniques to manufacturing system. Such selection can be made by describing (defining, analysing) the two widely used techniques, SD and DES, across a given range of criteria defined for comparison (shown in Table 3.1). These criteria correspond to the underlying assumptions of the methodologies and form guidelines to the selection of the adequate methodology in a specific modelling task. Then, considering the problem definitions, purpose, object, properties, characteristics and criteria, an adequate and applicable methodology for the specific problem defined in this thesis will be designated.

The outlined concept described by Lorenz and Jost [63] in Figure 3.1 is extended to account for underlying the detailed purpose and objects in order to precisely describe the criteria to select the suitable methodology in this thesis. Some of the major object and purpose characteristics described in Section 3.3 and 3.4 are summarized in the purpose and object graph, shown in Figure 3.2.

Given the above discussion on the purpose and the objects of the issue addressed, which were described earlier and specified in Figure 3.2, and the criteria selected in Table 3.1, SD meets the characteristics described.

One of the fundamental issues in the selection is also that, until recently, in the reviewed technical literature, to the authors' knowledge, there are no studies that consider the connection and/or control for the interaction between process and operational parameters to analyze the performance of a manufacturing system (**Paper B**).

Considering these characteristics, SD is chosen as a methodology to formulate the structure and interrelationships between parameters for a manufacturing system to analyse the performance of the given phenomena of the complex manufacturing system. The steps for selection of the best alternative out of the available modelling techniques are summarized in Figure 3.3.

Table 3.1: Criteria for selection modelling approach [89, 11, 14, 90, 66, 26, 41, 91, 90, 14, 80, 77, 13, 60, 73, 63, 52, 100].

Criteria	**SD**	**DES**
Relationships Interaction between parameters /variables/entities/factors	High important. Considered the effect of a variable on others, which is the basis that leads to the identification of feedback effects.	The effect among variables are less important, only individual matters. Most interested in setting up the sequential flow of events
Feedback Response to the changes occur in the system	All the aspects (entities or parameters) of the process are captured within a closed system, thus feedback plays a significant role in parameters value through time.	Parameters are processed linearly which is open loop structure, therefore feedback plays less role
Input data source or data availability	Both numerical and qualitative data type, assumption through experience, guess or prediction	Quantitative and exact data is important (required) that is statically approved data
Problem under study/scope of study	Strategic level	Operational or tactical level
Purpose/expected output/point predictability	understanding behaviour of the system, performance evaluation, decision, prediction, optimization, comparison, policy making, strategy development,	Point prediction, decision, optimisation, comparison, performance evaluation
Importance of tracking or analysing individual parameters	Holistic view of the system, not interested in tracking of individual	Mostly focused on the individuals. It is important to analyse/track individuals
Representation of system	Holistic view	Analytic view
Number of parameters	Large number	Small number
Time frame for simulation and analysis	Relatively long (years, months, weeks)	Short (weeks, days or hrs)
Focus of system	Wider focus	Narrow focus
Complexity	general system, abstract system and stress on dynamic complexity	Stress on detail complexity
Validity	SD model is more representative and its model structure is more explicit than DES; output are perceived similarly realistic for both	
System view	It is viewed as a series of stocks and flows	It is viewed as networks of queues and activities

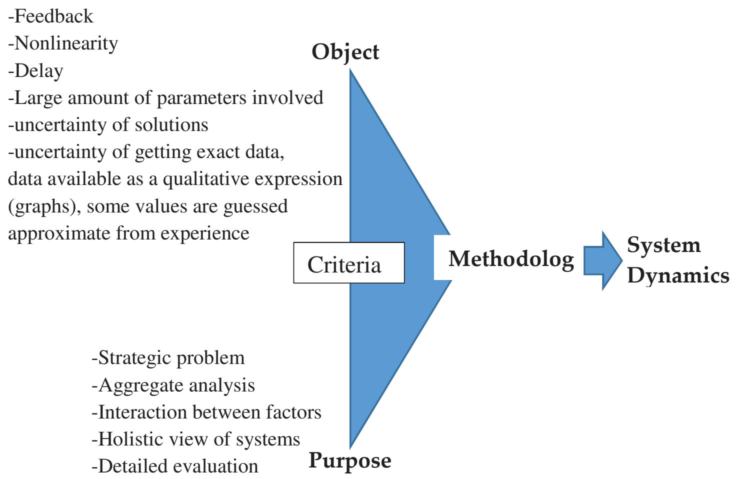


Figure 3.2: Characteristics defined to choose suitable modelling methodology.

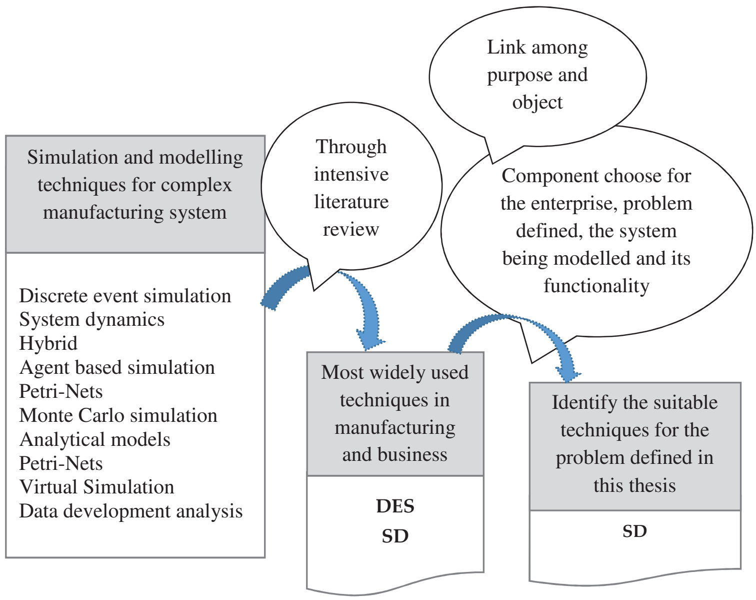


Figure 3.3: Steps for selecting the most suitable methodology for the given circumstances.

3.6 Fundamentals concepts of system dynamics modelling

1. Traditionally, in the process of decision making, the analyst seldom realizes the pervasive existence of feedback loops in controlling everything that changes through time. It is customary to think in a linear way (open loop), as shown in Figure 3.4 [37]. For example, an action is decided for a problem observed and it is expected that this action resolves the problem and believed that this is the end of the issue.

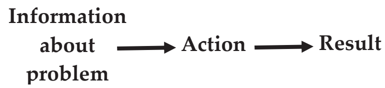


Figure 3.4: Open loop impression of the world.

However, in a realistic perception, everything is connected to everything else and the system reacts to the solution [87]. Today's solution will become tomorrow's problem. That is a problem leading to an action that produces a result that may create further future problems and actions, or indirectly influences the original problem, as is shown in Figure 3.5. The actions made alert the state of the system, which might also trigger side effects. When the nature of the problem alters, the initial action isn't valid anymore, accordingly a new action for each change is proposed. These actions and every change in nature is set within a network of feedback loops.

In analysing the performance of the given system, the analyst should account for the influence of the non-linear and closed loop structure of the given system, time delays that might exist between actions, and other connected and interacted sub-systems, which are usually ignored. If not, the result may turn out completely different from what was anticipated.

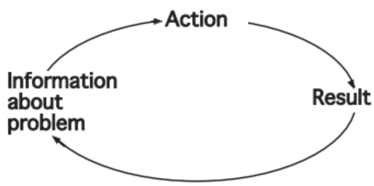


Figure 3.5: Closed loop structure.

2. Positive and negative feedback loops

Change takes many forms, and the variety of dynamics around us is surprising. The dynamic complexity of the system arises not from the amount of the system's components, but from the intricate combinations of interactions among system elements over time. That is, a change of one factor affects others, and feedbacks to each other, this shows how dynamic complexity behaves in the system. This is caused due to the system's internal feedback mechanism, which can be either negative (also called balancing) or positive (also known as self-reinforcing) loops [87].

The most fundamental modes of behaviour of a system over time are exponential growth, goal seeking, and oscillation [87]. A negative feedback loop shows goal seeking behaviour; a negative feedback with time delays in the loop displays oscillation behaviour. A positive feedback shows exponential growth behaviour. S-shaped behaviour (growth) arises from nonlinear interactions of a combination of fundamental positive and negative feedback loops structures. A system consists of many subsystems of different behaviours with short and/or long time delays. The decision process in this case is significantly influenced by the nature of the aforementioned feedback system. Essentially, it is not only to create models and observe the behaviour of the system overtime but also to find ways to create system behaviours that are more desirable.

If the behaviour of the result deviates from what was expected at the beginning (for example if a system behaves goal seeking while it was expected to be exponential growth), the model can assist in finding the critical variables that dominate the behaviour of the system and control the behaviour by manipulating these variables.

3. Causal loop diagram, stock and flow diagram

To model the given problem using system dynamics, the mental model (causal relationships) of the problem is first represented. The causal loop diagram (CLD) is a mental model that captures relationships between parameters and how information from an event is feed back into the system to alter the causes that created the event. The different modes of system's internal feedback loops and the connection points with active feedback loops, that could affect the defined problem, can be identified from the CLD (an example is shown in Figure 3.6).

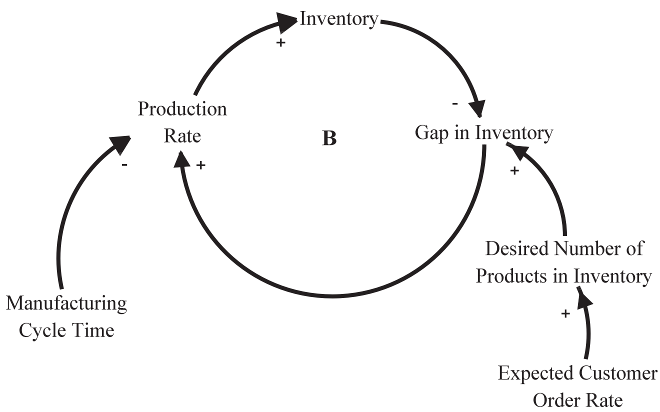


Figure 3.6: Example of causal loop diagram representing a problem for inventory management.

Considering the interaction and feedback among different parameters of the model elements, the CLD is mathematically expressed, which is then converted to computer simulation for further analysis. The building blocks of a SD model are represented in four elements [87]. Table 3.2 presents the available building blocks with their definition and their distinct characteristics [38]. The building blocks are represented in a stock and flow diagram with the general structure shown in Figure 3.7(a). As an example, the CLD of the inventory management shown above in Figure 3.6 is also formulated into a stock and flow diagram as illustrated in Figure 3.7(b).

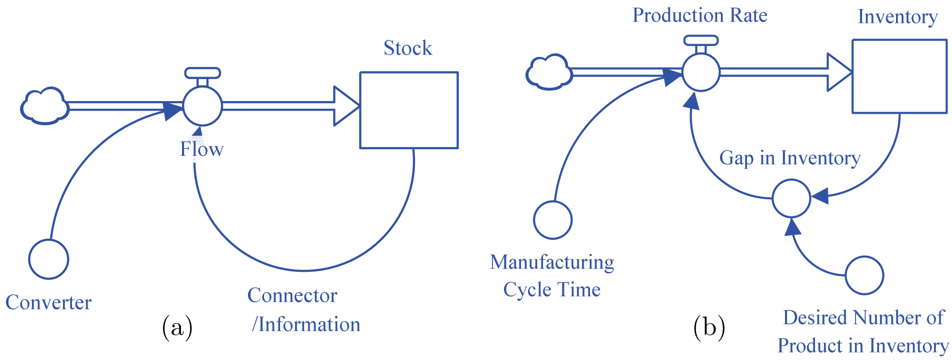


Figure 3.7: a) Elements of SD building blocks; (b) Stock and flow diagram representation of inventory management of manufacturing system.

Table 3.2: Building blocks /elements of system dynamics.

Building blocks	**Definition of terms**
Stock	Something that accumulates. It is expressed by an integral equation
Flow	Activity that changes magnitude of stock by adding to it (inflow) or subtracting from it (outflow). It is expressed by differential equation
Converter	Stores equation of its own or constant; does not accumulate
Connector	Transmit inputs and information

The complex SD modelling of the given processes follows the approach illustrated in Figure 3.8. The process can be categorized into three phases: preliminary, specified and comprehensive analysis.

In general, the complex modelling process starts with a problem definition. This is followed by defining the purpose and time frame in which the behaviour of the system will be investigated. Then the system model boundaries are specified and after that the CLD, which might constitute many feedback causal loops interacting with each other, is developed. The CLD is mathematically represented and is then converted to computer simulation for further analysis. This simulation model is formulated by converting the CLD to stock and flow diagram. Equations are specified to analyse the simulation result quantitatively. Then the model is tested and simulated and the simulation results from different scenarios are evaluated and compared. Lastly a relevant conclusion and new policies (strategies) that can improve the existing system are suggested and evaluated.

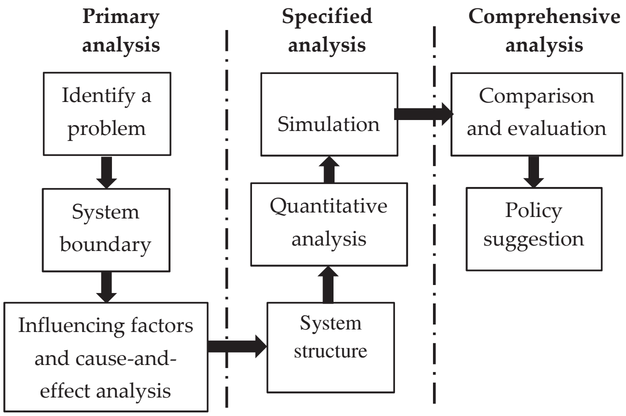


Figure 3.8: Flow chart of system dynamics modelling, adapted from [53].

The research in this thesis aims to model the process of engine block manufacturing. The models consider various combinations of manufacturing system parameters and their interactions to investigate the system's performance, understand demand fluctuations (disturbances), compare the different configurations of manufacturing systems, and identify potential ways that can improve the process of manufacturing systems. In practice, usually it is considered and assumed constant production with no external variations, constant demand (no high variation), same type of workpiece material in different batches, and same design specification. However, the dynamic nature of the system over time, which is ignored, should be accounted for.

A general view of a system dynamic model describing the interaction between process and operational parameters is shown in Figure 3.9. Each module constitutes specific conditions of the system and connecting all of them together into a unitary model. In detail, the assumption, delimitation and components of the model will be describing in the following Chapter 4, under Section 4.3.2.

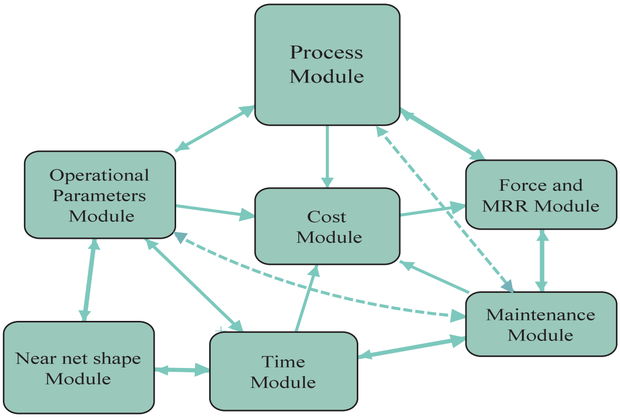


Figure 3.9: Structure of SD module representing the relationships between manufacturing system parameters.

Summarizing, in this chapter different simulation techniques have been described. The characteristics and applications of the two most widely used approaches - SD and DES - are compared, and a suitable tool is selected in order to analyse the given phenomena under study. The essential simulation criteria are identified to understand each method. Finally, the basic principles of system dynamics and the mechanism of developing evaluation methods based on a system dynamics approach are described.

Chapter 4

Results and Discussions

This chapter discusses the results of the significant research contributions posed in Section 1.4 in relation to the appended papers. The analysis of energy use of a primary process, i.e., casting and the performance analysis, and evaluation of the manufacturing systems of a secondary process, i.e., the machining process in the application of SD modelling and simulation of a complex manufacturing process are presented.

4.1 Outline of the major research contributions

A generic model for evaluation of the performance of manufacturing systems was developed as described in **Paper B**. The generic model has been validated for various case studies in production engineering. Generally, component manufacturing consists of a chain of connected processes that convert an input material into a final component or product. Primary processes such as casting, forming or powder metallurgy bring the material into a state close to the final shape [34], whereas secondary processes as machining, grinding and surface processing give a part the final shape within the specified tolerances [42]. They both alter the geometry of the starting work material [102]. Performance of the manufacturing systems depends on how well the resources are balanced between the two types of processes and within each operation.

Figure 4.1 summarizes the major research contribution areas, the processes considered, the used methodology and findings.

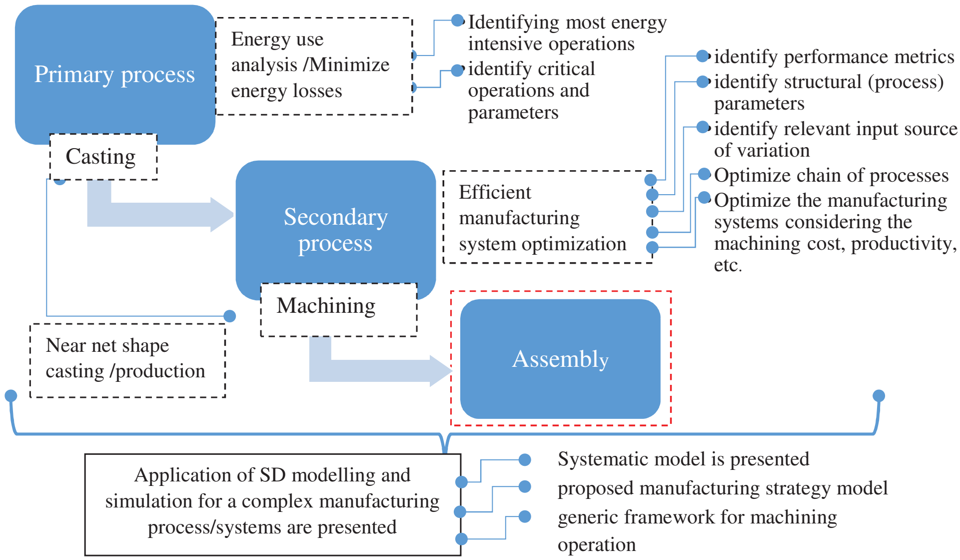


Figure 4.1: Outline of research contributions [1]

4.2 Primary process: Analysis of the energy use casting - Paper A

As a case study of the analysis of primary manufacturing processes, **Paper A** investigates the energy use during casting of engine blocks. The opportunity that might reduce the energy losses during melting and holding were explored and potential energy saving areas were identified.

The growth of the manufacturing industry is increasing the extraction and use of natural resources in order to meet each nation's own energy and material demands. Energy is of such great importance to each society since it is critical for economic development and growth. The vital resources of our planet remain limited, however.

Casting represents an energy intensive process. Minimizing the energy consumption and/or loses during the casting process, in order to stay competitive and to sustain the natural carrying capacity of the ecosystem, is one of the great concerns of a manufacturing company. In the research conducted not all of the steps in the casting process were accounted, instead the main energy intensive operations in the process were considered. For these operations, parameters that characterize the nature of the process were identified; the operations and the methodology followed are illustrated in Figure 4.2.

Accounting energy consumption, energy waste, and possible areas where energy can be saved, is necessary for efficient process management. The energy efficiency of any foundry largely drives on the performance of the melting process. The findings from investigation described that melting, holding and pouring were the prominent energy intensive operations, described in Figure 4.2. Amongst these, melting and pouring accounts for about 70% of the total energy consumption, and the melting process accounts for about 55% of the energy. The main parameters that characterize and influence the energy consumption of melting, holding and pouring have been identified in **Paper A**.

The energy losses during a melting operation are losses generated through radiation, convection, and conduction e.g., through opening of furnace, through furnace skin/wall/surface and other unaccounted losses, and during holding operation due to delay(holding time). These losses can be potentially controlled by minimizing holding time and keeping the molten metal from contact with air (by, for example, keeping the lid of the furnace area of opening to a minimum possible, and minimizing the opening time of the furnace lid). Holding time (delay) has the highest impact on energy consumption, almost 1/3 of the energy losses in the melting process are caused by delay. For example, with the results presented in the paper, it was possible to save about 1,321,200 KJ of energy when the delay was reduced by 10 minutes (current average delay is about 40 minutes).

From the total melt, almost 60% by volume of a cast accounts for the engine block, the other 40% is placed in the structure of the mould (gates, runners, risers, etc.). Thus, there are a huge amount of material and energy losses. Knocking out heated structural material and using it as an input in the casting process was one of the opportunities to minimize these energy loses. The material lost as structural material is recycled as an input in the casting process. Usually knocking out (fettling) of moulds is conducted at almost ambient temperature, however, if there is a mechanism to do the fettling operation at higher temperature, huge amount of energy can be saved. In the case study conducted, the simulation result shows that with the current capacity of the melting process each 10°C of recovered heat can save up to 460,800 KJ energy.

The result from simulation aids to detect possible areas in the system that has the potential to reduce/eliminate energy losses (consumption). Parameters that have the highest impact on energy consumption have been identified. Among them, holding time (delay), area of opening, time of opening and scrap temperature account for the highest energy consumption.

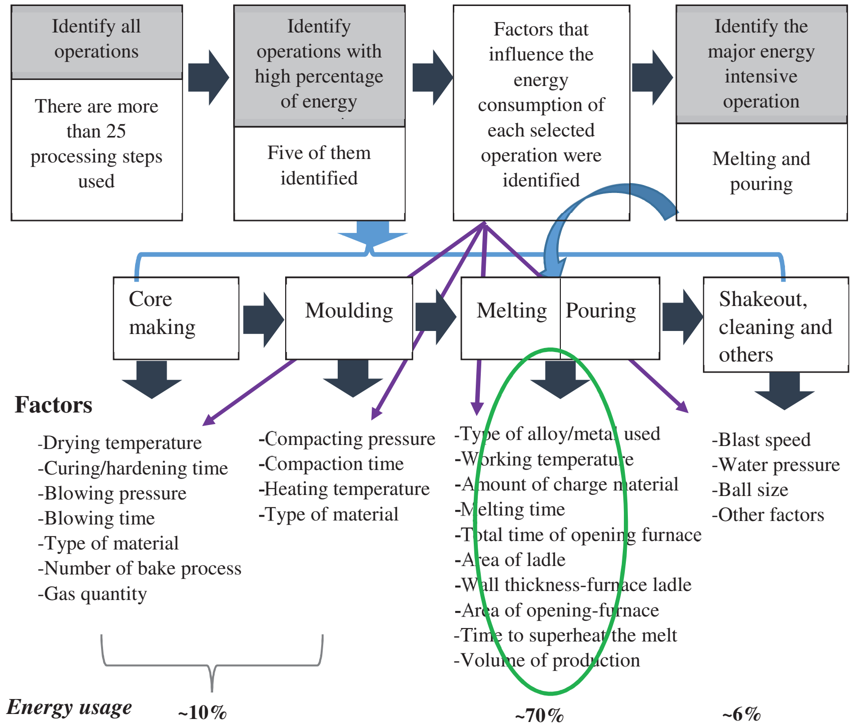


Figure 4.2: Steps to identifying the main energy intensive stations in engine block casting.

4.3 Manufacturing system performance evaluation: secondary process

In today's volatile business environment, manufacturing industries face a multitude of challenges to meet ever-increasing customer desires and demands to provide new and more customized products at the most cost-effective price. The big concern for the manufacturing industry is to be competitive in the market (in economic, technical and environmental terms). In a competitive manufacturing environment, companies are steadily looking for ways to evaluate, improve and update the performance of the manufacturing system for better control of the performance.

An investment in a new manufacturing system as well as modification of an existing system requires sound decisions. These modifications might be related to either product variety or improvement of the product. Moreover, in a competitive environment, one of the key decisions a manufacturing company has to make is selecting appropriate manufacturing systems from the available alternatives. Improper selection can negatively affect the cost, productivity, quality, and capability (capacity) and may cause decrease in profitability and quality of the company.

Selecting a manufacturing system is a difficult decision process that requires advanced engineering knowledge, expertise and experience. Many factors and information are needed to be integrated to make the right decision. Changes in customer demand, workpiece material, part design, and new product introduction may influence the performance of the manufacturing system and consequently the decision to be made. Accordingly, manufacturing companies need to be adaptive to current production changes that are due to new product requirement and market changes. To cope with and respond to these changes, and to stay competitive, an advanced methodology that can analyze the performance of manufacturing systems is required.

This is one of the challenges that is observed in most of the companies that succeeded methodologically to evaluate the performance of the existing manufacturing systems and to invest in new manufacturing systems.

Manufacturing companies are adopting various strategies to measure and enhance performance of their manufacturing systems. One of the limitations of the customary performance measurement systems used today for the evaluation of manufacturing systems is the inability to take into consideration the technological performance measures, which are essential to fully optimizing production systems. This limitation is reflected in the existing simulation models that do not consider the adaptation of the process parameters to the changes in the operational conditions. As a result, the systems perform non-optimally with direct impact on the quality of the produced parts. Implementation of an adequate strategy to respond to the system flexibility requires a better understanding of the relationships between the process input and output parameters on one hand and the system parameters on the other hand with respect to the input disturbances and related to the specific performance measures. In other words to study how the cost, productivity, capacity and quality of the manufacturing systems alter when the system is affected by unexpected variations/disturbances. This is one of the major activities considered in the case studies.

4.3.1 Engine block manufacturing system

The case study was conducted at an automotive manufacturing company producing engine blocks. The company manufactures different variants of engine blocks, but the variant object considered here was grey-cast iron, six cylinder holes. Currently the engine block is manufactured in two autonomous manufacturing systems. These are - dedicated manufacturing system (DMS) (i.e., a transfer line) and a flexible manufacturing system (FMS). DMS is designed to machine a specific part at fixed volume over the life of production while FMS is designed for a variety of unforeseen parts in undefined volume. While in FMCs most of the machine tools are flexible (general) purpose machines, DMS involves special (dedicated) machine tools that are unable to accommodate changes at effective cost.

The FMS was installed recently (few years ago) in order to solve the inflexibility of the former technology. Advanced development of the product (for e.g., new features), workpiece material changes and development of product design (design changes) require the existing system either to be responsive and flexible or reconfigurable. The FMS is not as efficient as it was thought from the beginning; it might be flexible at adapting to the unexpected changes but is not efficient for mass production. Accordingly, there is a need to install a new manufacturing system and to know/cognize which type of system is more appropriate for satisfying a given set of requirements.

A manufacturing system is a chain of interconnected production machine tools where the performance of the whole system is determined by the performance of each individual unit in its interaction with the other units in the chain, as illustrated in Figure 2.1. The machine tools in each system have to be evaluated and compared for any specific features they are producing. Notably, the entire process of an engine block requires a number of different machining operations while the workpiece passes through around twenty stations in each manufacturing system. Each machine tool at a station creates different features by performing particular operations. Some of the major operations are face milling of the lateral side of the engine block, face milling of the rear, front and top side of the engine, boring of cam and crank shaft, boring of cylinder hole, reaming of dowels and transmission hole, etc.

Indeed, evaluating every station in the modelling environment is complex, time consuming and infeasible process. Consequently, selecting the significant stations and processes/operations is desirable. The steps for selecting the stations and operations are briefly described and shown in Figure 4.3. For example, the quality control (inspection and testing), conveyor system, cooling system, material handling (gantry and robot), heat treatment as well as others are the same and have the same processes performed in both manufacturing systems.

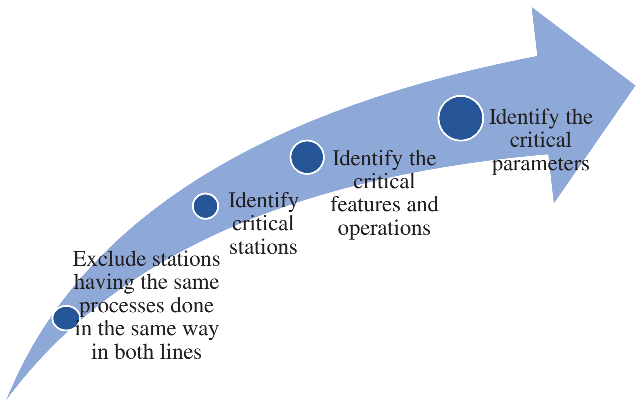


Figure 4.3: Steps for selecting significant stations and operations.

Development of a generic method and a framework that can be adapted for any similar components manufacturing system, processes, and various market situations is considered here.

As a matter of fact, **Paper B** develops a generic SD model for the performance evaluation of manufacturing systems. The model could be modified and simplified in conformity with the process specification and particularities of the manufacturing system. Essentially, it could be used for decision processes.

Considering the generic model as a framework, three case studies are investigated. For each case study at least two performance analysis tools for the manufacturing systems are developed. The model was designed to contribute to the understanding and evaluation of the cost and productivity of the manufacturing systems, while used as a decision tool for selecting an appropriate system. The model includes critical variables and parameters of the machining process and manufacturing system as well as the performance metrics. A modular technique is followed in order to make the modelling approach operational, i.e., creating modules for the specific conditions of the system and connecting all of them together into a unitary model. The model consists of a feedback loop structure of the operational parameters, process parameters, force/power & MRR, near net shape and maintenance modules (sub-models). It also encompasses the manufacturing metrics - the cost structure to capture the cost per part of manufacturing. These loops are at different levels and various timescales. The step-by-step process of the entire development methodology is described in Figure 4.4.

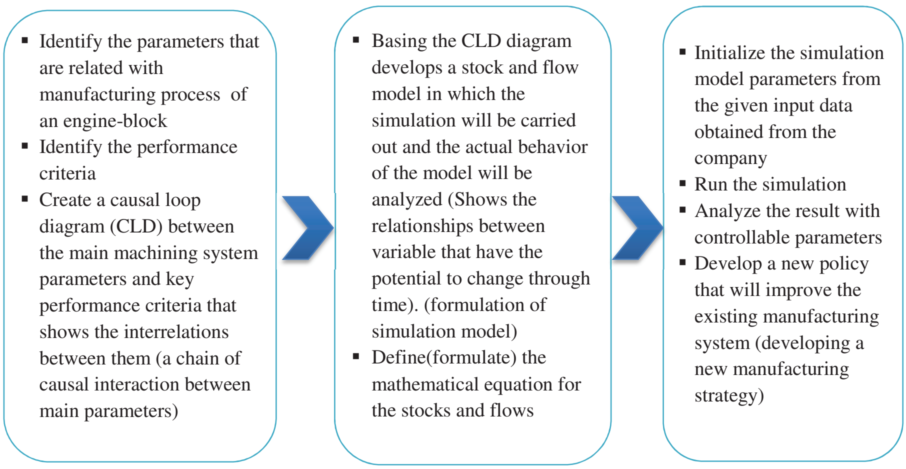


Figure 4.4: Step by step for the entire modelling approach.

As already mentioned, the purpose of the model developed is to investigate and analyze the performance of the individual production stations and the whole manufacturing systems. For each case study, an independent SD model of the existing system was developed and a policy that optimized the current manufacturing conditions was also proposed. Here, the aim is to compare the manufacturing system configurations and to select the appropriate system that can meet current and future requirements, both external (e.g., market demand variations) and internal (e.g., workpiece material or/and design changes).

4.3.2 Conceptual framework for manufacturing system

The generic model concept is studied in **Paper B** and the structure of the model is described in Figure 4.5. The modules (sub-models) are connected to each other and the cost calculation module evaluates the aggregate cost based on the output cost from each module. The structure of the operational parameters relationships module does not change regardless of machine tool, operations, or manufacturing systems configuration type. The maintenance process is modelled using either the maintenance module or the MTTR & MTBF module or both of them, in which case this signifies a broader representation of the maintenance process. The maintenance module constitutes the main maintenance activities on the machine tool components. The machine tool components might not be the same for different machine tools. Hence, this module should be refined to adapt to the specific requirements. The structures of the remaining modules is also determined by the machine tool type, in particular, and by the manufacturing system's characteristics in general. The operational module is triggered by internal or external variations which are defining the dynamic nature of a manufacturing system. This dynamic behavior is created in the interrelation between the systems with market. Thus, the manufacturing system represents not only a technological function but particularly a business one. Meanwhile, the individual processes are triggered by internal variations (workpiece material, design modification) and/or external variations (market demand variations).

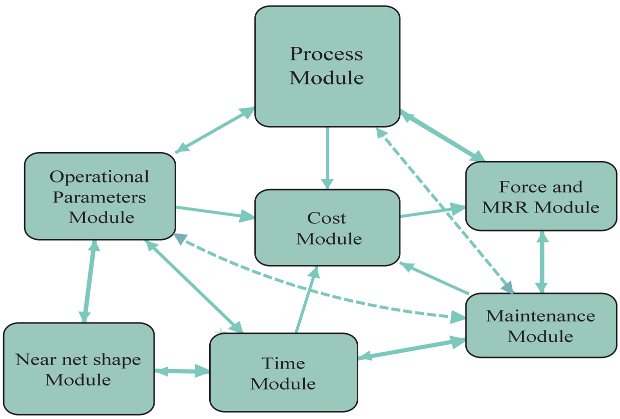


Figure 4.5: Structure of generic model.

4.3.3 Generic model's components

The major components of the generic framework, as described in Figure 4.5, include:

1. The machining process module:
   - the parameters related to different processes/operations.
   - the relationships between processing time, cycle time, takt time, feed rate.
   - the relationships between feed rate, spindle speed, cutting speed.
   - the relationships between cutting speed and tool life.

2 The operational module:
   - the relationships between order rate, backlog and desired production. This function takes into consideration market demand fluctuations.
   - the relationships between capacity, uptime (available time), production rate and desired production.

3 The maintenance module:
   - the life of the different machine tool components in which maintenance activity is conducted.
   - the relationships between the machine tool components wear rate, repair or replacement rate, time to wear, time to repair or replace, downtime for corrective maintenance of the components.
   - the relationships between corrective maintenance, downtime for preventive maintenance(of machine tool components) and downtime for cutting tool changing.

   The MTTR and MTBF:
   - the relationships between total production time, uptime, downtime, overall equipment efficiency.
   - the relationships between process reliability, meantime to repair (MTTR) value, meantime between failure (MTBF) value, time to repair between failure, total production time, number of stops and down time.

4 The force and MRR module which:
   - the relationships of the dynamic process cutting force, material removal rate, cutting speed, dimension of the cut part, feed rate, deformation and static stiffness.

5 Time module is the total production time and takt time adjustment module:

- the relationship between takt time and total production time adjustment; this aims to achieve the desired production capacity and to work according to the desired production time.
  This module is applicable during new strategy/ policy development where there is an adjustment of total production time and flexible total takt time.

6 The cost module:

- Investment cost/capital cost – machine tool cost
- Cutting tool cost
- Maintenance cost - cost for corrective maintenance, cost for preventive maintenance, manpower cost for maintenance activity
- Spare part cost - replacement worn out components, operators overtime cost
- Overtime cost
- Real estate cost - factory adaption cost and the floor area used by the specific machine tool

4.3.4 Assumptions and delimitations

At the initial stage of developing the manufacturing system structure, it is not trivially to find reliable information about system parameters and therefore it is necessary to set an assumption or estimation. The following assumptions were considered for the generic model's structure.

- Machining time is the effective cutting time only. Cycle time is dependent on cutting, loading/unloading, setup, idle (free for other activities) times for all sequence of operations (roughing, finishing) and number of machine tools. cycle time is therefore the sum of all these times divide by the number of machine tools composing the system. All these times are independent variables which have relatively less significant effect than machining time, and consequently assumed constant. Machining time is regarded as a dependent variable.

- Unit cost and cutting tool life are dependent variables.

- Maintenance is considered independent in the case of planned/scheduled maintenance and dependent in the case of unexpected failure.

- Depending on the market demand, the threshold of some independent variables may differ (the takt time and total production time). However, a maximum threshold is set to avoid going beyond the limit of the system condition (capacity).

- The model can be adapted for different types of machine tools and manufacturing system configurations. The only difference is the calculation of machining time, cycle time, takt time, and total production time, which are dependent on the type of operation, on the design layout of the manufacturing systems (DMS or FMS) and on the input variations (market demand, workpiece material).
- The model is developed based on the independent input variables and dependent output variables.
- The structure of the machining process module that represents relationships of the process parameters can be varied depending on the machine tool types, the operation types, and the layout of manufacturing system.
- The generic model and the other models are developed based on the case studies conducted. Therefore, the operational and process parameters are selected either by directly measuring them during production, or by using historical data, engineering knowledge, expertise and operator's own experience.
- The main machine tool components that have the highest probability to wear include: spindle (with gearbox, ball bearings), ball screw, guideways, and automatic tool changer. Note that automatic tool changer is a component only for general purpose machine tools.
- The performance metrics (measures) considered are cost, productivity, quality and capacity.
- The performance measures for availability and reliability, are not considered separately as performance measures of the machine or system, they are rather included in the maintenance structure (MTTR and MTBF), which is described in **Paper B**.
- Quality which is defined by the surface finish and tolerances, is considered as a constraint in the process model. This is due to two reasons, (i) unavailability of data and (ii) the model output depends on the accuracy of the data provided. The process parameters value is set within the design specification limit in order to produce the required surface finish (quality of parts).
- There are no constraints of input resources, labor force, economy, etc.

4.3.5 Design considerations

The system is designed to fulfill both technological and operational requirements. The quality of the produced part is dependent on the machining system's capability. The adjustment on the machining system setups is constrained by the design specification. Therefore, the quality of the parts (surface finish, tolerance) is dependent on the machining system's capability. Optimization of process parameters and the adjustment of machining system setups are in turn determined by the quality requirements (as shown in Figure 4.6).

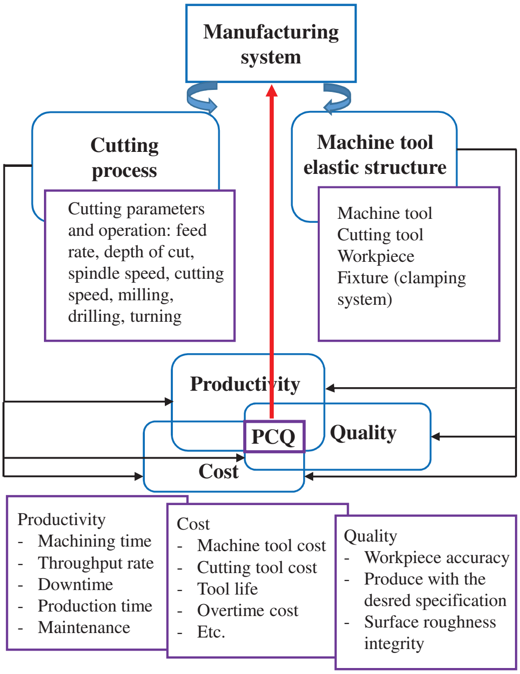


Figure 4.6: Conceptual map for generic model (restructure the graphs).

4.3.6 Manufacturing system performance evaluation procedure

The manufacturing system performance evaluation and selection procedure is presented as follows:

1. Developing a SD model for manufacturing system performance evaluation considering external and/or internal variations such as demand variation, workpiece material, design changes etc. The model is structured based on product properties, machine tool characteristics (types), operation type (part machined), and manufacturing system's characteristics.

2. Identifying/understanding the different source of variation: demand, workpiece material, design specification change, introduction of new features to be machined. These modify the manufacturing system working conditions.

3. Identifying dependent and independent variables and performance measures.

4. Providing the state input values for the parameters, run the model according to the procedure presented in **Paper B**. For different values of the independent input variables, evaluate how robust the performance (output) is. The control of the variable values, as already mentioned above, should be set within the design specification limit.

5. Evaluating the result and making the final decision: the result can be investigated and discussed for further improvement. A new policy for the current working conditions can be proposed. This can facilitate the evaluation and selection process of different machine tool and manufacturing system configuration types.

4.4 Application of the generic model in the case study

Figure 4.7 provides an overview of the structure of the case study conducted.

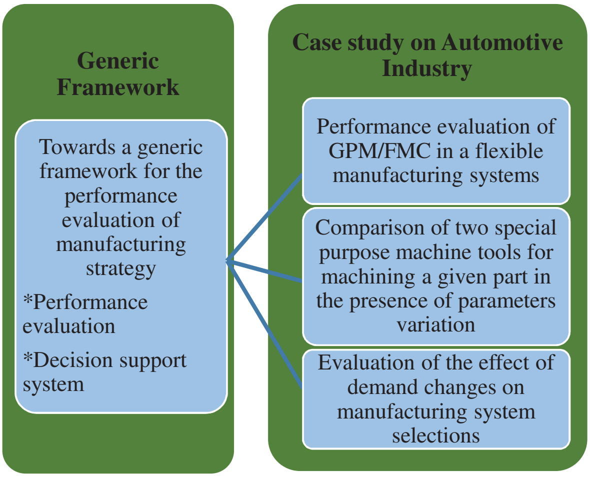


Figure 4.7: Structure of the case study conducted. GMP - General purposemachune. FMC - Flexible machine.

The following sections summarizes the case study studied in each paper.

4.4.1 Performance evaluation of a FMC in a flexible manufacturing system: Paper C

The performance of a general purpose machine tool in a flexible manufacturing system in the presence of market demand fluctuations is investigated and evaluated (**Paper C**). As a primary datum, the first station in the production line was chosen for investigation. The operation performed in the machine is the face milling of the longer sides of an engine block. A SD model (for a flexible machine tool that comprises the interrelationships of process and operational parameters for a given face milling operation) for the existing manufacturing system was developed. A model for a new strategy or policy that improves the existing working conditions (considering the available resources) was proposed. The performance cost, productivity and capacity were evaluated.

The current manufacturing system was planned to achieve a given takt time regardless of level of variation. However, in the new manufacturing strategy or policy proposed, if there is a variation in the system, then there is the possibility to adjust the takt time (by controlling the feed rate and cutting speed, see the control strategy and process control described in Section 2.4 and 2.5). For example, a decrease in the volume of the demand increases the cost per part (unit cost) of production in the current system. Therefore, a new strategy was developed to improve or overcome such a situation.

The simulations in both cases (the current and the proposed conditions) were run with variations in demand (higher and lower). The simulation was run for 180 months, considering the capitalized life span of the manufacturing system which was estimated to be 15 years. In both conditions, the range of product demand requested was fulfilled.

Current manufacturing conditions: When the requested product volume was high or was increasing, the unit cost was lower than when a decreasing demand volume was assumed. That is, a high demand resulted in a high unit profit. The machining time for an increase or decrease in demand volume was almost the same; consequently, the unit cost (production cost, maintenance and overhead costs) was the same.

New proposed policy (strategy): in this scenario the requested demand volume was fulfilled. When the requested demand was lower, there was a strategy proposed to slow down the production by delaying takt time. The takt time is delayed by controlling the feed rate and cutting speed with in the capability of the system. Accordingly, the independent feed rate and cutting speed were correspondingly reduced. These variations, feed rate and cutting speed are shown in Figure 4.8.

The new proposed policy had an advantage of decreasing the unit cost per part. For example, for a decreasing demand, the cutting time (takt time) was high, and accordingly maintenance, tool, and spare parts costs were decreased. This resulted in a decrease of cost per part. The policy developed was useful to improve cost performance by adjusting the takt time and process conditions without decreasing productivity. From the proposed policy scenario, there was a maximum improvement in cost of 6.27% per machined part for higher and lower demand variations, respectively (see Figure 4.8). The peaks on the graph show a sudden increase in unit production cost. These are produced by the maintenance (e.g., component replacement) conducted throughout the lifespan of the flexible machine tool in the flexible manufacturing system.

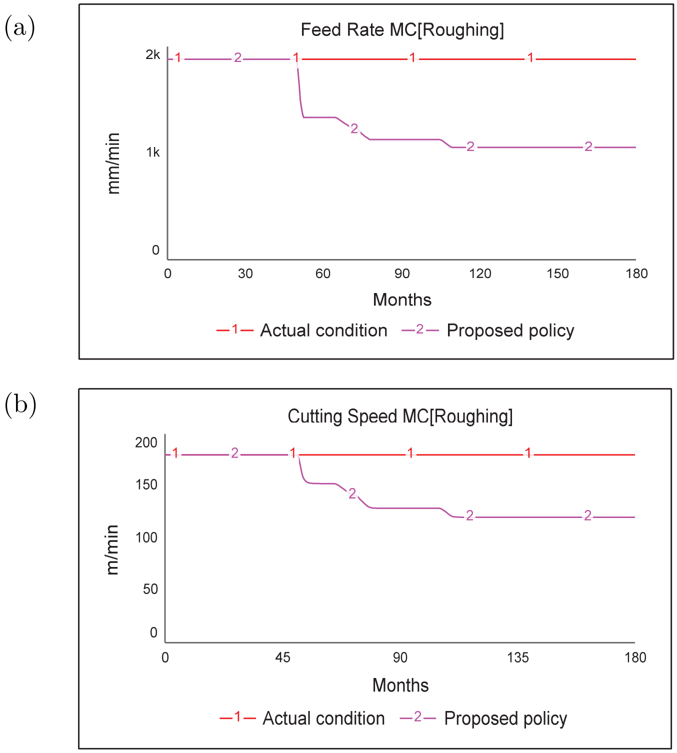
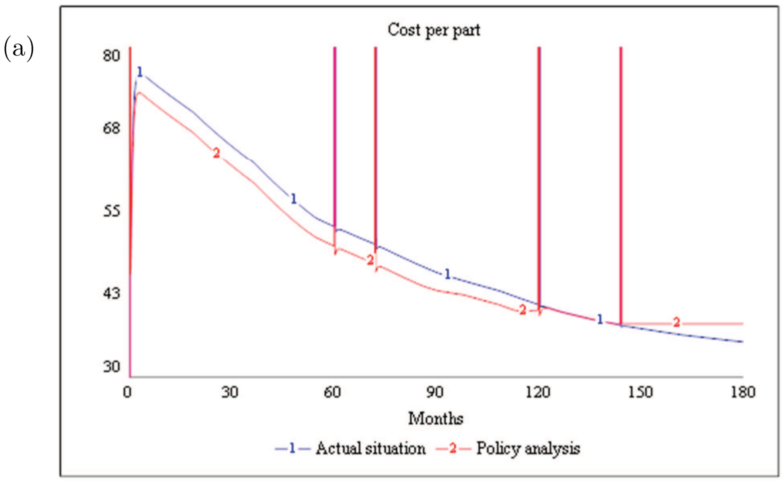


Figure 4.8: A decrease in demand comparison (a) Feed rate (b) Cutting speed.



(b)

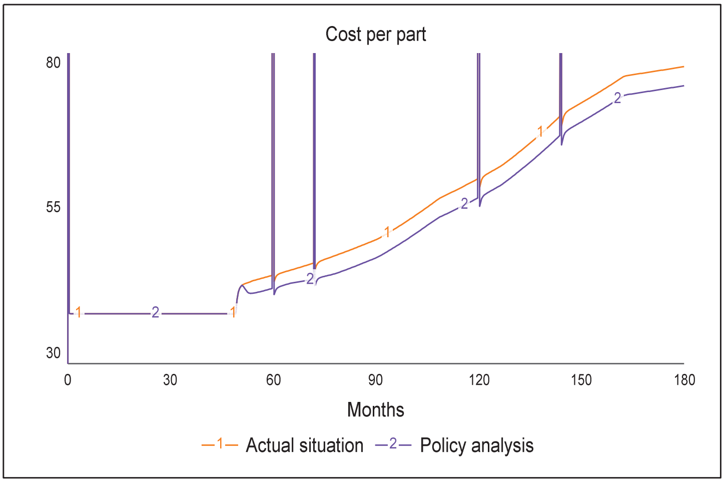


Figure 4.9: Cost per part comparison for actual condition and policy proposed:a) Increasing demand, b) Decreasing demand.

Conclusion: A model was developed, a range of different demand variations was analyzed on the performance of the GPM in a flexible manufacturing system. A model for a new strategy was proposed that could improve the existing manufacturing condition, with a comprehensive understanding of, and consideration for, the interrelationships of process and operational parameters. In general, the methodology could help the analysist to investigate the performance of machines and to make a decision at the investment stage or to improve the existing production systems. Moreover, the parameters which may influence the performance of manufacturing systems could be investigated.

4.4.2 Evaluating SPM1 vs SPM2 in DMS and FMS respectively: Paper D

Paper D presented a new concept for evaluating the performance of special purpose machines (SPMs) and comparing with other, alternative system. The SPM that was applicable for machining a given part's features within a given manufacturing system's specifications, and for achieving the higher productivity (capacity) and lower cost was proposed. As already mentioned in Section 4.3.1, the critical (significant) stations chosen, the machine tools and operations considered are shown in **Paper D** [Table 3 and Fig. 6]. The SPM1 (station 12) from the DMS and SPM 2 (station 16) from FMS were considered for investigation.

These SPMs perform similar operations but they have different design. They perform boring of cam and crankshafts, reaming of dowels and transmission holes in both manufacturing systems (DMS and FMS). The locations of cam and crankshafts in an engine block are illustrated in Figure 4.10.

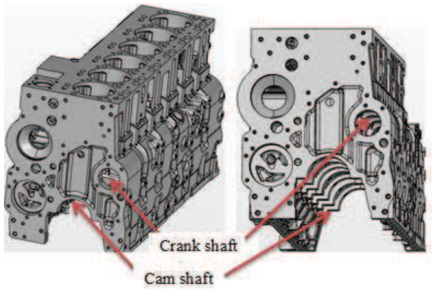


Figure 4.10: Part features - Cam and crankshaft of an engine block in different views.

Two SD models for each SPM were developed by adaptation and simplification of the generic model in order to fit the specific case development - for the current manufacturing condition and for a new proposed policy (strategy). The structure of the models comprehensively incorporates the manufacturing process for boring of cam and crankshaft and reaming of dowels and transmission holes of an engine-block that is produced in the FMS and DMS. There were around twenty part features that were taken into account, which utilized many different cutting tools. The capability, unit cost and productivity performance of each machine tool were evaluated and compared under demand variations.

Results showed that both SPMs have the capability to produce the given part features. If the demand was exceeding 4750 parts/month, the SPMs were unable to fulfill the product volume requested even for the new proposed strategy. This might be due to the maximum design specification value settled for the process parameters, which was required to provide the desired quality specification. Moreover, adjusting the process parameters for the two cutting tools (T801-807 & T901-907) simultaneously was challenging and not valid. Figure 4.11 shows the feed rate for different cutting tools. The unit cost for a special purpose machine in a FMS was larger than the SPM 1 in DMS for both conditions: for higher and lower demands. It was observed that performing the process using SPM1 reduced the unit cost by 12% in comparison with SPM2, as illustrated in Figure 4.12. Accordingly, a change in manufacturing strategy (policy), had insignificant effect on the performance of the machines and manufacturing systems. It was robust for both machine tools to the change of machining strategy.

The methodology proposed allowed for the evaluation and analysis of the performance of machine tools and manufacturing systems. Essentially, this promotes machine tool selection by taking the precise features that are to be manufactured from a life cycle perspective rather than considering the properties at the time of purchase.

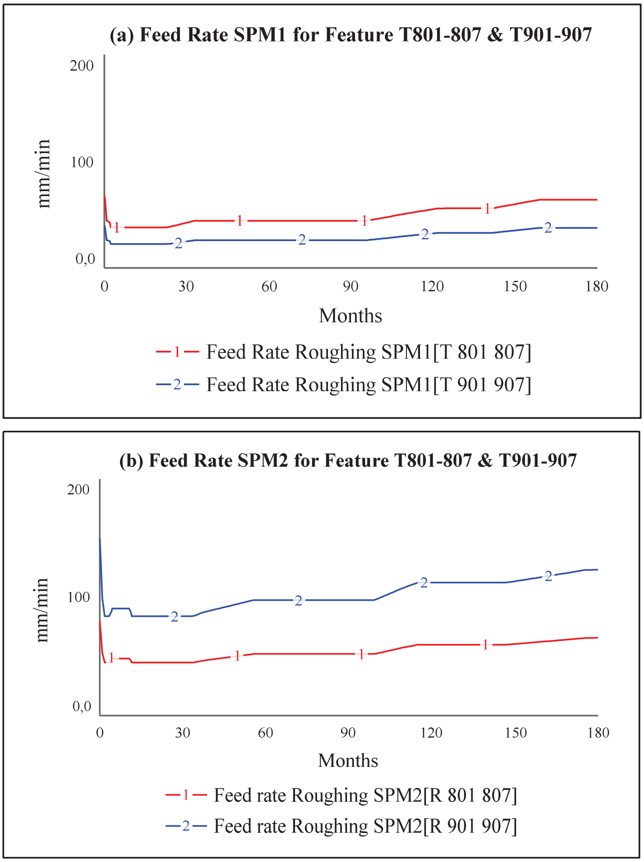


Figure 4.11: Feed rate for SPM1 and SPM2 for given part feature.

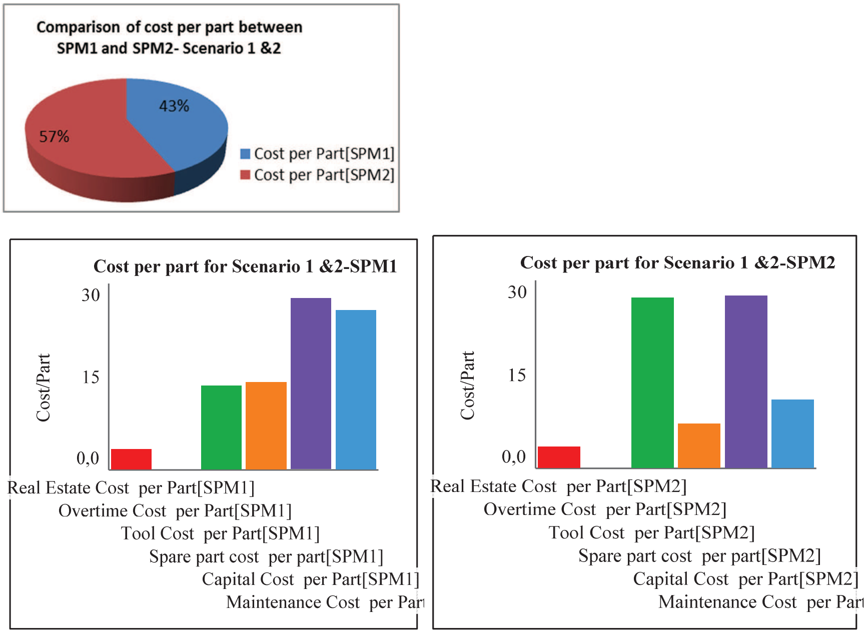


Figure 4.12: Unit cost analysis SPM1 vs SPM2 and cost components for larger demand.

A demo is presented that can analyze the possible changes and control strategies in the system [6]. It is a step-by-step approach followed for the investigation, designed for analysis, comparison, selection, and control of process parameters.

4.4.3 Manufacturing systems DMS & FMS: comparison: Paper E

By adapting, editing and re-using blocks of the generic model proposed in **Paper B** to fit to the given case, **Paper E** developed independent computational and modelling tool to evaluate and compare the performance of dedicated and flexible manufacturing systems for machining a given set of features. The face milling of the longer sides of an engine block production was considered. The simulation models took into consideration technological performance measures and considerations like the adaption of the process parameters to the change in the operational conditions, which are essential to fully optimizing manufacturing systems.

A total of four SD models, two for each manufacturing system were developed, for current manufacturing conditions and for the new proposed policy (strategy). Each model was evaluated to higher, lower and cyclic demand fluctuations for analyzing the effect of these variations on cost, productivity and capability of a special purpose machine tool in a dedicated manufacturing system and a general purpose machine tool in a flexible manufacturing system (SPM in DMS and FMC in FMS).

The two scenarios considered were the reference scenario also called current manufacturing conditions, and the policy analysis scenario also called new strategy, respectively. The scenarios and variations considered are shown in Figure 4.13 below. The product demand was varied between 3000-5000 parts/month.

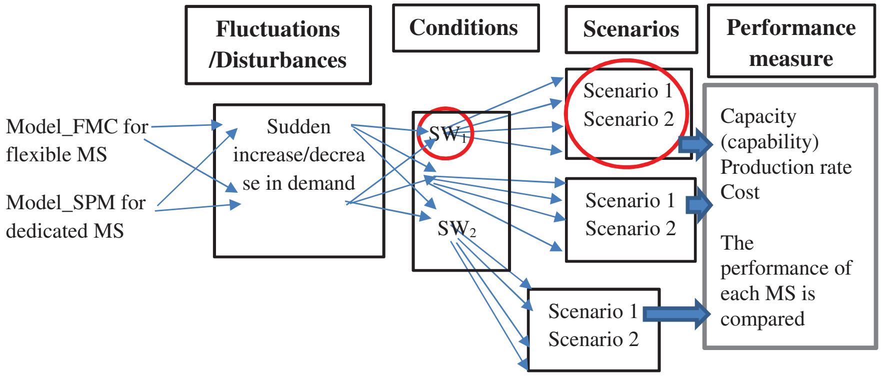


Figure 4.13: Scenarios, conditions, fluctuations, performance, considered in the MS (only the condition and scenarios which are circled considered in this paper).

Scenario 1: Current manufacturing conditions

In this scenario the system responded to the fluctuations in demand through the adjustment of production time (overtime, increase in number of shifts, and so on). If there is rising or dropping in demand the machine tool will operate for a longer time or will be used for a shorter time respectively.

Scenario 2: New manufacturing strategy. Following actions are implemented

- Changing the critical process parameters in accordance with the variation of the requested product either by speeding up or slowing down the process. To speed up or slow down the process, the feed rate, the cutting speed, the spindle speed, and other interconnected parameters were varied to optimize the manufacturing system through through the process control strategy described in Section 2.5 and optimizing process parameters according to the principles described in **Paper E**.
- During a rising in demand there was no overtime cost, as demand increases, the takt time was reduced by increasing the feed rate instead of continuing producing overtime for the FM (GPM) in the FMS

- Slowing down production rate during a drop in demand feed, reduced the feed rate and cutting speed which resulted in cutting tool life optimization. Consequently, the frequency of replacement and the time required to replace worn out tools were reduced, resulting in a reduction in cutting tool cost. The life of the machine tool components was increased, which decreased the frequency of maintaining and changing the worn-out machine tool components, thus indirectly reducing the cost of production for the FM in the FMS. Similarly, adapting the manufacturing strategy to the FMs during a cyclic demand pattern resulted in a potential decrease in unit cost performance, Figure 4.14 and Figure 4.15 show the variation in machining process parameters and the unit cost comparison between scenarios. There has been an approximately 5% and 23% of cost per part to be saved during a decrease and cyclic demand variation, respectively, by adopting a new manufacturing strategy.

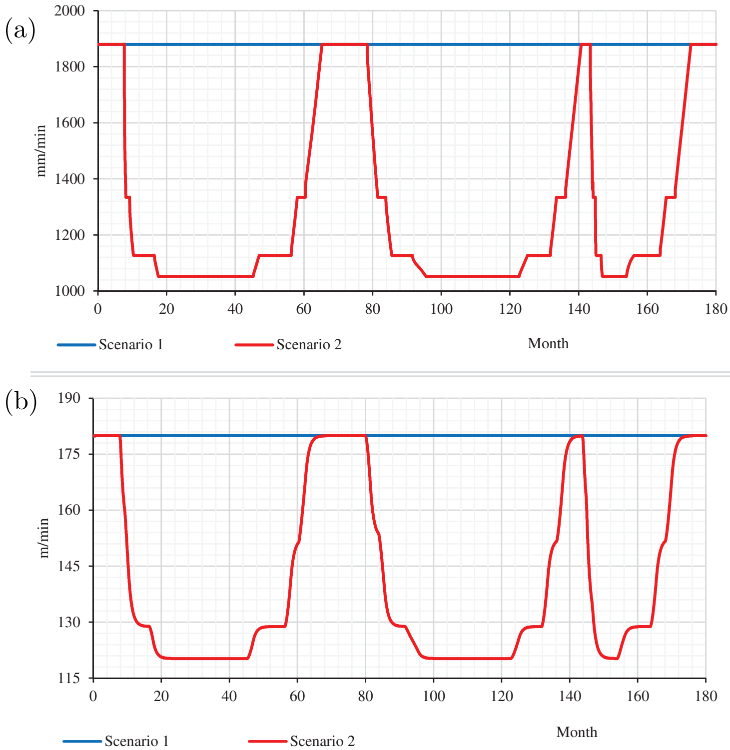


Figure 4.14: The behavior the process parameters change during a cyclic demand fluctuation. a) Feed rate FMS – Scenarios 1 Vs. 2 (b) Cutting speed for FMS – Scenarios 1 Vs. 2

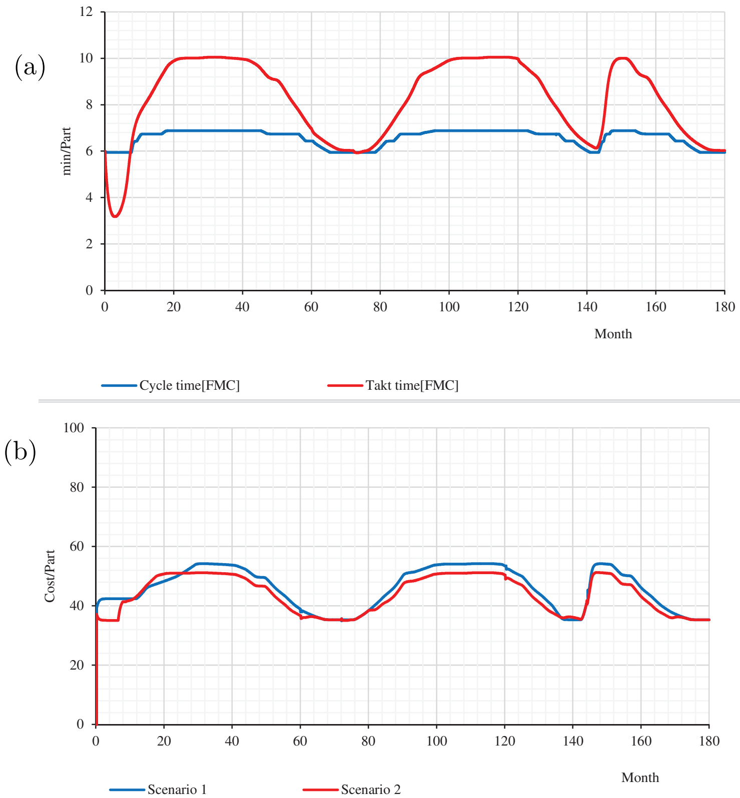
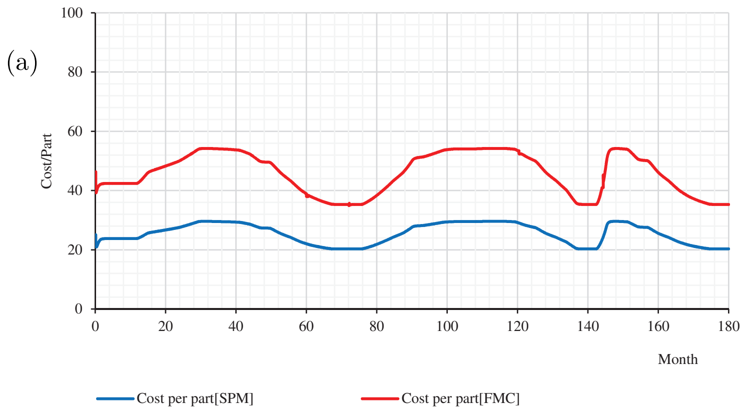


Figure 4.15: a) Cycle time vs. takt time - (Scenario 2), b) Unit cost per part for flexible manufacturing system during cyclic demand.



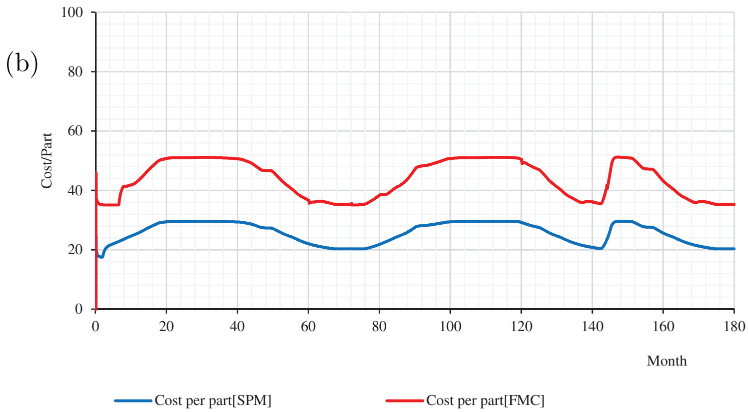


Figure 4.16: Unit cost for DMS and FMS during cyclic demand.(a) Scenario 1 (b) Scenario 2

The unit cost performance for a dedicated manufacturing system was lower than the performance of a flexible manufacturing system during a cyclic demand pattern, as seen in Figure 4.16.

For a higher demand variation, any change in the manufacturing strategies of the dedicated manufacturing system did not make a significant difference in performance as compared to scenario 1 (current manufacturing conditions). The cutting process parameters, feed rate, cutting speed were tuned for optimizing the system, Figure 4.17 shows the fluctuations in cutting process parameters in response to an increase in demand volume. However, it didn't make any significant improvement, rather it worsened the behavior of the general purpose machine tool in the flexible manufacturing system, as shown in Figure 4.18. Even the unit cost is higher for the new strategy than the for current manufacturing condition. Figure 4.19 shows unit cost of FMS.

For both scenarios, to comply with the requested product volume fluctuations, one SPM in a dedicated manufacturing system and two parallel FMC in a flexible manufacturing system were required.

Moreover, during lower demand conditions, both manufacturing systems achieved the productivity performance measure. However, using the FMC of the flexible manufacturing system there was a possibility to improve and optimize the cutting conditions by changing the manufacturing strategy.

For both scenarios and for all conditions of fluctuations, the SPM of the dedicated manufacturing system shows better cost, productive and capacity values than GPM of the FMS. The new strategy had an advantage to oversee possibilities of minimizing capacity utilization of the system during a lower demand and to optimize the unit cost of production. In spite of this, changes in manufacturing strategy were not needed for the dedicated manufacturing system to attain the performance

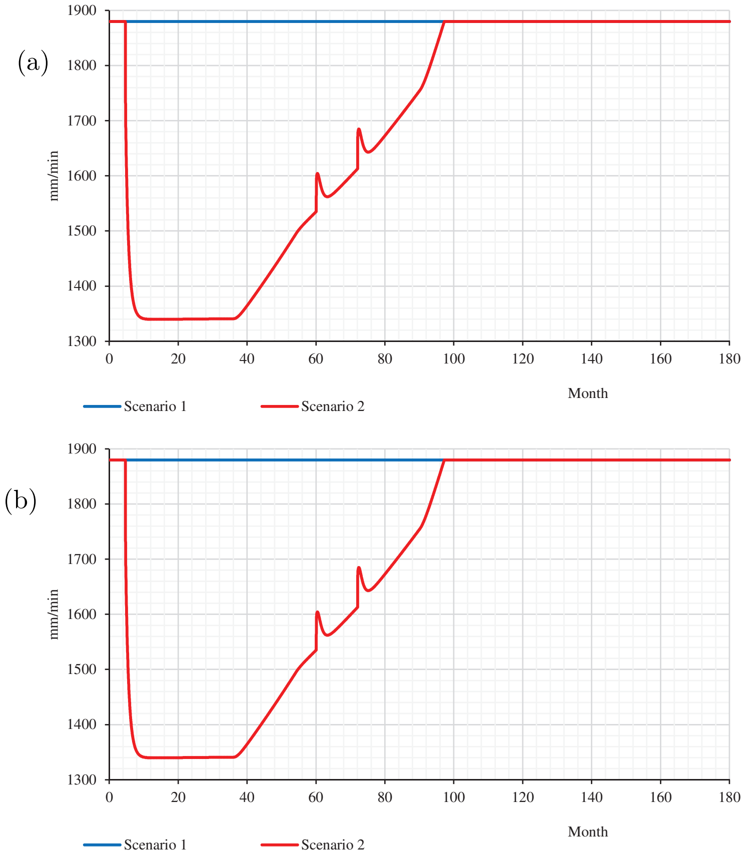
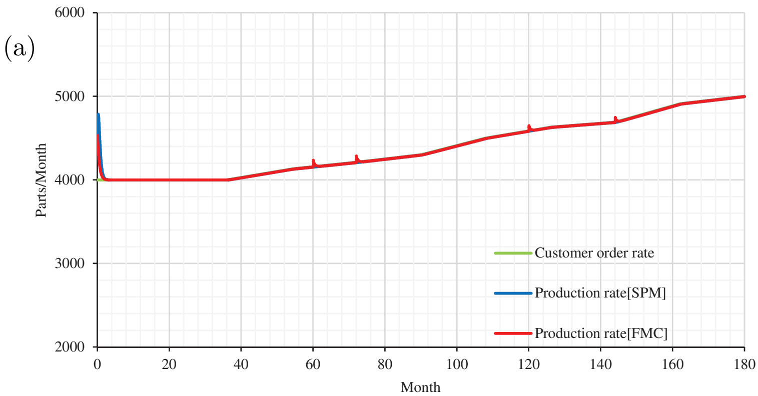


Figure 4.17: The behavior the process parameters change during a higher demand fluctuation. (a) Feed rate FMS –Scenarios 1 Vs. 2 (b) Cutting speed for FMS – Scenarios 1 Vs. 2



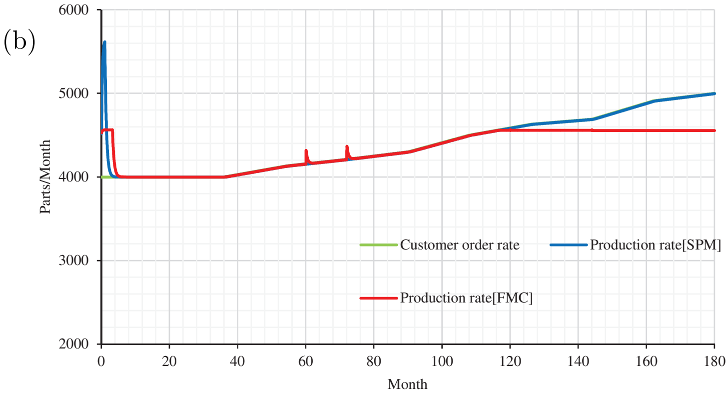


Figure 4.18: The performance analysis of DMS and FMS for an increase in demand variation. (a) Scenario 1 (b) Scenario 2

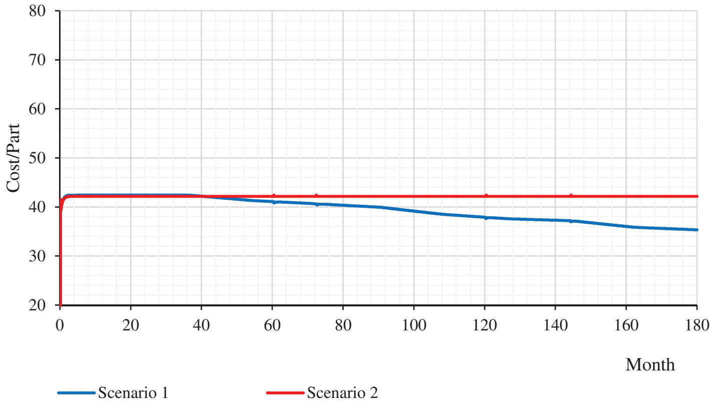


Figure 4.19: Unit cost for FMS during a higher demand.

measures intended.

Conclusion: The main idea behind **Paper E** is to integrate of some more realistic physical models of manufacturing processes within the system simulation models; the effect of the interdependence between process and technological parameters on a manufacturing system's performance is usually neglected. Accordingly, this paper provides researchers as well as practitioners with a quantitative and qualitative analysis structure for optimization and for exploring the performance of the manufacturing systems with consideration to the interaction between process and operational parameters.

In general, the models were intended to contribute systematically to the evaluation of current processes and manufacturing systems, and for designating potential avenues that can optimize the system parameters. Similarly, the model could aid companies in the investment in new manufacturing systems by evaluating the performance of various parameters. It is therefore a viable methodology to assist in performance analysis, optimization and the selection of manufacturing systems that would meet the future requirements of component manufacturing. The model is validated by designing the model, simulating the model and comparing the results with the existing data.

The Table 4.1 summarizes the case study investigated in the secondary process.

Table 4.1: Summary of the case study investigated.

	Paper C	**Paper D**	**Paper E**
Purpose of the model	Analyze economic, productivity and capability performance of the machine tools and manufacturing systems		
Analyze (investigate)	Performance analysis of GPM in a flexible manufacturing system	Performance analysis of two different SPM oriented in dedicated and flexible manufacturing systems. Comparison of these two machine tools in the respective systems	◇Performance analysis of GPM in FMS and SPM in DMS. ◇Comparison of each machine tool with the perspective manufacturing systems. ◇Manufacturing system optimization. ◇Optimize process parameters and hence improve the system behavior
Operations	Face milling of the lateral sides of engine block	Boring of cam & crank shaft, reaming of dowels and transmission holes	Face milling
Machine tool type	General purpose machine	SPM1 and SPM2	GPM and SPM
Manufacturing systems	FMS	FMS and DMS	DMS and FMS
Variations	Higher/lower increase/decrease demands	An increase and decrease in demand	Increase/decrease and cyclic demand variations
Major challenges /constraints	A key challenge is the lack of sufficient and reliable data at the preliminary stage of designing or purchasing a machine tool–system dynamics modelling requires historical data that needs to evaluate and analyses the performance of the given problem to be studied. Due to the unavailability of historical data, the variations due to workpiece materials and design changes are not accounted on the case studies.		
Future possibilities	The methodology allows the model to be modified and to incorporate other aspects that can be accounted. The major advantage is to re-use blocks or parts in other circumstances, which will be considered later in the model.		

4.5 Near-net shape production modelling

Considering a primary process such as casting and a secondary process, e.g., machining process, the idea of a near-net shape production model was also investigated in the generic method developed. The concept was developed to explore possibilities to produce parts with better geometrical and dimensional tolerances and accurate surface roughness by reducing the manufacturing resources. Essentially, it was used to analyze the relationships between successive operations and to balance the resources between the two different classes of processes in the sequence. It contributed to reducing the number of intermediate roughing machining processes, the manufacturing cost, and it could cut more than two thirds of the production cost regardless of the casting process. The modelling concept, mathematical expression and detailed concept are described in the generic model, **Paper B**.

The cost for near net shape manufacturing and machining processes, respectively, should be compared to the conventional casted process. The cost invested in a near-net shape production concept during casting and machining in relation to traditional manufacturing will be a future work. For example, to make it near-net shape during casting, what will be the manufacturing (including equipment) cost, energy consumption, material cost and time? Accordingly, for the cost of machining, the energy consumed, and other related costs are computed. Moreover, the cost for traditional (conventional) manufacturing and machining will be computed. Then, compared on the basis of energy consumption, number of operations, material cost, manufacturing cost, and work in process performance. A methodology will be designed for these computations and comparisons.

Chapter 5

Conclusions and Future work

This chapter presents conclusions, answers the research questions, and addresses industrial implications and future research directions.

5.1 Conclusions

The scientific goal of this thesis is to develop a simulation platform for evaluation and control of the dynamics of manufacturing systems.The thesis explains in the first part, the necessity of developing a methodology to evaluate the performance of manufacturing systems. The concept of dynamics of complex manufacturing system is introduced and several control levels are analysed.

The research contribution addresses the development of a generic framework for modelling the performance of dynamic manufacturing systems and controlling decisions among available alternatives of manufacturing system configurations [RQ 1.2]. The core of the methodology is represented by the complex interaction between process parameters and the system's operational parameters in response to external perturbations (e.g., demand uncertainty) and/or internal disturbances (e.g., workpiece material or design changes). Evaluation and control of complex manufacturing systems is performed on a simulation platform that subsumes the interconnection and the feedback loop structure of the operational parameters, machining process parameters, force/power and MRR, near-net-shape production and maintenance modules [RQ 1.1]. The simulation model also includes the manufacturing metrics-the cost structure for capturing the unit cost of manufacturing.

The generic framework is further adapted for studying specific systems in a component manufacturing company [RQ 1.3]. The framework can be restructured, modified or arranged according to the characteristics of a given manufacturing scenario, provided that the system is designed to fulfil both technological and operational requirements. Using the generic model, three case studies are presented.

The case studies were performed in a company manufacturing engine-blocks for heavy vehicles.

Consequently, to adapt new requirements regarding variety, volume and technological development of the product, a strategy for existing working conditions of the process is developed. The strategy is evaluated under uncertainties regarding demand volume variations. Principally, the strategy is employed by controlling the process and/or system parameters. Usually, the primary process parameters, like the feed rate and cutting speed, and the system parameters, e.g., total production time etc., are controlled within the specification limit value to respond to demand fluctuations to produce the volume of product requested, either by speeding up or slowing down the process [RQ 1.1].

Keep in mind that changing these process parameters not only effects the output of the system but alter the other interconnected parameters too. This has the advantage of possibly reducing the unit cost of production during a drop in demand volume by lowering process parameters to a safe level with regard to the lower demand request. Slowing down production during a lower demand variation reduces process parameters, i.e., the feed rate, cutting speed, spindle speed etc. Thus, the cutting tool life, i.e., the time interval to change the cutting tool (tool change time) increases, reduce frequent interruption of the machining operation for tool change, consequently the production is not affected as often and the machine components are not worn out as easily. In addition, the inventory cost of producing the parts not requested will be eliminated, reducing overhead costs.

A case study for resource use analysis during primary processes has also been investigated and presented. The critical operations and the operations that have the highest energy consumption and the greatest potential for energy savings have been identified.

5.2 Industrial implications

From an industrial application point of view, the presented approach and the methodology developed in the thesis will allow a company to evaluate and control the performance of their manufacturing systems during internal (e.g., workpiece material change) and external (e.g., market volume) demand variations.

Particularly, the methodology can be used by a company as a decision support system for selecting a suitable machining station and/or strategy for manufacturing system configuration during demand fluctuations, in relation to the selected performance measures. This will help users make decisions on future investment and/or extensive improvements of the existing system. In addition, controlling the system and/or process parameters, facilitates the selection of the parameters that optimize the system. Finally, in the primary process, i.e., casting, the method enables companies to systematically evaluate current operational systems and designate potential avenues for minimising energy use in production, hence becoming more sustainable.

Coupling back to the research questions, the results presented in the thesis and the journal papers as detailed in Section 1.6, answer the research questions of this thesis. RQ 1.1 (see Section 1.4) the critical process and operational parameters that characterize the dynamics and performance of manufacturing systems have been identified and briefly discussed in Chapter 2. RQ 1.2 (see Section 1.4) given the complexity and non-linearity of the dynamics of the manufacturing system, the most appropriate type of model (tool) that can effectively analyse the characteristics of dynamic systems was presented in Chapter 3. RQ 1.3 (see Section 1.4) a generic model (framework) was developed and presented in **Paper B**. This is validated through the different case studies and presented in Section 4.3 and 4.4.

5.3 Critical review

Manufacturing companies are adopting various strategies to enhance the performance of manufacturing systems. The methodology and proposed tool in this thesis sum up the process analysis and the performance evaluation of complex manufacturing systems. Therefore, the thesis demonstrates that simulation modelling is the most appropriate and effective tool to investigate the characteristics of dynamic systems without disrupting the actual working conditions; it requires less time and reduces the high cost that the actual system might incur. The simulation model assists the decision-making process by considering the performance measures of the production during uncertainty.

5.4 Future work

Future research direction:

1. It is essential to mention that input variations determined by workpiece material and design were not simulated and validated in the case studies, only the structure and their relationships were presented in the modelling. The main reason was the unavailability of data. In addition, the manufacturing system of a secondary process was not designed to adapt to external and/or internal demand variations. Moreover, the strategies (policies) proposed to improve the existing system were not validated in the actual production line. The generic framework approach presented in the thesis was evaluated for a large automotive manufacturing company producing engine blocks. In order to evaluate and validate the different internal and /or external demand variations, one possibility, it would be to evaluate the approach in a company that has an experience of various market demand fluctuations in their system. For example, to select a company that manufactures a large number of different components, and manufacture a product made by different workpiece material.

2. The generic model framework proposed can be adapted by editing and reusing blocks to fit in the given case. Therefore, one of the future direction could be: to further enhance the understanding on the complex interaction of manufacturing systems, and to consider the static and dynamic stiffness of machining systems. At process level, the performance of manufacturing system was evaluated and controlled by soft control, i.e., by cutting parameters, feed rate and cutting speed. Further evaluation of the dynamics of manufacturing system through hard control considering other functions, i.e., tool geometry, tool material, cutting fluid, fixturing, etc. is of research interest.

3. Since comparison of the manufacturing system configuration started with the analysis of each station, i.e., machine tool, therefore a selection of an appropriate machine tool is essential.

   The performance of general purpose machines (adapted for flexibility) and transfer stations (dedicated for specific operations) were evaluated in a FMS and DMS (transfer line) configuration. It was demonstrated that the transfer line provides low manufacturing costs for the production of a limited range of products in high quantities, but robust to changes. The FMS is economically justified for the medium volume requirements of families of parts, i.e., product varieties.

   However, the current market demand changes and advanced technology development require a system that is both low cost and respond to different market demand fluctuations without the need for large investment. Therefore, one future direction could be, to consider a new type of special SPM in a station. The new SPM is a relatively new class of reconfigurable machine, it is used to adapt quickly to the changes. It is designed to be flexible and dedicated, i.e., which has an advantage of both flexible and dedicated machines. It is designed to customize to machine a range of operations.

   The SPM can be designed based on current and future requirements of a manufacturing system as well as market changes. Their modularity can be reconfigured with minor modifications to the machine configuration that can manufacture various products (volume and variety). These machine tools can be used in the transfer line for mass production and can be adapted to the manufacturing system requirements and demand changes. It is the author's view that this is advantageous, for future investment, to change the dedicated machine in a transfer line to the new type of SPM. It is of an interesting research approach to consider, investigate and evaluate this new SPM in a transfer line to an industrial limitation.

4. The performance of the manufacturing systems depends on how well the resources are balanced between the primary and secondary processes and within each operation. Therefore, one of the future research directions could be further development of near-net-shape production.

The cost of near net shape manufacturing and secondary processes, respectively, should be compared to the conventional primary processes. The cost invested in a near-net shape production concept during primary process and secondary process in relation to traditional manufacturing will make possible future research direction. For example, to make it near-net shape during the primary process, what will be the manufacturing (including equipment) cost, energy consumption, material cost and time? Accordingly, for the cost of a secondary process, the energy consumed, and other related costs are computed. Moreover, the cost of traditional (conventional) manufacturing during primary process and the secondary process will be calculated. Then, they are compared on the basis of energy consumption, a number of operations, material cost, manufacturing cost, and work in process performance. A methodology has to be designed for these computations and comparisons.

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