MASTER THESIS ON

A Decision-Support Methodology to Design Reconfigurable Manufacturing Systems

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List of Abbreviations

AHP	– Analytical Hierarchical Process
CD	– Changing Demand
CL	– Cellular Layout
CNC	– Computer Numerical Control
CCT	– Configuration Change Time
DCF	– Discounted Cash Flows
DML	– Dedicated Manufacturing Line
DMS	– Dedicated Manufacturing Systems
DMT	– Dedicated Machining Tools
DNC	– Direct Numerical Controlled
ENPV	– Extended Net Present Value
FMS	– Flexible Manufacturing Systems
GA	– Genetic Algorithm
IS	– Identification System
LCEAM	– Life Cycle Economic Analysis Model
LSS	– Large-Sized Manufacturing System
M	– Manufacturing Strategies
MA	– Management Infrastructure
MSD	– Manufacturing System Design
MHS	– Material Handling Systems
MC	– Machine Capacity
MF	– Machine Capability
MSS	– Medium-Sized Manufacturing System
MS & W	– Machine Sizes and Weight
MHSS	– Material Handling Storage System
MHE	– Material Handling Equipment
MRS	– Machine Level Reconfiguration
MUC	– Machine Usage Cost
MCC	– Machine Configuration Cost

NAL	– Needed Agility Level
NC	– New Circumstance
NRL	– Needed Reconfiguration Level
NPV	– Net Present Value
PE	– People Infrastructure
PLS	– Plant Layout System
PVF	– Production Volume Flexibility
PD	– Product Development
PL	– Product Layout
PSS & F	– Production System Size and Functionality
PF	– Product Flexibility
PT	– Processing Time
ROA	– Real Option Analysis
RMS	– Reconfigurable Manufacturing Systems
RMT	– Reconfigurable Machining Tool
RIM	– Reconfigurable Inspection Machines
RS	– Reconfiguration Smoothness Value
RM	– Reconfigurable Machine
RC	– Resource Capacity
RU	– Resource Utilisation
RF	– Resource Flexibility
RMSM	– Reconfigurable Manufacturing System Design Model
RWL	– Resource Work Load
SRS	– System Level Reconfiguration
SU	– System Utilisation
SSS	– Small-Sized Manufacturing System
TE	– Technology Infrastructure
TRS	– Market Level Reconfiguration
TUC	– Tool Usage Cost
TCC	– Tool Configuration Cost
TNOP	– Total Number of Operations

TCT – Tool Changeover Time

WIP – Work in Process

Summary

Globalisation is driving today's manufacturing businesses in an uncertain and competitive market. The customers are now getting smarter day by day requesting variety of quality products, quickly, at lower costs. To adapt to these highly changing customer requirements, the product lifestyles, product-process technologies, the product demands are rapidly changing. The traditional manufacturing systems such as a Dedicated Manufacturing System or a Flexible Manufacturing System, are rigid systems which do not allow any modifications in their architecture to allow the changing product functionality or capacity requirements. Thus, a new manufacturing system, a Reconfigurable Manufacturing System is introduced which allows the system to reconfigure and adapt itself in the changing market and manufacturing conditions.

A Reconfigurable Manufacturing System (RMS) is a system which is designed around a product part family, allowing rapid changes in its architecture by utilising reusable hardware and software resources, allowing the system to reconfigure itself subjective to the changing functionality and capacity requirements. As far as the literature is provided on this concept, no work has been presented on presenting a systematic design methodology to design and reconfigure a RMS. With no information on how and when to design and reconfigure a RMS, the manufacturers are still continuing to practise traditional re-engineering and other methods. Additionally, it is becoming troublesome to plan the reconfiguration as it requires evaluating excessive data which may sometimes lead to make an error and can eventually affect the system ramp up time, and its production costs and time. Thus, concerning the theoretical and practical issues, an effective and efficient methodology with decision support tools is developed.

A Life Cycle Economic Analysis methodology to justify the choice of investment in RMS with respect to other manufacturing systems is developed. Subsequently, a reconfiguration process incorporating the design and reconfiguration aspects at the production system level, i.e. system and machine level, plant layout system and material handling system level and incorporating operations management such as defining the products and grouping them in families and assigning operations in the RMS is developed. The objectives are to highlight the reconfigurability aspects and to minimise the reconfiguration effort, i.e. the reconfiguration cost, the reconfiguration time and the ramp up time and provide decision supports in designing and reconfiguring the system. Based on these two methodologies developed, a Life Cycle Economic Analysis Model (LCEAM) and Reconfigurable Manufacturing System Design Model (RMSM) is developed. The LCEAM justifies the Net Present Value (NPV) of a RMS in comparison to other traditional manufacturing systems and can facilitate a manufacturer to decide whether investing in RMS is a right choice subjective to different product and market requirements. The RMSM facilitates a manufacturer in deciding whether reconfiguring an existing system is required or not, determines the amount of reconfiguration effort, determines the manufacturing equipments, system investment costs and the daily production phase cost and times.

The models, LCEAM and RMSM developed are validated considering an industrial case study. The case study considered is a machining of an automotive cylinder head family and power transmission case family. Firstly, a RMS is designed for an automotive cylinder head, based on the initial market conditions and a configuration designed is proposed with the daily production costs and time. Later, the system is reconfigured for a new product family, the power transmission case and a new reconfiguration design is proposed. Subsequently, the limitations of this developed methodology are discussed further. Lastly, the research is concluded with the future recommendations.

Chapter 1: Introduction

Manufacturing businesses nowadays are coping with an increasing competitive environment. This competitive market is characterised by product uncertain life cycles, changing process technologies, smarter customer needs who requests the products quickly at lower costs. To survive and prosper in a company's ultimate objectives such as profit, reputation and market share, manufacturing systems are required to be able to react quickly and effectively in today's dynamically changing market environment (Koren Y. , 1999).

Henry Ford invented the flow lines known as Dedicated Manufacturing Lines (DML's) which manifested the beginning of mass production paradigm. These lines were merely comprised of series of workstations with tools assigned to produce a single product. DML system had very high production rate and hence capable of producing a product at reasonably low price. But, these systems were designed to manufacture just one product for a life time, and thus they offered limited flexibility in manufacturing other product types (Mourtzis, 2014). With the emerging changing needs, these systems were unable to adapt to the market and customer requirements and started becoming obsolete.

In later years, the manufacturing requirements flourished. Variety, quantity and speed were held to be the new strategic goals of the manufacturing industries. This lead to the development of Flexible Manufacturing Systems (FMS) which combines the seemingly conflicting objectives of high flexibility and averagely high productivity. The FMS consisted of Numerical Control (NC) and Computer Numerical Control (CNC) machines which had capability (flexibility) to produce wide variety of products easily without making any changes in its hardware and software set up. With such high flexibility, the manufacturers could adapt to wide product variety, but contrarily due to its rigid architecture, it yielded a relatively slow production rate and could not respond in terms of capacity adjustments (Mehbrabi, 2002). Due to the pre-defined functionality and complex hardware and software structure, their investment costs were very high and created capital waste, which did not give a major breakthrough in the industries.

Later, globalisation evolved and many firms started addressing the market requirements globally. Standing in the global competition, the new priority for the firms were to be responsive to the dynamic changes. Thus, the speed of system's responsiveness was a new strategic goal of the manufacturing firms (Koren Y. , 1999). With technological advancements of the traditional manufacturing systems coming to a limit, the manufacturers switched to different practises such as agile manufacturing, lean manufacturing, continuous improvements, etc. But at a point, these practises came to a limit and there was a new need of technological advancements to adapt and accommodate rapid changes.

Emerging from the new needs, a responsive manufacturing system is required which can be rapidly designed, is able to convert quickly to the production of new product models, able to adjust quickly in capacity requirements, able to integrate process technology such that product variety with unpredictable quantities can be adapted. To meet these requirements, the concept of the Reconfigurable Manufacturing Systems (RMS) is introduced (Koren Y. , 1999). A RMS is a manufacturing system with an open hardware and software architecture system with a key characteristic, *"reconfigurability"*, which calls for an ability of the system to restructure the production system through rearrangement and reuse its resources to adapt to the changing functionality and capacity changes. Performing such modifications, a system can have a tremendous potential to offer an economical solution in comparison to traditional manufacturing systems (Mehrabi, 2002).

1.1. Background Introduction

A Reconfigurable Manufacturing System (RMS) is designed for rapid adjustment of production capacity and functionality in response to new market conditions and process technology (Mehrabi, 2002). A typical RMS is designed with Reconfigurable Machines (RMs) having Reconfigurable Machine Tools (RMTs) that are utilised to manufacture a family of products as well as a product quality Reconfigurable Inspection Machines (RIMs) that inspect the product during its manufacturing (Koren Y. G., 2018). The structure of an RMS is an open structure which easily enables adding or removing production resources. The option of reconfiguration by adding production resources is planned at all the levels, such as hardware, software and controls, to enable adding of machines, in line inspection stations, gantries (material handling systems), etc.

As far as these technologies and work is concerned, no reflection is provided from the designer point of view. With such an extensive information available and dynamically changing market, it becomes troublesome for a manufacturer to determine the manufacturing equipments (i.e. the number and type of machines, the material handling system), evaluating the system configuration (the way that machines are arranged and interconnected in the system) and planning the processes (assigning operations to each machine in the system). So far some work has been presented which is believed are mere qualitative information and are believed to provide less information. With no systematic methodologies available, the manufacturing engineers are using re-engineering approaches to configure the system and propose layouts subjective to the product and market needs (ElMaraghy, 2006). Moreover, with no effective methodologies and appropriate (re)configuration strategies available, it makes a system designer to make some errors in the production environment which can sometimes eventually affect the system design time and costs. Thus, increasing the system's ramp up time and affecting the production performances of a firm.

To address this gap, an efficient and effective methodology with decision supporting tools are required to design the system, and evaluate various configurations based on the life cycle economic analysis, quality, system, reliability and preferences of decision maker's is needed (Mehrabi, 2002). With this methodology, a manufacturer can know better when and how a RMS system should be (re)configured in different conditions, and can proactively or reactively make decisions to select suitable configuration settings, measure the performance of the system and can make controllable policies in the future.

1.2. Problem Statement

The three goals of any manufacturing systems are low cost, high product quality and quick responsiveness to the market (Koren Y. G., 2018). Monitoring these goals in an uncertain manufacturing environment, in a RMS, is a challenging task. This is due to the reason that the RMS system is designed based on the initial requirements and subsequently is changing subjective to the changing product and market requirements. With no systematic approach or methodological theory available, it brings a necessity to develop a decision support methodology to design and reconfigure the RMS systems which is not only applicable in a practical manufacturing environment but also achieves the three goals (Mehrabi, 2002).

Generally, so far only the RMS design issues are highlighted. The operation management in RMS is also vital and have issues related to the reconfigurability, such as the part families' formation, reconfigurability planning, quality management, risk management and exceptional handling (Napoleone, 2018). Performing frequent configurations with no efficient reconfiguration strategies can majorly involve high amount of reconfiguration effort and can highly affect a company's rate of returns. Additionally, at the system level, design and selection of an optimal machining system configuration for a particular product family requires new methodologies. Evaluation of machining configurations are required which should be based on preferences of decision makers incorporating factors such as quality, cost and timing and part variation. Further issues related to system integration for RMS, such as integration rules, economic evaluation of alternative configurations, cost models, analysis and selection of machining systems should be incorporated (Mehrabi, 2002).

These issues make troublesome for a manufacturer to decide when and how to reconfigure a system. Thus, it is important to highlight and incorporate these issues as well as also provide a decision support, allowing a manufacturer to make (re)design and operational decisions during the system life span by analysing the system's life cycle costs. These issues have been just addressed qualitatively, and are required to understand better so that an economical strategy, i.e. a design methodology can be attempted which can not only address the design and operational issues at the production system level, but also at the plant layout system level and the material handling system level.

1.3. Research Objectives

The purpose of the research is to develop a methodology to design a Reconfigurable Manufacturing System (RMS) to meet the changing functionality and capacity requirements. The goal is to investigate the key design issues, the operations management issues and the reconfigurability issues in consideration with the cost, time and ramp up time. Moreover, the aim is to investigate the design requirements from the reconfiguration aspects and provide extensive decision support information to design and reconfigure a RMS in a dynamically changing market environment. This decision support methodology is developed in a form of a quantitative model.

The following are the objectives of carrying this research:

- *To investigate the critical issues and the requirements to design a Reconfigurable Manufacturing System*
- *To identify the characteristics of the RMS and the necessary conditions to develop the design methodology*
- *To identify the right indicators which will help to decide about reconfiguration*
- *To identify reconfigurability aspects to reconfigure the RMS*
- *To test the model (the methodology) in consideration with cost, time and ramp up time and validate on real manufacturing scenario*

In a nutshell, this research attempts to build a bridge on the knowledge gap by providing extensive knowledge of Reconfigurable Manufacturing Systems and presents a decision support methodology to design and reconfigure a RMS system in uncertain market and manufacturing environment.

Regarding, following are the research questions framed. The first set of questions are framed to provide extensive information of a RMS in comparison to the traditional manufacturing systems.

1. *What is a Reconfigurable Manufacturing System?*
2. *What are the characteristics of a Reconfigurable Manufacturing System?*
3. *Are these reconfigurability characteristics relevant?*

These questions are structured progressively to present a theoretical background of the RMS and to highlight their relevance in terms of positive effects and reconfiguration effort. Subsequently, these questions drive the research to the intermediate objective, concerning the requirements to develop the research methodology.

4. *What are the necessary and sufficient conditions required to develop the decision support methodology to design the reconfigurable manufacturing systems?*

After acquiring the necessary and sufficient conditions to develop the research methodology, the next step is to develop a methodology (Reconfiguration Process) to design a RMS.

5. *When and how a Reconfigurable Manufacturing System should be designed and reconfigured?*

The methodology developed is required to be validated on a real manufacturing case, such that the ultimate objective can be accomplished. Regarding, the research questions are framed:

6. *Is investing in Reconfigurable Manufacturing System a right choice in comparison to the traditional manufacturing systems?*
7. *In case of reconfiguration, which aspects should be considered and how to evaluate various aspects that may be available?*
8. *If reconfiguration is required to be performed, how an existing RMS configuration design should be reconfigured to the new required reconfiguration design?*
9. *If reconfiguration is performed, how the candidate configurations should be analysed considering the cost and time?*

1.4. Value, Scope and Limitations

1.4.1. Value

The academic value of this thesis is to research the major issues of developing a methodology to design a Reconfigurable Manufacturing System (RMS). So far, very few work has been presented on developing the RMS methodology. These work presented concerns only specific issues in the RMS at the production system level and the methodology at a complete plant level is missing. Thus, a RMS design methodology at a plant level, i.e. at a production system level, plant layout system level and material handling system level is presented incorporating all the issues from the literature point of view.

The concept of RMS's is still unfamiliar in manufacturing industries. Conducting a personal interaction with few manufacturers, it was observed that the concept of RMS was still unfamiliar. Many manufacturers are still practising continuous improvement methods and re-engineering methods to meet the changing needs. With a complete new concept and with no easy recognisable methodology, this work can provide extensive information concerning design and reconfiguration of a RMS in different market and manufacturing conditions. Thus, a quantitative "Reconfigurable Manufacturing System Design Model" is developed to facilitate a manufacturer to design and reconfigure RMS economically.

1.4.2. Scope

The scope is to develop a decision support methodology to design and reconfigure a Reconfigurable Manufacturing System at a production system level, i.e. system and machine level, at a plant layout system level and material handling system level. The objectives are to highlight the reconfigurability aspects in objective to minimise the reconfiguration effort, i.e. reconfiguration cost, reconfiguration time and ramp up time and provide decision support in a dynamically changing market requirements.

1.4.3. Limitations

There are some major limitations in this study that could be addressed in the future research. The study focusses completely on the issues which are required to be incorporated in developing a decision support methodology to design the Reconfigurable Manufacturing Systems. These key issues are Life Cycle Cost Analysis, Product Grouping, Module Configurations and the development of the Reconfigurable Manufacturing System Design Model.

Firstly, a Life Cycle Cost Analysis, a quantitative model to determine the Net Present Value (NPV) is developed. The model is developed in aim to provide a general understanding of the RMS investment in comparison with traditional manufacturing systems. The term NPV and expansion cost of the systems are emphasised. Reconfigurability aspects are not considered to develop this model, as it is believed that analytical model will not be sufficient and a simulation model is required. As the simulation model requires a lot of complex modelling information; thus the goal was to develop a model to emphasise the NPV subjective to different product and market information.

Secondly, one of the main issue of developing the RMS design methodology is incorporating the product grouping methodology. The product grouping is a deep topic driving in a path of product-process subject. Thus, the issues regarding the product grouping in the RMS is focused, and required information in the form of product grouping methodology is presented. Thus, this topic is just covered up to an extent required in developing the RMS design methodology.

Thirdly, at the production system level, i.e. at the machine level, each base machine accommodates specific module (tool) configurations. These module configurations are group of modules equipped on the base machine according to the set of machining features assigned on each machine. To know more the technical requirements, it is important to know the product and machining details and technical module requirements. With knowing this information, the technical machining operations requirements can be translated into tangible requirements to determine the modules and its configuration. As this topic drives to Reconfigurable Machining Tools (RMT's), necessary assumptions are drawn from the literature to develop the RMS methodology and the topic, "module configurations" is just covered breadthwise.

Thus, the product grouping and module configuration aspects are just considered qualitatively and will be incorporated to develop the RMS methodology. Thus, the RMS functionality requirements will be covered qualitatively. Additionally, adapted from this methodology, a Reconfigurable Manufacturing System Design Model (RMSM) will be developed to validate the methodology assuming a case study and different manufacturing scenarios to accomplish the research objectives. The model will not be developed with an intention of optimisation or providing an ideal configuration solution, as it required researching com computational modelling data and algorithms to develop a simulation model. Thus, the model is developed just to address limited requirements.

These limitations are further discussed in the discussions and more information is provided to develop the work in the future.

1.5. Model Development and Approach

A *"Life Cycle Economic Analysis" (LCEAM)* and *"Reconfigurable Manufacturing System Design Model" (RMSM)* is developed. These models provide system design and configuration in consideration with costs and times involved.

Microsoft Excel has been used as a developing platform. The model supports a user to facilitate in making decisions on:

- Determining the Net Present Value (NPV) and expansion costs in comparison with Dedicated Manufacturing Lines and Flexible Manufacturing Systems. This is aimed to justify the investment choice of RMS subjective to different product and market conditions.

- Determining the manufacturing equipments at the production system level subjective to changing market requirements. Moreover, to monitor the resource utilisation rate and system flexibility rate of the production system.
- To measure the configuration aspects to estimate whether a system is required to reconfigure or not.
- Proposing a RMS configuration based on the manufacturer's preferences in consideration with total production phase cost and the production phase time.

1.6. Thesis Outline

The research is distributed in 9 chapters, including this as a general introduction chapter. The other chapters are framed in the following manner:

Chapter 2, presents a theoretical focus to examine the key roles of the traditional manufacturing systems. These manufacturing systems are categorised chronologically, analysed and compared from the manufacturing point of view.

Chapter 3, introduces the Reconfigurable Manufacturing Systems. The chapter answers the following questions: *1. What is a Reconfigurable Manufacturing Systems? 2. What are the core characteristics of the RMS? and 3. Are these reconfigurability characteristics relevant?*

Chapter 4, presents the research framework. This chapter draws the RMS design principles, RMS design approach and sufficient and necessary conditions to develop the RMS design methodology. This chapter answers the following question. 4. *What are the necessary and sufficient conditions for the design of the reconfigurable manufacturing system?*

Chapter 5 presents the research process to develop a decision-support RMS design methodology. Various methods, from the design and reconfiguration point of view are researched and analysed in order to develop the methodology to design the RMS.

Chapter 6, presents the design methodology of the Reconfigurable Manufacturing System. This chapter consists of qualitative as well as quantitative steps to design the Reconfigurable Manufacturing System Design Model. This chapter answers the following question, *5. When and how a Reconfigurable Manufacturing System should be designed and reconfigured?*

Chapter 7, presents the results acquired from the Reconfigurable Manufacturing System Design Model. This chapter answers the following questions, *6. Is investing in Reconfigurable Manufacturing System a right choice in comparison to the traditional manufacturing systems? 7. In case of reconfiguration, which aspects should be considered and how to evaluate various aspects that may be available? 8. If reconfiguration is required to be performed, how an existing RMS configuration design should be reconfigured to the new required reconfiguration design? 9. If reconfiguration is performed, how the candidate configurations should be analysed considering the cost and time?*

Chapter 8, presents the Discussions drawn from the gaps in this research.

Chapter 9, presents the Conclusions and Future Recommendations.

Chapter 2: Traditional Manufacturing Paradigms

The chapter presents the traditional manufacturing paradigms based on the development of the production methods and the manufacturing systems. These paradigms are analysed chronologically from their flexibility point of view. These manufacturing systems are studied and their issues are highlighted.

2.1. Introduction of Manufacturing Paradigms

Several paradigms have evolved based on the development of the production methods and the manufacturing systems. These paradigms are Craft production, American production, mass production, lean production, mass customisation and global production which are classified as push and/or pull modes. Paradigms such as American production, mass production and lean production is push, while craft production and global manufacturing is pull (Mourtzis, 2014). It can be reflected that the lean production is a pull mode, as long as it is completely lean. The global production can be either push or pull mode. On a global platform, the supply chain is a hybrid between the two modes. For instance, a company may choose to stockpile finished products at its distribution centres to wait for orders that pull them to stores. Under the push system, manufacturers might choose to build up inventories of raw materials, especially those that go up in price, knowing that they will be able to use them for future production. These paradigms are defined and analysed based on the flexibility.

"Flexibility" is defined as the ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost effective manner (Sethi, 1990). Flexibility contributes to the system to bring it at ease to respond to the uncertainty in a manner to sustain the value delivery. Flexibility is broadly categorised into different approaches such as the manufacturing flexibility, operational flexibility, customer flexibility, strategic flexibility and capacity flexibility (Koste, 1999). In the process of manufacturing system design, this approach of flexibility is distinguished in three levels: 1. Basic Flexibilities (Machine Flexibility, Material Handling flexibility, Operation Flexibility). 2. System Flexibilities (Volume flexibility, expansion flexibility, routing flexibility, process flexibility, product flexibility). 3. Aggregate flexibility (Program flexibility, Production Flexibility, Market Flexibility). Accordingly, the development of these manufacturing paradigms are presented.

2.2. Craft Manufacturing

Craft manufacturing is a manufacturing technique applied like in the hobbies of a handicraft. The manufacturing process is simple and flexible, where various tools are used to produce a product precisely desired by unique individual (customers) requirements (Gola, 2012). Figure 1 below, shows the classification of the manufacturing systems. Most often, each product is highly precise and unique. E.g., furniture made against specific order, decoration elements of sport cars and sport bikes. Highly skilled workers (craftsmen) are engaged, producing high variability products at low production volumes.

Craft manufacturing is highly flexible and at the same time expensive too. This type of production is not important from the manufacturing system's design point of view but is interesting if focussed on the task flexibility.

2.3. Dedicated Manufacturing Systems (DMS)

In the 1900s, industries grew and the production practises took a dramatic turn. Henry Ford invented the system of mass production and dedicated manufacturing lines. The idea behind the mass production was to produce high volume of same parts, with no variety at relatively cheap price. This conception of mass production contributed to the development of dedicated manufacturing systems which generally appears in two forms:

- Continuous Manufacturing Systems
- Intermittent Manufacturing Systems

2.3.1. Continuous Manufacturing Systems

In continuous manufacturing systems, each production run manufactures in large lot sizes and the production process is carried out in a definite sequence of operations in a pre-determined order. The goods produced here are made to stock and not for specific orders. Each process and operations for a particular product are standardised, apparently making the scheduling, routing and the sequencing of the whole process a *"standard process"* (Gola, 2012). Due to this, the in process storage becomes unnecessary, eventually reducing the material handling and transportation facilities. First in First Out (FIFO) rules are prioritised in the system. Thus, these systems have low flexibility and high efficiency.

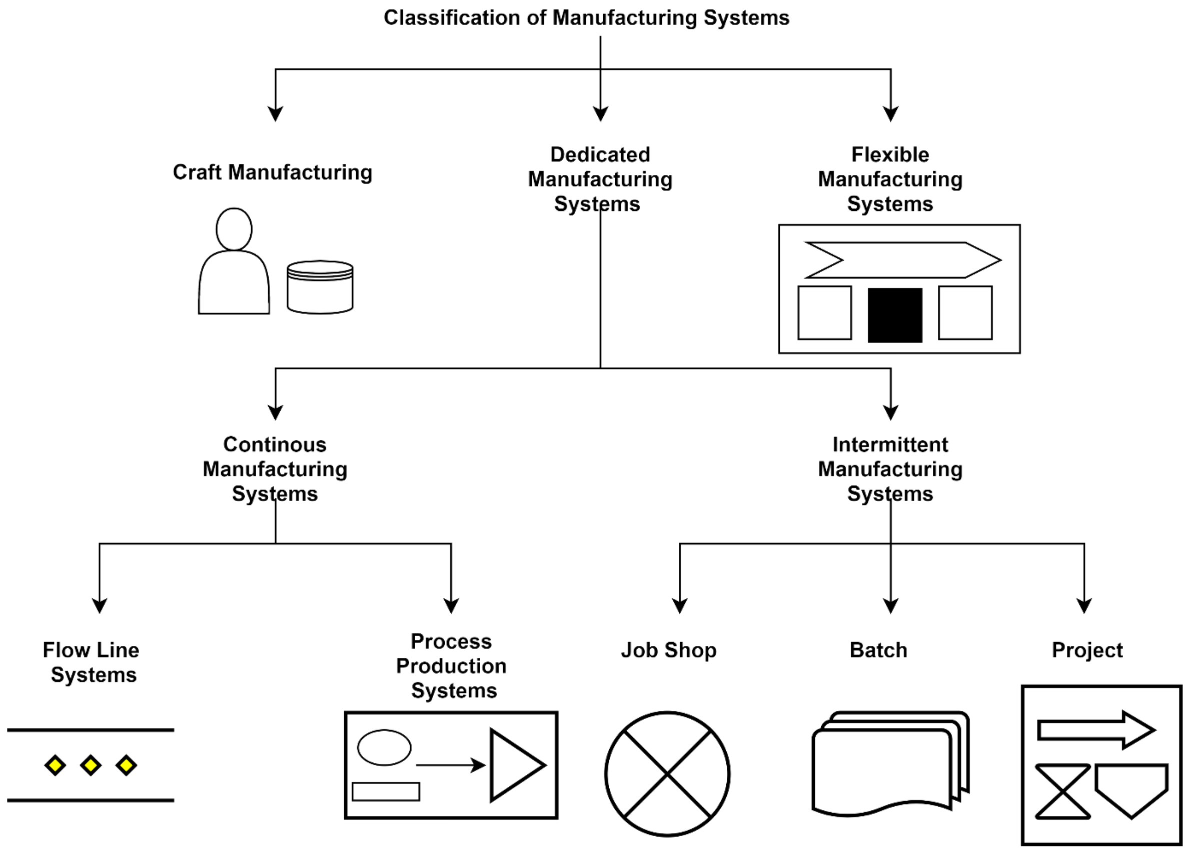

Figure 1 Classification of Manufacturing Systems

Continuous systems are sub-classified into two types, namely mass and flow-line production systems and process production systems.

- *Mass and Flow Line Systems* are designed for production of a specific part type with high volumes. It uses transfer line concept (Dedicated Manufacturing Lines) (DMLs) with Dedicated Manufacturing Tools (DMTs). This type of machine tool is custom-designed for particular operation and therefore, its resources are minimised (Moon, 2006). Thus, the machine cost is low, the system performance is robust and produces a part cost-effectively at high volumes and desired quality. E.g., automobile parts.

- *Process production systems* is the system where the production of goods are done by combining the supplies or raw substances using a formula or recipe. E.g., food and beverages.

2.3.2. Intermittent Manufacturing Systems

Intermittent manufacturing systems are the systems in which the flow of the material is intermittent, meaning they are not continuous or steady. The goods manufactured in here are specially to fulfil the orders made by customers rather than stock. Intermittent systems are used to produce the products where the design of the products and the production processes require continuous adjustments. Moreover, considerable storage between the operations are required, so that the individual operations can be carried out independently for further utilisation of men and machines. Thus, these systems are designed to be highly flexible to handle wide variety of products and demand sizes, making the system highly flexible and poorly efficient.

Intermittent manufacturing systems are sub-classified into three types, namely job shop production systems, batch production systems and project production systems.

- *Job shop production systems* tend to manufacture small lots of a variety of parts. Most parts in the job shop require a long set-up time between each operation and a process sequence of machines. A job shop is created by locating similar machines together, resulting in a functional layout. E.g., drilling machines are usually contained in one area and grinding machines in another area.
- *Batch production systems* are similar to job shop production systems. In here the products are produced in batches. E.g. Drugs and pharmaceuticals.
- *Project production systems* produce a single, complex product according to customer requirements. In this production system, the resource allocation changes as well as the routing and schedule. E.g., shipbuilding.

Analysing the flexibility level of Dedicated Manufacturing Systems (DMS's), it is clear that the continuous manufacturing systems have zero flexibility. Contrarily, intermittent systems have high flexibility, but their high variability and changeability makes the systems efficiency zero. (Gola, 2012). But it could be reflected that, the flexibility and efficiency is not completely zero, but low. This is because the DMS's are just designed particularly around one product part. Hence, DMS's have limited flexibility associated to the product part.

2.4. Flexible Manufacturing Systems (FMS)

In the middle of 1960s, market competition became more intense and complex. Industries were confronted with the challenge of changing their manufacturing orientations to meet demands of current market region. This increasing market pressure introduced the Flexible Manufacturing Systems.

Flexible Manufacturing Systems (FMSs), consists of Computer Numerically Controlled (CNC) or Direct Numerical Controlled (DNC) machines to produce wide variety of parts in a pre-defined product part family. Various machining cells are interconnected, via loading and unloading stations, by an automated transporting system. The objective is to produce wide variety of parts with averagely variable demand sizes, with minimum changeover time and changeover cost. The CNC machines are equipped with flexible CNC machine tools. By contrast to DMTs which are designed just around the specific part and thus are inexpensive, CNC's are designed before the operation requirements are known and, thus, they often have wasted resources that make customers pay for features which are not needed (Moon, 2006). Thus, they can handle different product variety but mostly have high capital waste as many companies are producing only few product models. Moreover, these CNC machines have excessive functional elements and have complex hardware and software architecture, thus making them resist in capacity changes. With this system architecture their investment costs become very high. Additionally, other issues such as lack of reliability and integrability of software, issues in incrementing the production capacity, etc. make them less responsive to adapt to the changing market conditions (Mehbrabi, 2002).

The flexibility of the FMS systems is often too high and thus considerably affects the cost of producing a part. Along with high flexibility comes high functionality which often remains underutilised, apparently increasing the capital cost.

2.5. Summary

Dedicated systems are designed for only one product at each one sub-system. They operate at their maximum planned capacity, thus providing high throughput rate at low operation costs. These systems do not adapt to the changes in the terms of system's functionality and capacity. To adapt to the change, these systems require high technological and operational changes which comes with very high cost. On the other hand, FMS's handles wide product variety. These machines are of complex architecture designed around a standard operational envelope, providing more than required functionality which in most cases remains underutilised. FMS's approach of producing any part (within the machine envelope), with any mix of parts in any sequence increases the cost as it requires a parallel system structure which have 5 axis CNCs with a very large module magazine and multiple set of tools making them a very expensive solution.

Due to the rigidity and low flexibility of Dedicated Systems, these systems are decaying and becoming impotent in this global competition. Contrary, FMS sufficiently meet the production requirements but in terms of capacity adjustments, one whole FMS unit is required to be added, which again came with pre-defined functionality and excessive costs. With these risks and no secondary choice, the manufacturers continued to invest in FMS units. When asked, they responded, "to buy it just in case it may one day be needed" (Mehbrabi, 2002).

Chapter 3: Reconfigurable Manufacturing System

This chapter presents the theory of the Reconfigurable Manufacturing Systems. This chapter is divided into two sections. Section 3.1 defines the RMS, its characteristics and its relevance on the reconfiguration effort. Section 3.2. System Comparisons with RMSanalyses RMS features with other traditional manufacturing systems.

This chapter answers the following research questions:

1. *What is a Reconfigurable Manufacturing System?*
2. *What are the characteristics of a Reconfigurable Manufacturing System?*
3. *Are these reconfigurability characteristics relevant?*

These questions are believed to give a complete overview of the RMS and its characteristics and provide a detailed path to develop a methodology to design the RMS.

3.1. Reconfigurable Manufacturing System

From the overview of traditional manufacturing systems, it is clear that Next Generation Manufacturing Systems should allow flexibility in not only producing a variety of parts but also in changing the system capacity. The main skill required to accomplish this strategic goal is the *"speed of responsiveness."* (Heisel, 2006) Accomplishing this new goal is only possible if the manufacturing system is *"designed for reconfigurability"* to variably adapt to the changing product functionalities and capacities. To do so, the system should be of an open architecture which can ultimately accomplish: 1. Continuous upgrading of the system by integrating new technology and 2. Be rapidly reconfigured to accommodate future products and changes in product demand rather than scrapped and replaced (Koren & Shpitalni, 2011). This approach may prevent the Next Generation Manufacturing Systems from becoming obsolete.

3.1.1. RMS Definition(RQ1)

Koren (Koren Y. , 1999) defined a Reconfigurable Manufacturing System as, "A reconfigurable manufacturing system is designed at the outset for rapid change in structure, in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to abrupt market changes or in regulatory wants." *Later, Zhoa et. al* (Zhao, 2000) supported this definition as *"a manufacturing system in which a variety of products required by customers are classified into families, each of which is a set of similar products that corresponds to one configuration of the RMS."*

Supporting the above two definitions, the RMS can be defined as:

> *"A system where large variety of products are classified into families, associating set of similar operational features on each machine which can allow rapid changes in its architecture by utilising reusable hardware and software components rather than replacing them, in order to quickly adjust the production capacity and functionality."*

3.1.2. RMS Characteristics(RQ2)

The foundation of a RMS is based on its key feature, ***"reconfigurability".*** (Heisel, 2006)

Reconfigurability is the operational ability to switch in between the changing production requirements with minimal effort and delay subjective to a particular product part family. Reconfigurability is simply a conversion and modification of the system's structure, functionality, capacity and technology by upgrading and configuring the production resources and operating requirements rather than replacing. This may correspond to the design, the selection of production elements and the composition of production elements from a modular available configuration set.

> *"The reconfigurability of the system derives from the system configurability" (Heisel, 2006).*

For a system to be reconfigurable, it has to be configurable first. In order for a system to be configurable, it must consist of subsystems and components that have been designed in order to process certain key characteristics. These characteristics are: Modularity, Integrability, Customisation, Scalability, Convertibility and Diagnosibility (Koren Y. , 2006). Figure 2 shows the characteristics of the RMS.

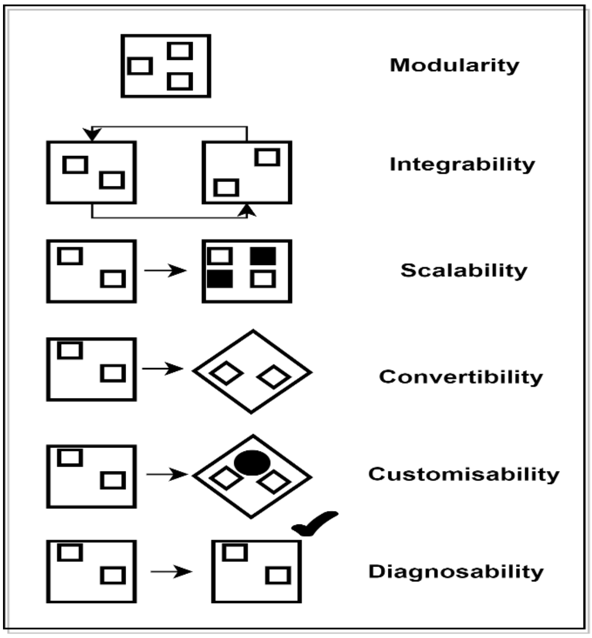

Figure 2 Characteristics of RMS

1. ***Modularity, the compartmentalisation of independent operational functions into units which can be manipulated and reused among alternate production schemes for optimal arrangements. E.g., Plug and Produce.***

In a RMS, the components are modular**.** This includes the resources such as system controls, software packages, machine tools, base machines, etc. This characteristic makes the system to effortlessly replace, reuse and upgrade itself to suit new product applications, adapting to the changes. Also it easily maintains the system and can reduce the life cycle of the system, making it economically stable (Koren Y. , 2006). Designing for modularity can reduce the system life cycle costs and making it more economically stable. Modular make the system mobile and influence and enable other characteristics.

2. ***Integrability, the ability and possibility to connect modules rapidly and precisely by a set of mechanical, informative and control interfaces for ready integration and future introduction of new technology.***

Integrability is a challenging characteristic. In spite of having numerous computing programs, the system remains complex in integration and communication. To aid in designing for integrability, a set of system integration rules must be established which should allow the designers to relate clusters of part features and its corresponding machine operations to machine modules, enabling the product process relationship (Shpitalni, 2010). Further, integrability brings the system together, and eliminate the system's internal redundancies, keeping the system alive in case of machine or material handling system failures.

3. ***Scalability, the ability to modify easily the production resources by changing the system components. E.g., adding or removing of machines at system level or tools at machine level.***

Scalability is the counterpart characteristic of convertibility. Scalability at the system level requires adding or removing of the machines, changing the machine configurations, choosing differing material handling configurations to expand the overall system capacity according to the product functionality and demand (Spicer, 2005). At the machine level, it may require adding or removing the spindles to increase its productivity or to simultaneously produce other product parts.

4. ***Convertibility, the ability to easily transform the functionality between existing systems and quick system adaptability for future products.***

Convertibility is an essential characteristic which transforms the resources at the system and machine level. At the system level, it accomplishes in expanding the range of system functionality, machine configurations, etc. while at machine level by switching the spindle speeds, tool angle or tool direction. This characteristic enables the system to quickly calibrate the machines after conversion and also allow the system to easily convert (Koren Y. , 2006).

5. ***Diagnosability, the ability to self-read the system health and to detect and diagnose the root causes of the product by quickly correcting them. E.g., machine reliability, product quality.***

Diagnosability has two aspects in the RMS: 1. Checking the system health by detecting the machine reliability and other uncertainties such as machine failure, tool breakage, etc. 2. Monitoring the product quality and identifying the root causes of unacceptable part quality (Koren Y. G., 2017). Both the aspects are believed to be important in designing the RMS. Diagnosability can rapidly tune the system to reduce the ramp up time.

6. ***Customisation, the ability of the system to craft customised flexibility and match system capability limited to a single product part family. E.g., for similar parts in a product family.***

Customisation is a vital characteristic of the RMS, distinguishing it radically from DMLs and FMSs. DML are *customised* hardware lines built with *"precisely the functionality"* needed to produce a single part while FMS have "*general flexibility"* to produce wide variety of parts (Koren Y. , 2006). RMS focuses on the "part family" which is defined under a group of parts that have similar geometric features, shapes, same level of tolerances and are within the same range of the cost. E.g. all types of hair dryers. *Customised Flexibility* means that the dominant features of a part family being manufactured will determine the overall system and machine configuration. This allows additional feature of *(re)usability* of multiple tools on the same machine, increasing the productivity, accuracy and machine life without compromising the flexibility (Koren Y. G., 2017). Reflecting, this makes RMS dynamic with several active tools cutting simultaneously, like a DML, but with an ability to handle a product part family like an FMS.

A system which is said to have these characteristics has a likelihood that it will have a high level of reconfigurability. A system that lacks these characteristics cannot be readily and cost effectively reconfigured.

3.1.3. Relevance of these characteristics on RMS (RQ3)

Every characteristic shows a remarking relationship with each other and directly or indirectly enhances the reconfigurability of the system. This reconfigurability derives by the reconfiguration activities performed. These characteristics should be such that it must accomplish the objective of minimising the reconfiguration effort involved with these reconfiguration activities.

A reconfiguration effort is composed of reconfiguration time, reconfiguration cost and ramp up time.

The definitions of the terms of reconfiguration effort are as follows (Zhang, 2006):

- The *reconfiguration time* is the time taken by the system to redesign the system or to rearrange the equipment. This reconfiguration time can be seen as an opportunity cost since it affects the service level due to the losses related to the reconfiguration period.
- The *reconfiguration cost* is the cost involved to reconfigure or adjust the system to satisfy the requirements of the product mix and or capacity. It is represented by the out of pocket costs which includes the activities relating the redesign of the system or to buy an extra machine or other system related equipment.
- The *ramp up time* is the time period at which the system reaches a stable production state (at required quality and production rate) after the reconfiguration.

Characteristic	**Reconfiguration Effort**		
	Reconfiguration time	**Reconfiguration Cost**	**Ramp Up Time**
Modularity	•	•	
Integrability	•	•	
Scalability	•	•	
Convertibility	•	•	
Diagnosability		•	•
Customisation		•	

Table 1 RMS characteristics relevance on Reconfiguration Effort

As presented in above Table 1, it is noticeable that the characteristics Modularity, Integrability, Scalability and Convertibility reduce the reconfiguration time and reconfiguration cost.

- *Modularity and Integrability* both reduces the reconfiguration cost and reconfiguration time. Due to the presence of modular architecture, this influences the integrability. Integrability influences the speed of the replacement of these modules and help in reducing the reconfiguration time. Lack of integrability between these modules can negatively impact the reconfiguration time (Napoleone, 2018).
- *Scalability and Convertibility* reduces the reconfiguration time and cost by appropriately selecting the configuration for the manufacturing system in order to ensure a certain

production capacity (ElMaraghy, 2006). This characteristic positively impacts in reducing the reconfiguration effort.

- *Customisation* is a very important characteristic. Indeed, this is the characteristic which really introduces the reconfigurability. It remarkably plays a vital role in customising the flexibility around a part family rather than providing general flexibility. This unique ability makes the system reconfigurable instead of flexible, where flexibility is more related to short term goals and reconfigurability is more related to mid long term goals, in situations of unchanged product families. (Koren Y. , 2006). This allows in reducing the reconfiguration cost. (Chaube, 2012).
- *Diagnosability* is the only characteristic associated with the ramp up time. It allows in process diagnostics by allowing in process diagnostics which dramatically shortens the ramp up time after the reconfiguration (Shpitalni, 2010).

3.1.4. Summary

Summarising, a Reconfigurable Manufacturing System is an open architecture system designed to quickly adjust the production capacity and functionality within a part family. Its key characteristic is reconfigurability which is derived from the core characteristics Modularity, Integrability, Diagnosability, Convertibility, Customisability and Scalability. These six characteristics are relevant and are significant components of reconfigurability capability. Customisation is additionally relevant because it synthesises reconfigurability. Thus, these six characteristics shows positive influence in reducing the reconfiguration effort and enhance reconfigurability.

3.2. System Comparisons with RMS

3.2.1. RMS features

RMS features are highlighted. Table 2 gives the system features of RMS in comparison with a Dedicated Manufacturing Line (flow line) and FMS (Koren Y. , 1999) (Koren Y. , 2006).

Features	**DMS**	**RMS**	**FMS**
System Structure	Fixed	Adjustable	Adjustable
Machine Structure	Fixed	Adjustable	Fixed
System Focus	Part	Part Family	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customisable	General
Simultaneously Operating Tool	Yes	Yes	No
Productivity	High	High	Low
Lifetime cost	Low (for a single part, when fully utilised)	Medium (For producing medium to high volume new parts)	Reasonable (for producing variety of parts at low volume) -otherwise high

Table 2: Comparison of System Features (Koren Y. , 2006)

- *In terms of system and the machine structure,* the RMS is adjustable. The modular architecture allows the machines and the modules to (re)arrange itself in any other particular configuration. For DML, the system and machine structure is fixed, whereas the FMS's system structure is adjustable where the machines can be relocated without changing its module configuration.

- *In terms of System focus,* RMS is designed for a particular product part family, well as DML is only designed for one product and FMS for wide variety of products under the machine envelope.
- *In terms of Flexibility,* RMS has customised flexibility, built around a particular product part family. DML has very low flexibility, as they are designed for only one product for a product life time and FMS have general predefined flexibility required to produce high product variety.
- *In terms of scalability,* RMS can be scaled up/down by adding/removing a particular machine or a module as required. Whereas in FMS, an additional machine unit can be added in the particular configuration. DML cannot be scaled as its technological units are fixed in a standard process.
- *In terms of simultaneously operating tools,* RMS and DML both allow simultaneously operating tools whereas FMS allows only one tool at a time.
- *In terms of productivity,* for RMS productivity may be high, depending on the type of the product and demand topology. DML has a very high throughput whereas in FMS, their high flexibility and wide variety of products affects the productivity, considerably making it low.
- *In terms of lifetime cost,* RMS cost is medium depending on the individual costs of the base machines and reusable modules in the system. The DML's costs are average depending on the number of workstation and tools on each line and FMS cost is very high as it includes purchasing cost of CNC machines and other automatic handling systems.

Although this table provide an extensive distinguish of the RMS features, some features may be not actually valid. Thus, following table presents the updated information.

Features	**Dedicated**	**RMS**	**FMS**
System Structure	Fixed	Adjustable	Adjustable
Machine Structure	Fixed	Adjustable	Fixed
System Focus	Product	Product Family	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customisable	General
Parallel Tools	Yes	Possible	Possible
Productivity	Very High	High	Low
Cost per part	Average	Medium	Very High

Table 3 Updated System Features

It can be argued that in terms of Parallel Tools, the RMS and FMS may both possibly have simultaneous operating tools. The RMS uses Reconfigurable Machine Tools (RMTs), which adopts the DMT approach and design a machine around a part family or a set of parts (rather than a specific part, so conversion by rapid reconfiguration of the machine is possible) and use CNC technology to drive the machine (Moon, 2006). Thus, RMT has a customised flexibility that makes it less expensive than general purpose CNCs.

RMS embraces the best qualities of DML and RMS systems, i.e. it focusses on product part family with the required throughput and functionality. This focus can allow a designer to plan a system that accommodates different variation of the same part family and can possibly cope with situations where both the productivity and the ability of the system to react to changes are of vital importance. Utilising this approach may possibly give high throughput rate as of DML with required functionality and can prove to be more economical than the general functionality of FMS.

3.2.2. System Capacity VS Functionality

The system capacity vs functionality of RMS comparatively to DML and FMS is presented. A DML operates at its maximum planned capacity, providing high throughput rate but very low functionality rate (ElMaraghy, 2006). DML *"mass produce"* the company's core products or parts at very high volume for an extensive production run. Due to high production rate at very low functionality rate, the throughput of this system is very high, substantially reducing the cost per unit of the product. Whereas, FMS produces variety of products, *"mass customising"* at a reasonable low capacity. FMS units come with pre-defined flexibility and high functionality, but remains typically underutilised in most scenarios (Mehbrabi, 2002). This reduces their throughput in comparison of DML and makes the system cost high, relatively increasing the cost per part.

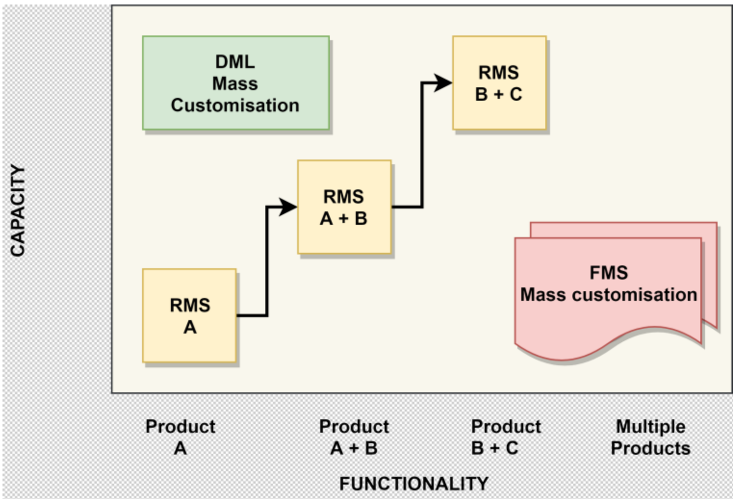

Figure 3: System capacity versus Functionality (ElMaraghy, 2006)

RMS are not constrained by the capacity and the functionality. RMS is designed to be scalable and modular. For e.g. in the Figure 3, the RMS can be customised to accommodate different product part families at required functionality and capacity in a production time horizon. Due to this customised nature of the RMS, the residual value of their modular components is expected to increase if they can be reutilised. This *"Plug and Produce"* practise may potentially reduce the manufacturing costs through diminished expenses for planning as well as can shorten the times for changes, leading in reducing the costs of retrofitting and conversion.

3.2.3. System cost vs capacity

In the manufacturing system cost versus capacity plan, DML cost remains constant at its maximum planned capacity (Koren Y. , 2006). Figure 4 shows the system cost vs capacity. In case of DML, to get additional capacity or to produce an another product, an extra line must be built. This extra added line doubles the capacity and tremendously increases the investment costs. Therefore, in terms of low demands, this extra line built can be idle, hence it is always questionable adding an extra line. FMS is scalable at a constant capacity rate through adding more machines in parallel, which also proportionally increases the cost in parallel for greater capacity. RMS is scalable at a non-constant capacity rate depending on its initial design, the manufacturing equipments and the changing market requirements.

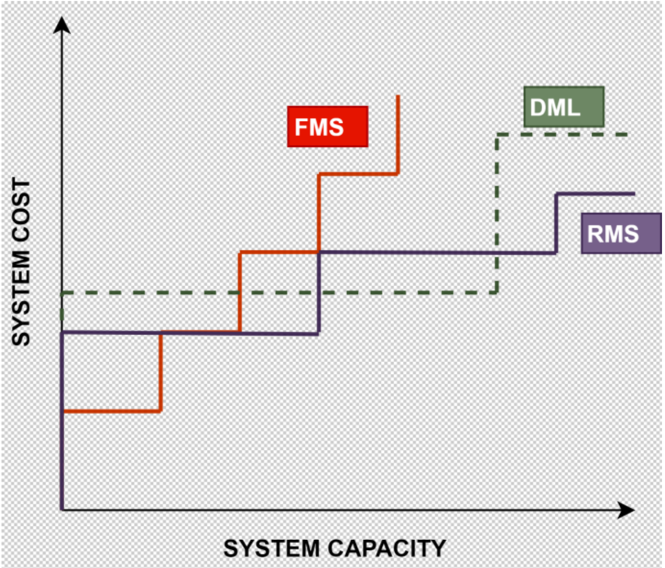

Figure 4: System Cost versus Capacity (Koren Y. , 2006)

3.2.4. Summary

Dedicated Lines are designed to operate at high production volumes, producing at least 75% of its maximum planned capacity. These systems produce only one product at high throughput rate. FMS can produce wide product variety when there are average demand sizes. If large demand sizes are requested where the products types are limited, then RMS may be a cost-effective solution.

3.3 Conclusion

In terms of cost, capacity and functionality, RMS is the best of both the worlds. Moreover, if designed with incorporating its definition and its core characteristics, RMS can enhance reconfigurability and can allow the system to react cost-effectively to uncertain market conditions. This focus can allow a designer to design the system that accommodates different variation of the same part family and can possibly cope with situations where both the productivity and the ability of the system to react to changes are of vital importance. Utilising this approach may possibly give high throughput rate or productivity as of DML with required functionality around product part family can prove to be more economical than the general functionality of FMS.

Chapter 4. Framework to develop RMS Design Methodology

This chapter presents the RMS design principles, RMS Design Approach and the issues and requirements to develop a decision support RMS methodology is analysed. Based on this, the remainder of the chapter is presented as follows, Section 4.1. Reconfigurable Manufacturing System Design Principlespresents the Reconfigurable Manufacturing System Design Principles, Section 4.2. Reconfigurable Manufacturing System Design Approachpresents the Reconfigurable Manufacturing System Design Approach and Section 4.3. Sufficient and Necessary conditions for developing RMS design methodology presents the sufficient and necessary conditions to develop the RMS design methodology.

This chapter answers the following research question:

4. *What are the necessary and sufficient conditions required to develop a decision support methodology to design the reconfigurable manufacturing system?*

4.1. Reconfigurable Manufacturing System Design Principles

Reconfigurable Manufacturing Systems should be designed, operated and controlled to rapidly adapt to the changing functionality and capacity requirements. Thus, to do so, the RMS should be built with a set of following principles. The first three principles are the core principles which define a reconfigurable system (Koren Y. , 2006). The others are secondary principles that can assist in designing a cost-effective RMS.

1. A RMS should be designed for adjustable production resources to respond to coming up market needs. This system should be able to:
    a. Rapidly scale the capacity in small, optimal increments.
    b. Rapidly adapt the functionality for the production of new products.
2. A RMS should be designed around a product part family, with just enough flexibility required to produce all the parts defined in that particular family.
3. To enhance the responsiveness of a RMS, its core characteristics should be embedded in the whole system as well as in its components.
4. A RMS should be able to handle the production resources with customised flexibility, so that its functionality and productivity can be readily changed when needed.
5. A RMS system should have large number of alternative material handling routes to produce a particular product part.
6. A RMS should be able to prevent its complete breakdown in unpredictable events.

The more these principles are incorporated in developing the methodology to design the RMS, the more reconfigurable the system will be. To make the system reconfigurable, it should be incorporated with key interrelated characteristics, i.e. i.e. Modularity, Integrability, Customisation, Scalability, Convertibility and Diagnosability. Implementing these principles will achieve the goal - *"A Reconfigurable Manufacturing System"*, which is able to rapidly adjust its production capacity and the functionality while maintaining high productivity.

4.2. Reconfigurable Manufacturing System Design Approach

Based on this principles, a Reconfigurable Manufacturing System Design Approach is presented in Figure 6. This approach is adapted from Francalanza et. al. (Francalanza, 2014). The function of the RMS is to adapt to the changing capacity and functionality requirements and as well as to handle process planning and investment planning.

There are several requirements which need to be met by RMS. This include product family formation, manufacturing and business requirements. Product family formation is defining and grouping the products in the RMS. It is important to analyse the product family requirements, i.e. the products to be produced at the beginning of the manufacturing life cycle and also should have the information of the future product families. With this, it is possible to plan the reconfigurability. The other requirements are operations management such as assigning and scheduling the processes in the system. The business requirements are the Cost per part, Investment Cost and other reconfigurability related costs.

The next activity is the Reconfigurable Manufacturing System Cycle. This is the heart of the design of the RMS. The process should commit in the following three domains, the reconfigurability domain, the enabler domain and the design element domain. Incorporating these three domains results into different candidate design solutions. At the reconfigurability domain, the manufacturers should commit to the flexibility of the production system level around the product part family. Additionally, it should commit to the reconfigurability, which is a longer term goal, at the production system level, plant layout system and material handling system level. This can be only achieved by the reconfigurability enablers, which are the characteristics, Modularity, Integrability, Scalability, Convertibility, Customisability and Diagnosability. These characteristics must be incorporated in designing the production system level, i.e. the machine level, the plant layout system and the material handling system.

The next stage of the design cycle involves the analysis of the candidate design solutions. This mostly involves simulation of the candidate design solution, where the solutions are generated based on the artificial history of the system. But, in this research this stage will be addressed analytically. These candidate solutions will be further evaluated and decided by the manufacturer to implement one satisfying solution from the available candidate solutions or again generate a better design solution. Once the solution is satisfied the criterion which meet the manufacturing and business requirements, the design will finally move to the implementation and ramp up stage.

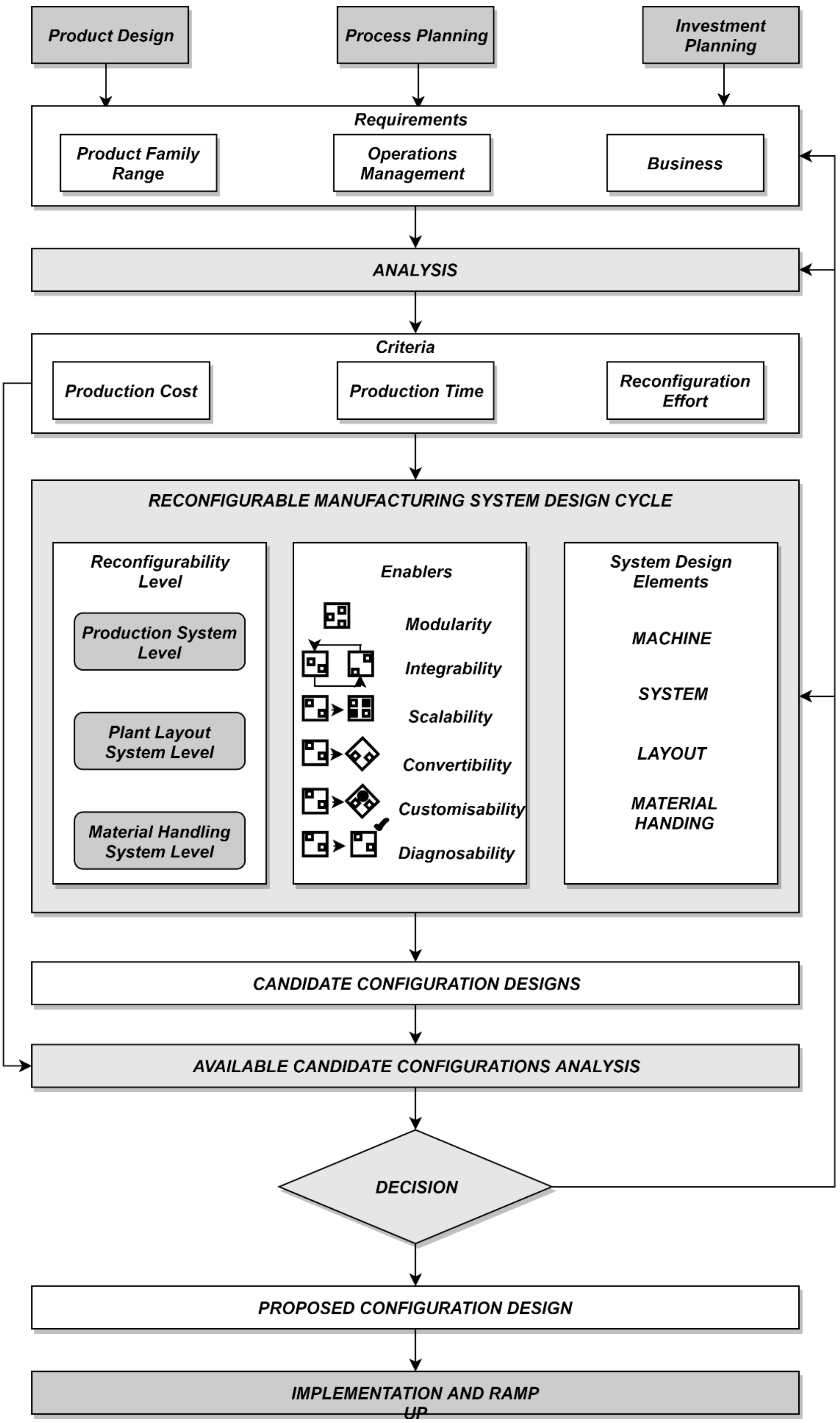

Figure 5 Reconfigurable Manufacturing System Design Cycle

4.3. Sufficient and Necessary conditions for developing RMS design methodology

This section is the answer to the research question: *What are the necessary and sufficient conditions required to develop a decision support methodology to design the reconfigurable manufacturing system?*

After presenting the necessary principles and the approach to design the RMS, a decision is made to develop a RMS design methodology incorporating these principles. To accomplish these principles, the RMS characteristics are analysed further to exploit their inter-relationship. This is because these characteristics are the design and reconfigurability enablers. So far these RMS characteristics are studied from the design and reconfiguration aspects. These characteristics are researched further from other aspects such as the operations management and the life cycle costs of the RMS system. Thus, these characteristics are studied in depth, and necessary conditions are drawn so that the characteristics and the solutions for these issues can be incorporated in designing the research process to develop an effective decision support methodology to design the RMS.

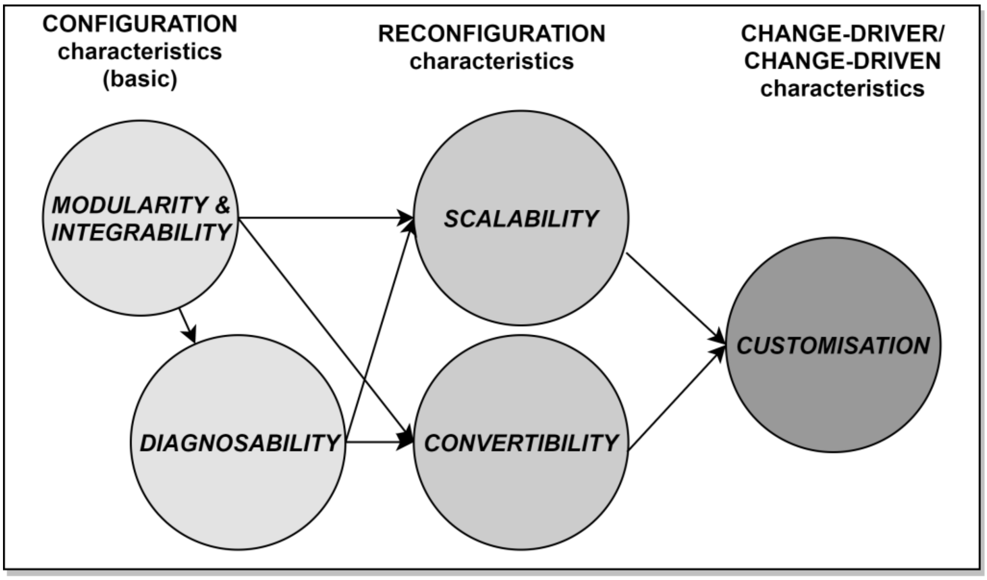

Figure 6 Relationship of the RMS characteristics

Figure 6 shows the relationship of the RMS characteristics with each other. *Modularity and Integrability* act as *"configuration"* characteristics. They do not guarantee modifications in production capacity and functionality, but they help in making the system configurable. Modularity is an important characteristic to consider. Designing a system with modularity is important as it influences the integrability. Designing a system modular requires a brief understanding of the manufacturing equipments, the product process relationship, etc. Moreover, at a system level, due to modularity, different system and machine configurations for a product family can be designed, evaluated and selected. Evaluating these configurations are a complex task as there might be many candidate configuration designs available. Moreover, these candidate solutions can have impact on system life cycle costs and the formation of part families and assigning the operations to the configurations. Thus, it is important to consider these issues and evaluate the configurations based on right performance factors and manufacturer's preferences.

Integrability, is a characteristic which integrates a RMS together. In other manufacturing systems, machine breakdowns are very common. These breakdowns harm critically the system productivity and sometimes can eventually breakdown the complete system (Koren Y. , 2006). In a RMS, the system is required to successfully isolate the machine failures from the system failure and thus permitting the production to continue (Freiheit T. S., 2004). A "built in redundancy" approach is necessary to consider such that it allows the system to adjust in case of intrinsic system events. Redundancy plays an important role not only for the configuration of a manufacturing system but also for its reconfiguration. Thus, it is important to integrate the system by material handling system, so that the candidate configurations can be evaluated economically, and select the machining systems to achieve minimum idle time and optimal system productivity.

Secondly, *Scalability and Convertibility* are the essential RMS characteristics. They make the system reconfigurable (Napoleone, 2018). Each configuration comprises of a particular design, the selection and the composition of the modules from a modular configuration set (i.e. physical modularity and integrability of the modules) specified according to the product family functionality and capacity requirements. It can be reflected that the configuration is not only required to be performed on the machine level, but also at the system level to allow the modifications of functionality and capacity by replacing the manufacturing equipments and also the operating requirements. Reconfiguring through the means of scaling or converting the system can deteriorate the productivity of the system and can eventually impact the system life cycle costs and reconfiguration costs and times. Moreover, no insights are provided how to scale, convert and perform reconfigurations. Thus, necessary methodologies are required to plan the reconfiguration, monitor the system costs and the reconfiguration costs and time. Also, it is wise to incorporate *diagnosability*, which can act like a real time decision support, allowing operational decision regarding reconfiguration for exceptional handling.

Moreover, due to frequent configurations, the sequencing of the process is also required to change. As a RMS is designed around a product part family, a wide variety of products are required to be defined and grouped into families so that the system is utilised efficiently (Galan, 2007). Thus, it is important to incorporate the product grouping aspects in developing the methodology as well as also foresee the potential requirements so that an appropriate method can be selected to reconfigure the RMS (Mehrabi, 2002)

Lastly, *Customisation* is a unique characteristic as it synthesises the reconfigurability. It can be said that this characteristic allows hypothesising that it can be trigger of and triggered by reconfigurability (Napoleone, 2018). Customisation allows to proactively face changes and makes the system to meet any physical or operational changes (ElMaraghy, 2006). Customisation plays an important role, as a set of similar features can be assigned to the machine configuration and appropriate module configuration can be assigned to each machine. Moreover, customisation plays a strategic role in decision making by either proactive decision or reactive decision taking ability. Thus, customisation can be interpreted as a *change driven* characteristic, i.e., *"triggered by"* reconfigurability. It ensures that the system can evolve to meet any physical or managerial change.

4.4. Summary

Thus, it can be summarised that it is important to incorporate these characteristics in developing a decision support methodology, as they are not only associated to the design and reconfiguration aspects, but also operations management and other managerial aspects.

- *Modularity and Integrability can be associated to the configuration period. They relate to the decisions on the system design, clearly bounded to the configuration period of system lifecycle.*
- *Scalability and Convertibility can be associated to the reconfiguration period and can be related to the operational decisions, bounded to the reconfiguration period of system lifecycle.*
- *Diagnosability can be associated to both configuration as well as reconfiguration period. This related to both design and operational decisions.*

- *Lastly, customisation synthesises reconfigurability. In terms of decision making, customisation has a strategic role. It leads to either a proactive or reactive approach to achieve reconfigurability.*

Thus, to accomplish the ultimate goal of a RMS is - "Exactly the functionality and capacity needed, exactly when needed", it is important to incorporate these characteristics and the required conditions such as the life cycle costs, manufacturing equipments, product part family formation, manufacturing processes, etc. to develop a decision support RMS design methodology.

Chapter 5. Research Process for developing RMS Methodology

After knowing the design approach and the necessary conditions required to develop the RMS methodology, the next step is to analyse all the approaches and methodologies available to develop a decision support methodology from reconfigurability point of view to accomplish sustainable design and efficient operational requirements. Section 5.1. Life Cycle Economic Analysis presents the research process (procedure) to develop the Life Cycle Economic Analysis methodology, Section 5.2. RMS Design Methodology presents the procedure to develop the RMS design methodology, Section 5.3. RMS Reconfiguration Methodologypresents the procedure to reconfigure the RMS system, Section 5.4. Implementationpresents the implementation of the RMS design.

5.1. Life Cycle Economic Analysis

Dedicated Manufacturing Lines (DML's), Flexible Manufacturing Systems (FMS's) and Reconfigurable Manufacturing Systems (RMS's) are the three production paradigms representing three ways of thinking and implementing the production systems. It is very important to clearly define the convenience of these three manufacturing paradigms subjective to the market and the product characteristics in which a manufacturer can choose a system and can justify an ideal choice of investment among these three systems. Koren (United States Patent No. US 6349237 B1, 2002) first proposed the idea of storing a life cycle economic analysis in a computer programming format. With this ideology, it can be conveyed that a RMS life cycle costs can be very unpredictable in changing market conditions, thus it is important to see how reconfigurability affects or influences the RMS system. Concerning the same, various methods presented till now on Life Cycle Economic Analysis are analysed to incorporate it in the design methodology.

Renna (Renna, 2017) proposed a Genetic Algorithm (GA) to design a hybrid manufacturing systems composed of DML, FMS and RMS. This method emphasises the inputs such as variable products and demand as well as the manufacturing operations required which can allow a manufacturer to plan the number of machines required over a planning horizon. Based on this requirements, a Genetic Algorithm (GA) in combination with Monte Carlo Simulation was proposed. The objective is to highlight the Net Present Value (NPV) so that an investment choice as well as the number of machines required to be purchased along the particular planning horizon can be made. Although this model provided a better understanding of the investment decisions to be made, it comprised of a complex simulation nature. But it become clear that the main objective is to calculate the NPV of all the three systems under different product and market scenarios. Regarding, other methodologies are researched which can provide better understanding of the NPV of all the systems and can provide some analytical modelling requirements to develop the methodology.

Bruccoleri et. al developed a quantitative simulation model emphasising the investment decisions subjective to several market and competition factors such as product demand dynamic over the investment period, product mix composition, product costs, etc. (Bruccoleri, 2006). The same objective, *"Net Present Value" (NPV)* is emphasised and can allow a manufacturer to make decisions based on the number of lines (DML), general purpose machines (FMS) or number of shells (base machines) and modules required (RMS) to meet the production requirements. It was clear that, that the ultimate decisions required to be made is regarding number of manufacturing equipments to purchase and the system NPVs in its changing product and market requirements. Moreover, a brief information is presented, such as the product and market information to be considered to frame the LCCA methodology. Figure 7 describes the approach to develop the LCCA methodology. Product Information and Market Information such as the number of products and their processing times are considered. Demand volume of all the products, the machine investment costs and the contribution margin of a product is considered as an input information. Based on this information, the manufacturing equipments required are determined, and is considered to determine the NPV's of the manufacturing systems. Hence, this method is considered to develop the RMS LCCA methodology.

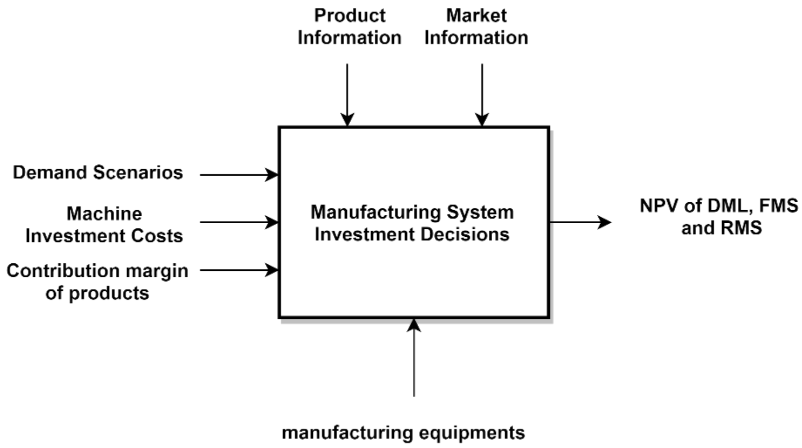

Figure 7 LCCA methodology development approach

Bruccoleri et. al developed this methodology based on a parametric approach. The parametric approach is an attempt to formalise the FMS and RMS models on the basis of the DML model through a technological factor and investment cost factor. The first parameter, technological factor, relates each CNC machine (in FMS system) and a RMS base machines and the modules (in RMS system) to a Dedicated Line (in DML) from the processing point of view. It considers into account that the throughput of a flexible system is lower than the one of a dedicated line. Whereas, the second parameter, the investment cost factor relates a CNC machine and a Reconfigurable Machine to a Dedicated Line from an investment cost point of view. It takes into account for higher investment cost of more flexible machines, but also for scope economies (Bruccoleri, 2006).

Later, a similar method was proposed based on the same parametric approach under the same objective, NPV of the systems (Amico M. P., 2006). This method considered developing the NPV model under strategic decisions "Real Option Analysis" (ROA). It can be said that, in dynamic changing conditions, NPV alone cannot provide enough data, as it is based on traditional investment methods such as Discounted Cash Flows (DCF). The DCF is based on single forecast of a cash flow and hence becomes a subjective input. ROA can deal with the project risk stemming from the income uncertainty and adjusts the risk associated with it to discount the cash flows. This might give a decision maker to include both the uncertainty in the project and the active decision making required for the project to be successful. Thus, ROA and DCF together acts as a complementary tool which results into Extended Net Present Value (ENPV), which accounts the traditional NPV plus the value of all the options. These options consider the expansion cost based on market forecasts.

This presented methodology also follows the same parametric approach. Thus, it was hard to conclude the NPV as they were varying drastically and were believed unrealistic. This is due to the reason that the approach is presented for scope economies. With this, it becomes very hard to directly compare the FMS and RMS investments, because of the need to select particular values of technological factor and cost factor. Moreover, there is no inter-relationship defined between these parameters and the NPV is proposed by varying the parameters from 0 to 1 (Bruccoleri, 2006). In another work presented by *M. Amico et. al* (Amico M. P., 2006), the parameters are varied and the highest NPV is proposed. Setting this highest NPV acquired, the extended net present value is determined. For e.g. the NPV of

FMS shows highest when the technological factor is 1 and the investment cost factor is 0.5. But practically, it can be said that if a machine has a high throughput rate, it will also have high purchasing cost. This implies that the parametric relation of technological factor (capacity) and the investment factor (cost) should be proportional to each other.

Based on this reflection, new relationship for the parameters, processing point and investment cost is defined for both the RMS and FMS system and the NPV is determined in comparison with DML. With these new defined relationship, the existing analytical methodology is improvised. Based on this information, a manufacturer can make decisions based on the machines required in the three manufacturing systems and their NPV's. Furthermore, their expansion costs are highlighted. Doing so, it is believed that this approach can provide a general understanding of the RMS comparatively to FMS and DML.

5.2. RMS Design Methodology

The RMS design is the design of the production system, the plant layout system and material handling system.

5.2.1. Production System Design

The production system design is the heart of the reconfigurable manufacturing system design process. The Production System Design consists of designing the RMS at the system level and the machine level.

> *The design of the production system is a challenging task (Jacobsen, 2002)."*

Koren et al (Koren & Shpitalni, 2011) presented a systematic design approach of the RMS. This methodology consisted of designing the RMS at the system level. A RMS is required to be designed each time a new product family is introduced. To design the RMS, one of the important requirements one must know is the number of machines required to fulfil the product and market requirements (Koren & Shpitalni, 2011). The number of machines can be determined based on the daily demand and the machine reliability. This determination further acts as an input to design a particular configuration in the RMS plant layout system. But determining simply the required number of machines in the system is same as determining the number of CNC machines in the FMS system. Hence, it is important to take into account the modularity characteristic, as designing the system with modularity will make the system modular and configurable, so that it can be later reconfigured. Thus, this approach was not useful and directs to research the requirements of modular manufacturing equipments which can be scaled and/or converted at their required point of use.

To adapt and handle the capacity and functionality changes, the system and the machine should be designed as an independent integral part of the system (modular system) with incorporating characteristics such as scalability. Designing a machine for modularity can allow equipment modules to add, remove, rearrange or reutilise necessarily. This influences the scalability, convertibility, customisability of the system and can enhance the reconfigurability. With this approach, the production system is designed for the number of base machines (machine blocks independent of modules) and number of modules associating each other independently. This aspect will allow the manufacturer to design the RMS system as well as also adapt to capacity changes. These machines will be categorised based on their capability (flexibility) and their production rates. To determine the production rate of each machine, one must determine the number of modules positions each shell can allow, which can ultimately provide us the production rate of the machine.

P. Spicer et al. (Spicer, 2005) developed a deterministic mathematical approach for the optimal number of module positions on a scalable machine. The scalable machine comprises of single module level, single module type and *n* module position architecture, i.e. 1/1/n. For a machine architecture to be scalable, the machine structure should be generalised as modular. If designed for modularity, various types of modules (tools) may be connected in the future.

The basic architecture of the modular machine consists of three basic parameters: module levels, module types and module positions. Module levels are the number of levels in which the modules can be attached. For e.g., in the Figure 8, there are three different levels. The first level consists of modules attached to the machine base, the second modules are attached to the first level and so forth. The machine's performance is directly dependent on the number of module levels, as it improves the machine's ability to react to different product types. On the other hand, as the level of modules increases, the scalability of the machine reduces as it greatly affects the integrability of the modules. This affects the scalability of the system. Hence, the goal is to design the machine with only single levels.

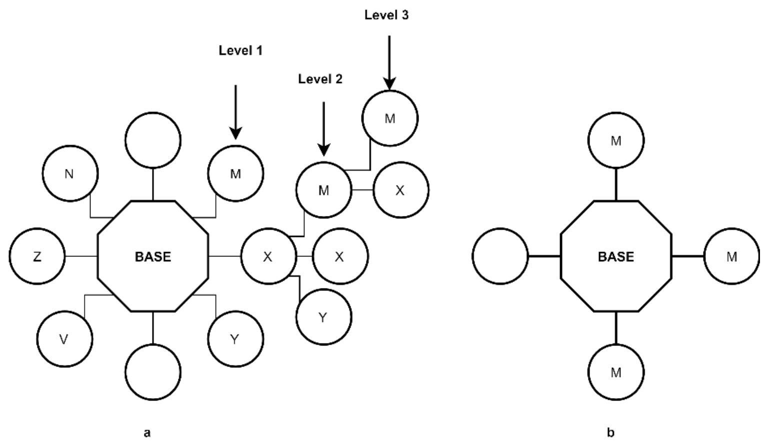

Figure 8 Machine Tool architectures a. General Machine tool b. Scalable Machine Tool

The second parameter is a measure of the number of unique module designs allowed on a machine. A manufacturer may put different module types on the machine according to the functionality required. The more the module types, the greater is the possibility of a machine to reach to different product designs. But adding different module types can affect the integrability of the modules and can greatly affect the production rate. Hence, the manufacturer should select same type of functioning modules, which will minimise the integrability issues and the complexity of reconfiguring the machine (in case of automatic tool changer) and will acquire a required production rate.

The final parameter, the number of available module positions is the most important parameter, as this parameter has a great impact on scalability. If designed properly, the machine production rate will increase with each additional module, increasing the capability of a machine to scale up the capacity.

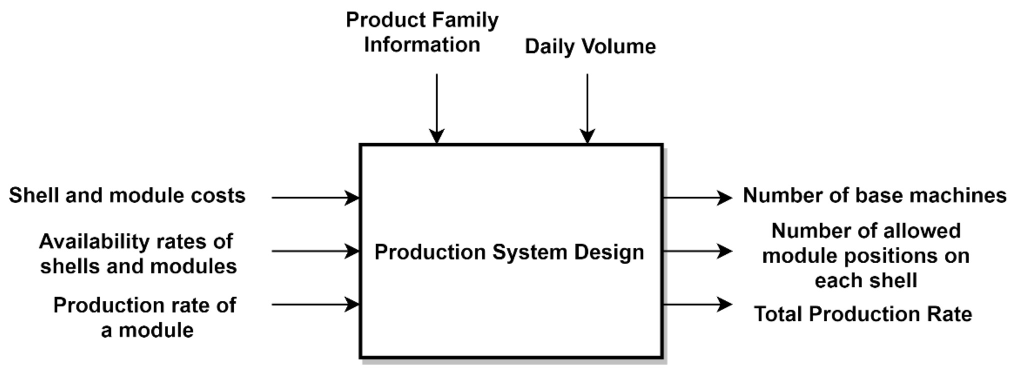

Figure 9 Production System Design Methodology Approach

Figure 9 *presents the production system design methodology approach. Ideally, designing the scalable machine (base machine) with cost-optimal module positions will significantly give a modular and scalable production system. With this approach, the production rate depending on the number of modules on each base machine, its scalability can be determined. Further, developing a methodology with this design approach can make a manufacturer to visualise the number of module positions required on each shell. Moreover, these aspects can assist a manufacture in making reconfigurability related decisions such as customising the system functionality (customisability) and scaling the system by checking if an extra base machine is required or more number of modules can be added at the available module positions. Thus this approach is incorporated for the RMS methodology at the production system level.*

5.2.2. Plant Layout System and Material Handling System Design

After acquiring the approach of designing the production system, the next step is to design Plant Layout System (PLS) and Material Handling Systems (MHS), which are the substantial aspects of designing a RMS.

A RMS layout completely differs from the traditional, robust and dynamic layouts. The traditional layouts are designed for different product types whereas in a RMS, a particular cellular configuration is accommodated for a product part family. A reconfigurable layout problem differs from the traditional layout problem as it consider the deterministic material handling and relocation costs and the stochastic operation cost in a dynamic and uncertain environment (Meng G. H., 2004). Traditional layout considers only current and upcoming planning periods. Viewing the current period as part, it designs the layout on the objective of minimising the relocation cost and material flow and inventory costs for the next period. A reconfigurable layout is based on deterministic product mix for the next planning period immediately after the data is available, while the traditional layout problems are based on future planning period, reconfigurable layout problem addresses the transition from the current period to the next. Due to widespread of this topic, the PLS and MHS topics are narrowed down to the required scope, i.e. designing a RMS cell configuration.

Calculating the number of RMS configurations:

As explained in previous section 4.2.2., the production system is designed with determining the number of machines and modules required. With the information of number of machines available in the system, the number of available RMS configurations can be calculated. Generally in practical cases, the total number of available configurations increases as the number of machines increases as shown in Table 4 Total number of system configurations for different number of machines. This enormous number of configurations eventually increases the work of the manufacturer.

Number of Machines	Number of possible configurations	Number of RMS configurations
2	2	2
4	15	8
6	170	32
8	2325	128
10	35,341	512

Table 4 Total number of system configurations for different number of machines

To calculate the number of available RMS configurations, a simple mathematical method is used (Koren Y. S., 2011). With this method, the number of RMS configurations can be calculated if the machines are arranged in number of production stages. In case of large production systems, the product is produced partially on one stage (workstation) and transferred to another production stage, until all the operations have been performed. Arranging the machines in the production stages is a key design step of RMS configuration, where every machine can be designed to have a particular module configuration required to perform the same set of operations. Thus it is very important to have required number of stages based on the product functionality and the best way in which the machines can be arranged. Designing a RMS configuration in production stages reduces the number of configurations comparative to the classical configurations, thus reducing the burden of the designer. With this approach, i.e. arranging the machines in the production stages, one can calculate the available configurations. Moreover, this mathematical results can be arranged in a triangular format, known as Pascal triangle, shown in the Figure 10 . The numerical value of each cell in the Pascal triangle corresponding to the number of machines and stages can be calculated as,

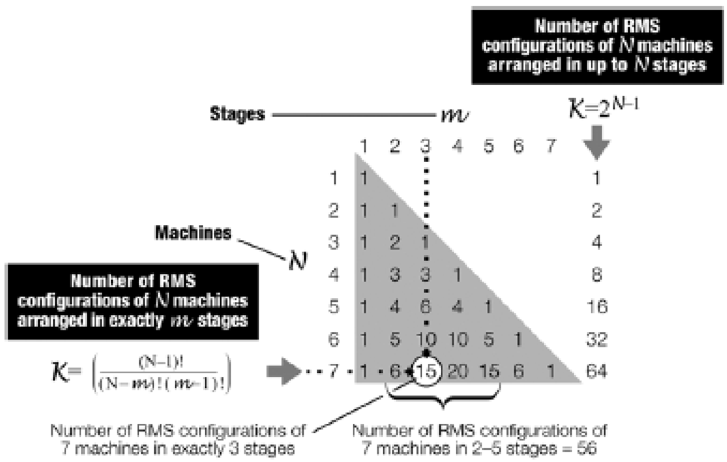

Figure 10 Pascal's Traingle (Koren & Shpitalni, 2011)

"The value of N machines in m stages = (the value for N – 1 machines in m – 1 stages) + (the value for N – 1 machines in m stages)."

The Pascal Triangle is very useful as it can make the designers to visualise the available configurations for designing reconfigurable manufacturing systems. Further, the number of configurations can be minimised if the machines are arranged in exactly number of stages. Additionally, the Pascal triangle also allows the designer to immediately calculate the number of possible configurations for N machines arranged in N machines arranged between i and j stages. (i, j < N).

Classification of Configurations:

After calculating the number of configurations (layout designs), one configuration design which meets the manufacturing requirements is required to be considered. Additionally, the configuration is required to thought not only from the design aspects but also from the reconfigurability aspects, to anticipate in the future requirements. The above configurations depend on the number of machines in the production system and the number of production stages planned. Thus, these configurations are of different configuration styles, which can be classified into symmetrical and asymmetrical configurations, defined on the basis of a symmetric axis passing along the configuration design.

1. **Symmetric Configurations:**

A configuration which resemble symmetricity when drawn a line along the axis of the configuration is called the symmetric configurations. Figure 11 shows the symmetric configurations of five machines arranged in different number of production stages.

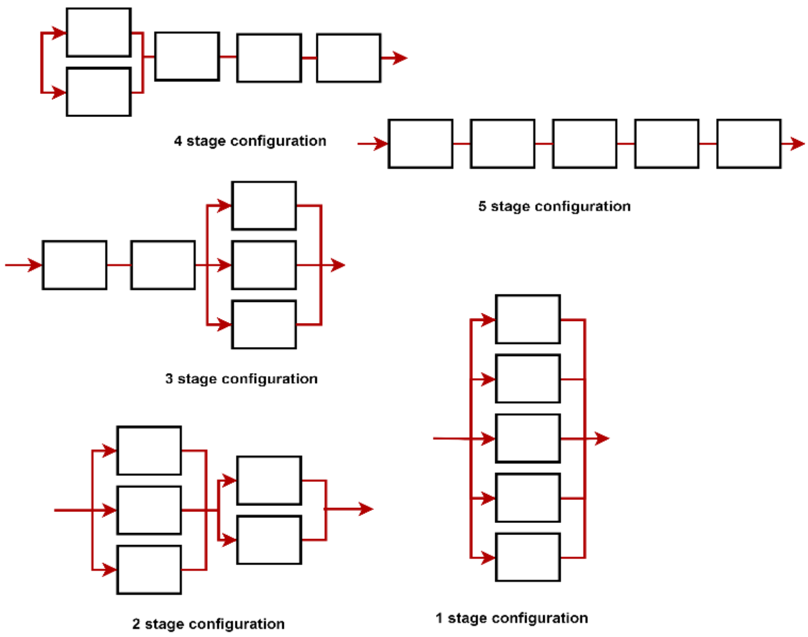

Figure 11: Symmetric Configurations

2. **Asymmetric Configurations:**

The configurations which do not seems the same when symmetric axis is draw along the axis are called asymmetric configurations. Asymmetric configurations are merely complex configurations because they are positioned differently and hence not practical in real manufacturing environment. These type of configurations are further sub-classified as: a) viable-process configurations and b) single process configurations with non-identical machines at atleast one stage.

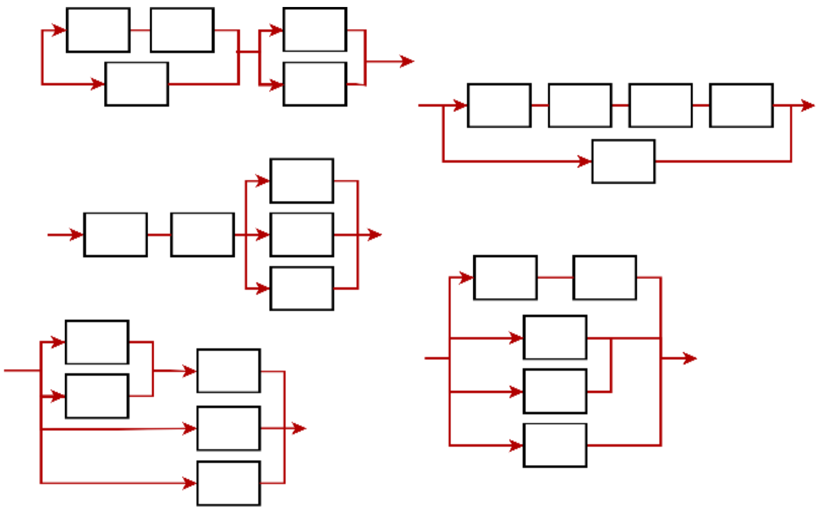

Figure 12 Symmetric Configurations

a. Viable-process configurations

The configurations in which there are many possible non identical flow paths for producing one part are known as Viable-process configurations. In this configuration, several process plans and corresponding setups are required to produce the part. E.g. in Figure 13a, there can be number of possible flow-paths such as *a-b-c-d-e, a-b-c-d-f, g-c-d-e, g-c-f, etc.*. The more the number of flow-paths, the more complex is it for the designer to evaluate the process plans for the same part. Moreover, in a case of RMS, there are more product types, which makes the flow paths much complicated. This is because, designing multiple process plans for one product or product family will be impractical. Additionally, different process plans and corresponding flow paths can deteriorate the part quality and can make quality error detection more complicated.

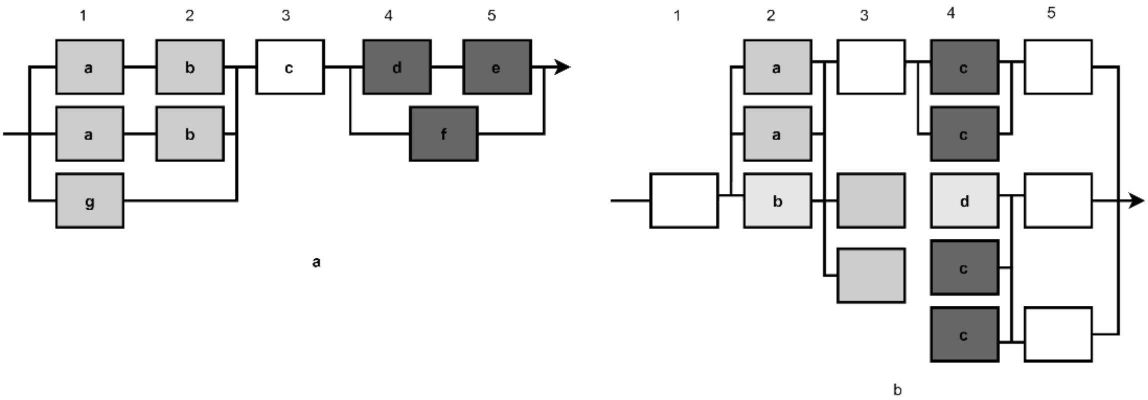

Figure 13 a. Viable process configuration b. Single Process configuration

b. Single process configurations

The configurations in which the process planning is identical in each flow-path but the machines are different in atleast one stage are known as Single process configurations. E.g. in Figure 13 a. Viable process configuration b. Single Process configurationb, machine b in stage 2 must be two times faster than machines a in stage 2, machine d in stage 4 must be two times faster than machines c in stage 4. Mixing different type of machines that can perform exactly the same sequence of the tasks in the same production stage is absolutely impractical. This will again increase the complexity of the system while performing the configurations and balancing the production stages.

Contrastingly, in a real manufacturing environment, symmetric configurations with identical and modular machines with single configurations should be considered.

Hence, asymmetric configurations are excessive complicated and impractical. They simply increase the effort of the designer and may not fulfil the configurability in the system. It is more likely that in a RMS context, only symmetric configurations should be considered (Koren & Shpitalni, 2011). *Symmetric configurations are always single process configurations with identical machines in each stage. They can be easily (re)adjusted in the system resulting to the ultimate goal- Reconfigurable System.*

The manufacturing system performance is influenced by system configuration and the material transfer between the operations. Every machine in the configuration is required to be connected with the Material Handling System (MHS). This aspect will help in minimising the Work in Process (WIP) and inventory carrying costs and improve the throughput of the system. Traditional layouts have buffers in the system which affect the WIP and the throughput time of the system (Freinheit T. S., 2003). Eliminating the buffers will accomplish the WIP and throughput time but it greatly impacts the system productivity, since a single failure can cause the whole system to fail. Thus, simply eliminating the buffers is an insufficient strategy.

As productivity suffers, parallelism provides a mean to improve the productivity without buffers (Freinheit T. S., 2003).

Thus, it is very important to consider a right type of material handling connectivity of the MHS among the machine arrangements.

Classification of Material Handling Connections

The machine arrangements in the configuration can be either completely dependent on other machines or not. These are known as crossovers. Crossover is where a product manufactured on a line blocked due to a failure down-stream can be transferred to another parallel line. These connections are sub classified as: a) cell configurations (with no crossover) b) RMS configurations (with crossovers).

a. Cell configurations (with no crossovers)

The configurations in which the machines are not dependent on each other and have no crossover is said to be a cell configuration. These configurations are simply several serial manufacturing lines (i.e. cells) arranged in parallel. Figure 14 Configuration with no-crossovers shows the configuration with no-crossovers. If one machine fails, the other machines stop and the complete line fails.

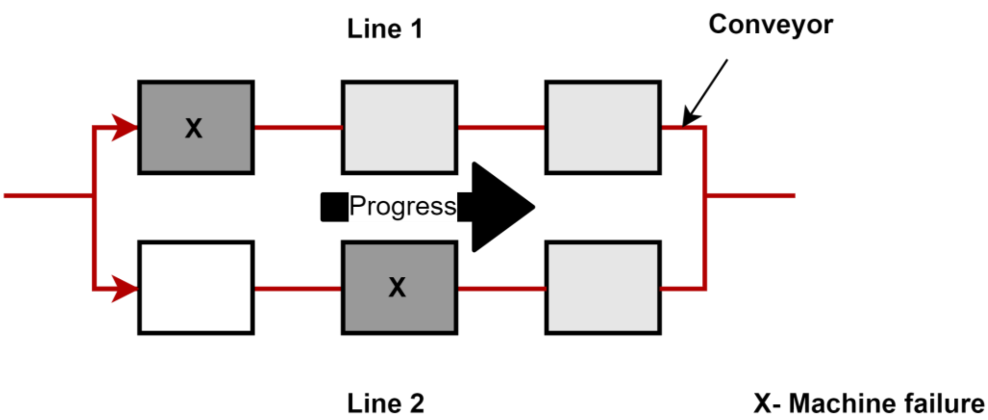

Figure 14 Configuration with no-crossovers

b. RMS configurations (with crossovers)

The configurations in which the machines are arranged in parallels-serial lines with a cross-over type of connection can be said as RMS configuration. A cross-over is where a product manufactured on a line blocked due to a failure down-stream can be transferred to another line (Freiheit T. S., 2004). Thus, each machines in the system are inter-connected. Figure 15 Configurations with cross-overshows the configuration with crossover connection. If a machine fails, the other machines still are functional and prevents the entire line from failing. This aspect isolates the machine failure and preventing the system failure. Moreover, each additional line in parallel with crossover adds less additional productivity. This productivity gain is further dependent on the machine availability. Hence, more productivity is gained from crossover when the machine availability is lower than when it is higher (Freiheit T. S., 2004). Moreover, it is important to note that the reliability of the material handling systems should remain high to realise the benefits of parallel systems configurations. For example, if an material handling equipment fails, then all the machines in that cell also will be unable to operate (Freiheit T. S., 2004). Thus, RMS configurations with cross-over connections have higher productivity rates in case of complex and large systems.

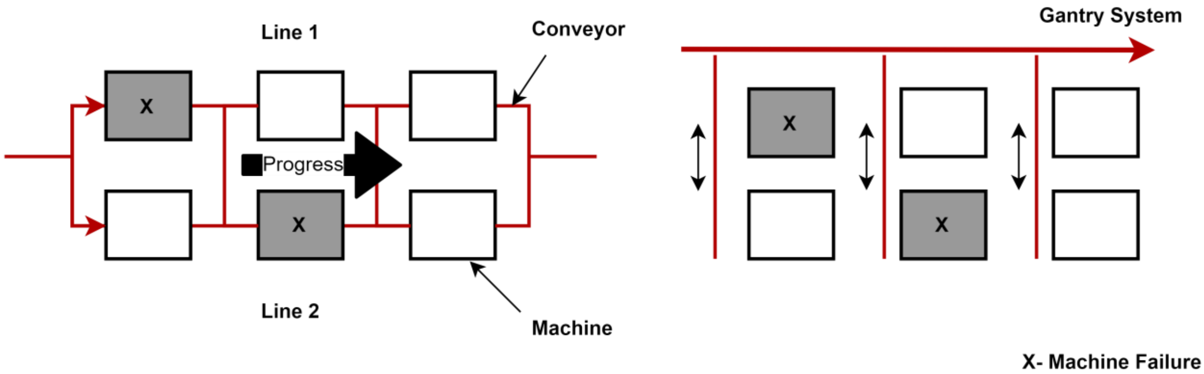

Figure 15 Configurations with cross-over

The RMS layout should be carefully planned. It should be able to adapt the product mix with changing functionality and demand requirements. Hence, it should provide ideally equal and efficient travel times for all the product families without distorting the product routing sequences. Additionally, the RMS layout design should hold a close and parallel connection with the material handling system. In multi-product multi-demand scenarios, the material handling system cannot become always available. Due to this, the prerequisite of designing each layout configuration is that the material handling system should be available with required availability rate and flexibility. Hence, the layout and the material handling system should be designed concurrently.

Hence, in large systems, with parallel serial lines with crossover type of connection, the configuration throughput improves and the work-in-process inventories reduces (Freinheit T. W., 2007).

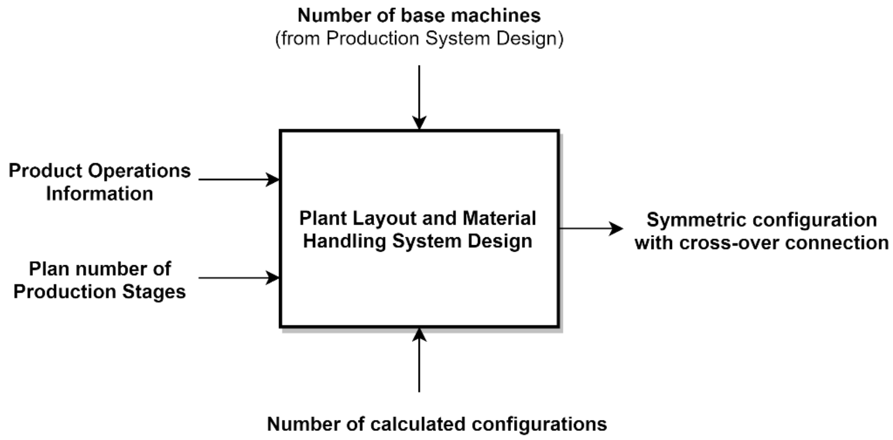

Figure 16 Plant Layout System and Material Handling System Methodology Approach

Figure 16 *shows the approach to develop the plant layout system and material handling system design methodology. From the number of base machines determined in the production system design, the number of configurations available should be calculated subjective to the number of production stages. Emphasising the complexity of the RMS configuration design around a product family with variable functionality and capacity changes, the symmetric configuration must be selected. The number of machines may be arranged in stages equal to the operation tasks of the part where each machine in a stage should perform identical machining operations. This arrangement should be followed by crossover connection, so the machine failure is isolated and the system does not fail. This integrability will facilitate responsiveness and hence will influence scalability and convertibility.*

5.3. RMS Reconfiguration Methodology

Once the RMS is design, it is required to readily reconfigure subjective to changing market requirements. The above design methodology presented merely emphasises the RMS from the design point of view. But the main aspect, the “reconfigurability of the system”, is lacking, and is a must requirement to integrate in the methodology to reach to the ultimate goal of designing the RMS.

To retain sustainable competitiveness, possessing reconfigurability becomes even more important. In addition to rapid responsiveness and lower cost, a higher reconfigurability can lead to a better performance (Koren Y. G., 2018).

5.3.1. Reconfiguration Link

A manufacturing system is said to be reconfigurable which can produce a wider range of products rather than single product and/or a with limited product families. Traditional manufacturing systems like Dedicated Manufacturing Lines (DMLs) cannot adapt to market fluctuations whereas Flexible Manufacturing Systems (FMS’s) adaptability has not been enough to respond to the increasing market changes. RMS’s do not only adapt to the product varieties but can also be open-ended to produce a new product or a product family (Mehrabi, 2002). But managing a wide variety of products in RMS is a complex task. This is due to the reason it leads a process planner to plan various ways and routes for the products to be produced in the system. So far, this approach is carried after designing a production system, which further builds pressure on a planner and can lead the system to not efficiently utilise the resources. Thus it becomes important in a reconfigurable manufacturing environment, to define the products, such that the system can be utilised efficiently. Moreover, it is important to control both the market and manufacturing requirements, where the system can be reconfigured appropriately, subjectively in terms of either capacity or functionality changes. To monitor the dynamic changes with the capacity and functionality requirements, it is important to establish an interface to group the products into families and assign particular operations to the machines, so that a system can be reconfigured and utilised efficiently.

Most of the methods presented till date for defining the products in particular families are based on operation clustering. Operation clustering is a general approach for designing the system and machine selection in manufacturing systems. Similar to this approach, a systematic methodology for automatic machining operation clustering in RMS design is presented (Ling, 2000). This methodology develops a decision support system for selecting the machines followed by an algorithm for obtaining identical parallelism-based clusters which satisfy the minimum feature spacing constraint where applicable. Similarly, a computer aided process planning (CAPP) and machine assignment system required for the dynamic nature of the RMS was developed (A. I. Shabaka, 2007). This approach selects different machines and required configurations to produce the products according to the required machine capabilities and further supports in machine selection and process planning activities.

So far these methodologies presented are developed considering a pre-defined manufacturing facility, where the manufacturing resources such as the machining systems and their module configurations are already known. These methodologies cannot be considered as a RMS system is required to be responsive to the product and market changes so that it can be reconfigured subjective to capacity and functionality changes. Attempting to develop a generic solution to the product grouping issue, different approach is required where wide variety of products can be defined and grouped before the manufacturing resources are identified. With this ideology, a methodology is presented for grouping and selecting the product families to design the RMS (M.R. Abdi, 2004). To design a RMS, the first step is to group all the general unclassified products in the family, group them into particular product families and select one product family to produce it on the system. The main idea here is to "*reconfigure the products*" which can be defined as to group products into families before manufacturing and then select appropriate family for particular production stages.

Reconfiguration Link

The reconfiguration link groups similar product demands and select appropriate families, which can be produced on production stages in the RMS design (M.R. Abdi, 2004). This link can serve as a means of linking the RMSs strategy as an input into its tactical design. In the reconfiguration link, product types are selected based on their features and market demands. The selected products are transferred to product design and development phase where the products will be redesigned based on modular structures. With this, different combinations of modules are achieved which can assist the production of different products with common resources. This modular approach of product/process design will facilitate reconfiguring the manufacturing elements in order to achieve variant modular configuration according to modular instances of products in the production stages. This can increase the adaptation to unpredictable changes in the product design and processing needs through easily upgrading hardware/software instead of replacing them. Figure 17 Reconfiguration Link for RMS design shows the methodology to define and the group the products.

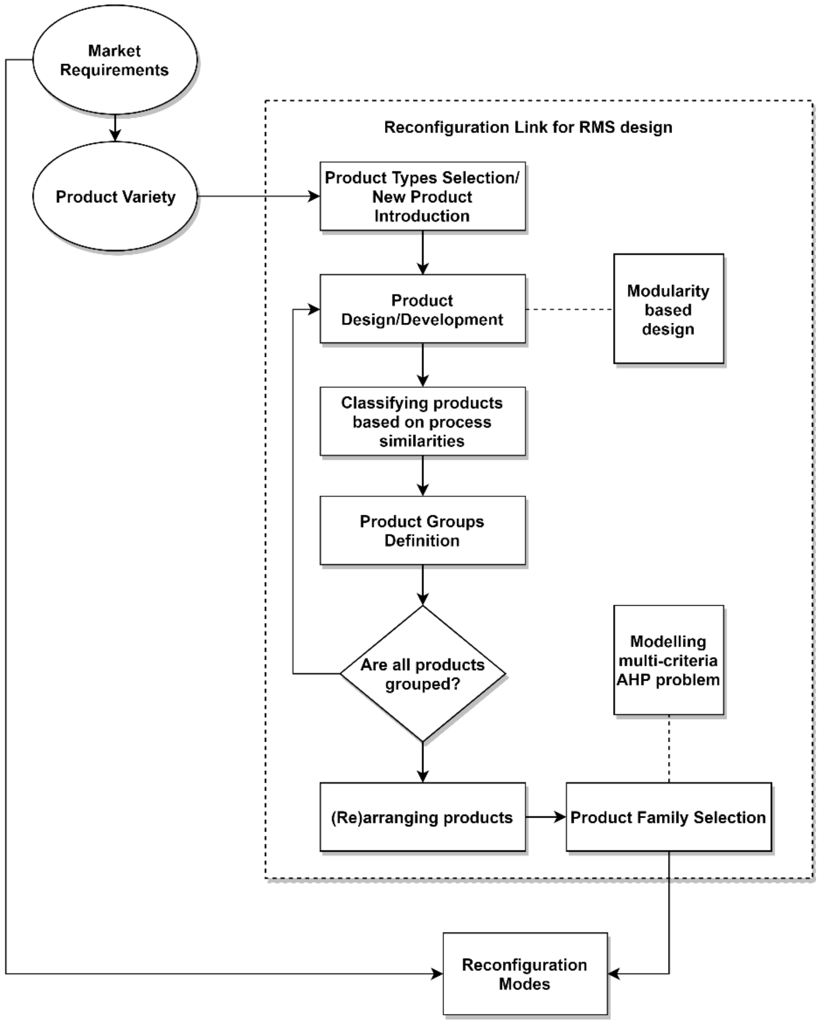

Figure 17 Reconfiguration Link for RMS design

This approach can actually reconfigure the product process design, group them together and select appropriate families in the system to assign the products based on their machining features on the production stage. This can actually reduce the reconfiguration effort, where only the module configurations will be arranged instead of relocating the machines. Thus, every new product introduced in the system must go through to the reconfiguration link and then assigned to the particular set of machines or sometimes to a new configuration design. This will establish an interface between the RMS design strategy and its tactical design through classifying the products in the product family based on the process requirements. This strategy should act concurrently and can apparently allow the process planner or the manufacturer to reassess the products by evaluating the system configurations as design outputs (feedbacks). This will allow the configuration design to be reusable. Maximising reusability can possibly arrange the products and assign them to families based on operational similarities at the most appropriate order over configuration stages. Doing so can highly utilise the production resources efficiently, and can remarkably impact in reducing the cost, time and ramp up time of the system, thus making a system highly responsive.

5.3.2. Reconfiguration Modes

A reconfiguration mode is a reconfiguration method which can be performed specifically to the changes of a product functionality or capacity changes. Generally, not in all the cases the reconfiguration link can be useful. Sometimes if there is a new product family introduced with different functionality and capacity, the existing system cannot be utilised. This can sometimes lead to design a new configuration design. These market and manufacturing uncertainties are more characterised by:

- The launch of new products part family which requires to be undertaken very quickly, and which leads to the rapid adjustment of the manufacturing system capacity to market demands,
- Rapid integration of new functions and process technologies into existing systems and
- Easy adaptation to variable quantities of products for niche marketing.

These changes are must to monitor to create a production system that are themselves easily upgradable and into which new technologies and new functions can be readily integrated. Thus, it is essential to have a close control on these conditions, to check whether the reconfiguration required is in terms of new product type, i.e. adding a new functionality or in terms of new capacity changes. If these changes required are essential, one must know their possible reconfiguration method on which the system can be reconfigured. Regarding to this approach, Table 5 Reconfiguration driver and methods describes the possible *"Reconfiguration Drivers"* and their methods are illustrated (United States Patent No. US 6349237 B1, 2002)

Driver for Reconfiguration	Reconfiguration Method
New Product Family	Design a New Reconfigurable System
Changing Product Demand	Change Incremental Production Capacity on existing system
New product within the existing product family	Add or change the product functionality
Introduction of New Product Family	Reconfigure the existing RMS system
Improved quality or productivity requirements	Integrate new process technology into existing system

Table 5 Reconfiguration driver and methods

Driver 1. New Product Family: Design a New Reconfigurable System

Every time a new product or a product family is introduced, a new RMS will be installed with the required capacity and the functionality needed for this product. Consequently, the RMS design enables the upgrading the system functionality when an additional new product is introduced.

Driver 2. Changing Product Demand: **Change Incremental Production capacity on existing system**

In a manufacturing time horizon, the production volume may substantially increase or decrease according to the initial planned capacity. To meet this changing volume requirements, the existing system might over-utilise the manufacturing resources or may be sometimes incapable of meeting the requirements. Thus, the RMS capacity might be needed to be scaled up or down subjective to the product and market information.

Driver 3: New Product within existing product family: Add or change the product functionality

In the manufacturing time horizon, a new product can be defined in the same family or an existing product goes into product re-development process. The functionality on the system is needed to be upgraded to meet the new machining operations and processing requirements. With this, the required functionality should be added or the functionality no longer required should be removed on the existing system. Thus, the system is required to be customised, by adding or replacing the modules around the new functionality requirements on the machines.

Driver 4: Introduction of New Product Family: Reconfigure the existing RMS system

Every new product family introduced in the RMS system requires reconfiguring the system. This is because both the functionality and or capacity is changing. Thus, reconfiguration activities in terms of both hard-type and or soft-type reconfiguration at the production system level, plant layout system and material handling system level are required to perform to change the existing configuration design to the new configuration design. For e.g. rearranging the machines at the system and or integrating reusable existing module with new modules at the machine level.

Driver 5: Improved quality or productivity requirements, Integrate new process technology into existing system

Today's most efficient production system can go inefficient, and can even become obsolete as soon as it goes online. Hence, this problem can be avoided by RMS, by integrating advanced components and controls in RMS, which improve the system productivity and the product part quality.

These drivers will act as a motivation to carry out a systematic design approach and control of the RMS in changing environment conditions. With reconfiguration link and the reconfiguration mode, the manufacturer can make an ideal decision on selecting the appropriate reconfiguration mode. Based on this modes, a generic RMS methodology can be developed and performed.

5.3.3. Needed Reconfiguration Level

Before actually reconfiguring an existing system, it is important to check whether reconfiguring an existing system is important or it can be reutilised. If the reconfiguration is required, then again it is important to know till what extent or at what level the reconfiguration activities are required to be performed. But more important is to understand *"when"* to reconfigure a RMS (Saad, 2003). Reflecting to this question, it can be said, that a right time to reconfigure a RMS system is when it no longer is able to fulfil the daily production volume, i.e. when the system's throughput and other performance metrics deteriorates. These performance measures are to satisfy the market demand and the management goals by making better use of resources by altering the existing configuration. It can be also reflected that, "A *Reconfigurable Manufacturing System must be also reconfigured when a new product part family is introduced"* (Yu, 2012). But practically, this might not be always a case. Hence, it is required to see the influence of the market on the manufacturing system and management, so that the reconfiguration effort required can be measured to make a wise decision of reconfiguring the system or not.

Few authors suggested a design strategy, by analysing the traditional manufacturing systems with the manufacturing objectives and firm's competitive criteria. An Analytical Hierarchical Process (AHP) was framed to validate the selection of the preferred manufacturing systems (Abdi, 2004). But this method was merely for selection of the preferred manufacturing systems rather than estimating the reconfiguration effort. *Matta et. al* (Matta, 2008) proposed an optimal reconfiguration policy to react to product changes based on uniformly distributed market demand and technological requirements. *Meng et. al* (Meng G. H., 2004) introduced a layout system as a reconfigurable layout problem. Assuming that the production data are available only for the current and upcoming production period. The main issues of selecting a suitable type of layout for components of a manufacturing plan were analysed using the AHP.

Surveying through these methodologies, most of the work presented did not consider measuring the reconfiguration effort at a complete plant level. From the design of the RMS, it is clear that a RMS system is completely integrated at the production system level, plant layout system level and material handling system level. Additionally, *Garbie et. al* (Garbie I. P., 2008) suggested that the Agility Level along with the design and managerial aspects are the most important factors to consider in measuring the reconfiguration effort, and hence presented a new measurement methodology of a Needed Reconfiguration Level for manufacturing firms based on the current agility level of the plant and the status of the manufacturing system design. Later, this methodology was further developed, emphasising the measurement of the reconfiguration effort in the RMS by taking into consideration the globalisation issues and aspects (Garbie I. , 2014). Thus, this methodology is adapted to develop the framework to measure the Needed Reconfiguration Level in changing configuration periods.

The Needed Reconfiguration Level (NRL) is a configurability index associated with the Production System Level, Plant Layout System Level and Material Handling System Level. The NRL is evaluated based on managerial, manufacturing and market criterion. These are based on the elements such as Agility Level (AL), the current state of Manufacturing Systems Design (MSD) and the New Circumstance (NC). The elements are evaluated based on the manufacturer's preferences and are compared pair-wise and are framed using Analytical Hierarchical Process (AHP) to measure the NRL, i.e. the level of reconfiguration required. With these approach, the analysis of the manufacturing firms to measure the NRL is presented in brief.

Analysis of Manufacturing Firms to measure NRL

The analysis of the manufacturing firms includes the Agility Analysis, Manufacturing System's Design Analysis and New Circumstance Analysis.

1. **Agility Analysis**

The effect of the agility level plays a very important role in evaluation of manufacturing firms. (Garbie I. , 2014). This evaluation is based on four elements such as Technology Infrastructure (TE), People Infrastructure (PE), Management Infrastructure (MA) and Manufacturing Strategies (M). These elements play an important role in enhancing the agility of the manufacturing system. Technology is one of the fundamental reasons to enhance agility as it concentrates on what modifications it can allow. Respectively to people, the education and skills of the workers plays an important role. A manufacturing firm can be referred to a continuous learning and knowledge development organisation based on the knowledge of the employees. For management, the analysis can help to maintain or improve the firms Key Performance Indicators such as the productivity, introduction of new products and new products produced, planning, scheduling, quality control, etc. Whereas, analysis of manufacturing strategy is related to the present and the future of modern manufacturing strategies, for e.g. strategic thinking, strategic learning and strategic planning.

With respect to these four elements of the agility level, one can determine the agility level of the reconfiguration alternative. To determine the agility level for the reconfiguration, the manufacturer should set the required agility level to reconfigure the system based on the manufacturer's and the upper level management's preference. For e.g. if the current agility level of the Technology Infrastructure is 25%, and the required Agility Level for reconfiguring the existing system is 80%, then the agility level required for reconfiguration is 80-25=55%. The 55% is called as the Needed Agility Level (NAL) for reconfiguring the system (Garbie I. P., 2008).

2. **Manufacturing System Design Analysis(MSD)**

The manufacturing system design (MSD) in manufacturing firms include several factors such as production machines, material handling systems, plant layout, computerised network and human force. These elements are categorised in three important elements:

- **Production System Size and Functionality (PSS & F)**

A production system consists of one to several machines (workstations). These production systems are can be a production line, assembly line, cellular system, flow shops, job shops, etc. depending how the machines are arranged. The production systems are associated with several factors such as types of operation, number of machines, number of shifts, number of working hours, etc. To reconfigure an existing system, the company will reutilise the system's resources of the existing system to form a new configuration design. The efforts involved in reconfiguring this system depend on the production system size, its arrangements and the functionality (Garbie I. , 2014). Accordingly, the Production System Size and Functionality (PSS & F) is categorised into Small Sized, Medium Sized and Large Sized production system sizes. Moreover, each system depends on the machine capacity, machine capability (flexibility) and Machine Utilisation and Availability. These elements are structured in Figure 18

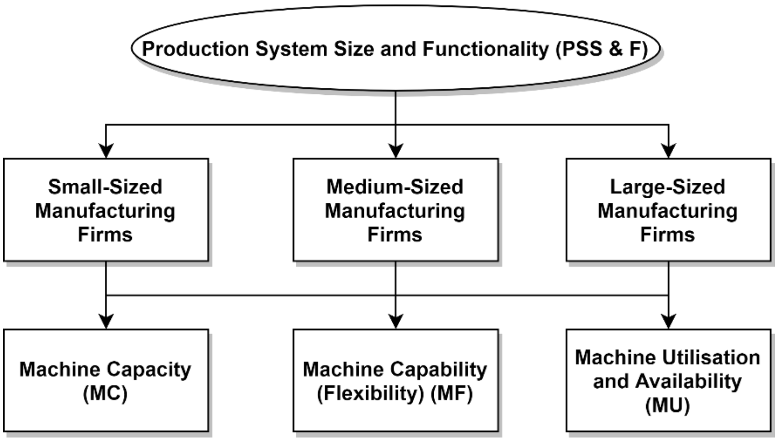

Figure 18 Elements of Production System Size and Functionality (PSS &F)

With this, the relative weights of each criterion by the decision makers or groups of decision makers and then pair-wise comparison can be performed to estimate the value of PSS & F.

- **Plant Layout System**

Perhaps the most popular criterion used to design the plant layout system is to minimise the objective of the distance travelled. Without no doubt, it can be said that minimising the distance will minimise the material handling cost. But, minimising this distance, in case of reconfigurable manufacturing system, can sometimes create congestion in a concentrated are and can possibly increase the complexity of the Material Handling System (MHS). This is because the system elements, for e.g. the machines in the system can be converted from one location to another (convertibility), or an additional machine can be added (scalability) where there is a reserved spot. Additionally, it should be taken into account that the layout is flexible enough to accommodate changes such as product design, process design and schedule design while carrying out the reconfigurability of the system. So, the pre-requirement of designing the layout that it fulfils the current requirements and also anticipates in the possibility of future expansion.

As shown in Figure 19, There are three general Plant Layout System types, Cellular layout (CL), Product Layout (PL), Functional or Process Layout (FL) (Garbie I. P., 2008). The CL is required to be selected. If it is a PL or FL, it should be converted in CL.

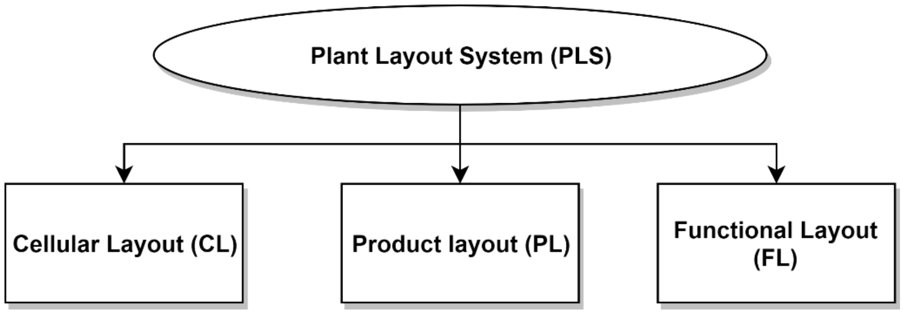

Figure 19 Elements of Plant Layout System (PLS)

- **Material Handling System**

The material handling system is the backbone of a manufacturing system. Choosing a right type of handling methods and right equipment is an integral part of layout design. Thus, it is extremely important to integrate effective material handling methods and equipment in the layout. Designing and reconfiguring the material handling systems follow the same principles as reconfiguring the plant layout systems. The MHS requires a high degree of familiarity with the types, capabilities, limitations and cost of material handling equipment. Moreover, the PLS is highly dependent on the MHS. No other activities can affect each other as much as plant layout system and material handling system. Thus, in the process of reconfiguring the system, it is very important to consider the PLS and MHS concurrently.

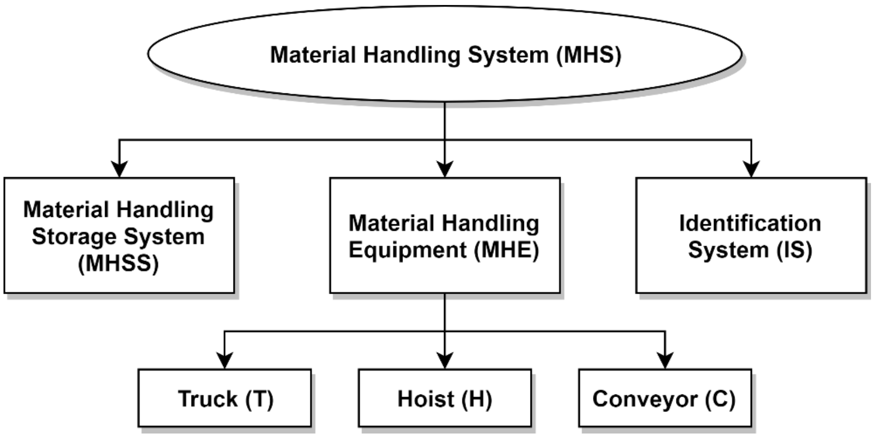

Figure 20 Elements of Material Handling System (MHS)

As shown in Figure 20, MHS is divided into Material Handling Storage System (MHSS), Material Handling Equipment (MHE) and Identification System (IS). Further, the MHE is characterised by based on the application serving between fixed points or fixed paths (e.g. conveyors, Hoists for limited areas, or Truck for large areas).

3. New Circumstance (NC)

The New Circumstance (NC) plays an important role in measuring the reconfiguration level. This factor highly influences system design and its reconfiguration. The market circumstance is categorised in three elements: New Product (NC), Product Development (PD) and Changing Demand (CD). The reconfiguration activities needed to be performed are directly dependent on these circumstances (Garbie I. , 2014). For New Product or New Product family, a new RMS configuration is required to design. For Product Development, necessary functionalities are required in the production system. It required adding a new functionality on the production systems or removing an existing one. The CD brings the necessary changes required to increment the production capacities. Thus, these three elements highly impact the amount of reconfiguration activities required to be performed.

AHP is an effective approach to determine the NRL (Garbie I. , 2014) *With the AHP process, the Agility Analysis, status of Manufacturing System's Design and the New Circumstance can be analysed to measure the NRL. A relative weight can be determined for each element by pairwise comparisons. This can facilitate a manufacture to make appropriate decisions to evaluate these factors and can provide an understanding whether a reconfiguration is required or the existing system can still sufficiently meet the production requirements. Thus, determining the NRL provides a clear understanding beforehand, what will be the reconfiguration effort involved in reconfiguring the system and till what extent and at what level the reconfiguration activities, such as at the production system level, or plant layout and material handling system is required to be performed. This approach can sometimes eliminate the need to reconfigure a system and can substantially save the reconfiguration time, cost and ramp up time.*

5.3.4. Reconfiguration Process

Based on the measure of the NRL value, a manufacturer can decide whether reconfiguring an existing system is required or not. If reconfiguration is required, a manufacturer is required to (re)design or reconfigure the existing system. This (re)design can be called as Reconfiguration Process. Subsequently, the reconfiguration process is required to carry out systematically at the production system level, i.e. at a system and machine level, plant layout system level and material handling system level.

Concerning to *"when"* to reconfigure a RMS system, *Saad et. al* (Saad, 2003) also highlighted the other major issue, *"how"* to reconfigure a RMS system. Saad et. al conveyed that the reconfigurability aspects in designing the RMS are missing. Concerning these issues, a multi objective taboo search simulation optimisation model which generates possible Virtual Configurations subjective to required performance measures was presented (Saad, 2003). As this presented method contained of highly programming data, it cannot be considered as a decision support method. Relatively, from the literature point of view, it can be said that the other methodologies are presented responding to the changes and from the reconfigurability point of view, such as modelling the sequential production stages, restructuring, simulation and reprogramming of the manufacturing system, which are again too complex to understand.

To reconfigure a RMS system, it is important to consider the scalability and convertibility, as these characteristics are the essential reconfiguration characteristics, as explained in chapter 4, section 4.1.3. Additionally, one of the important characteristic to consider is the customisability, as customisability further enhances the reconfigurability. Incorporating these characteristics, a reconfiguration process can be attempted to develop from the reconfigurability point of view. But, it was observed that only developing a reconfiguration process from the design and reconfigurability point of view is not important, but it is also important to control the RMS process and monitor the system performance in the changing manufacturing environment. Concerning to these issues, *Garbie et. al.* (Garbie I. , 2014) supported these issues and also suggested that it is important to design the manufacturing system with considering some flexibility, in terms of functionality and capacity around a product part family. Additionally, it is important to monitor these flexibilities such that the system is responsive to internal product functionality or capacity changes, ensuring there is no excess flexibility in the system which can create capital waste.

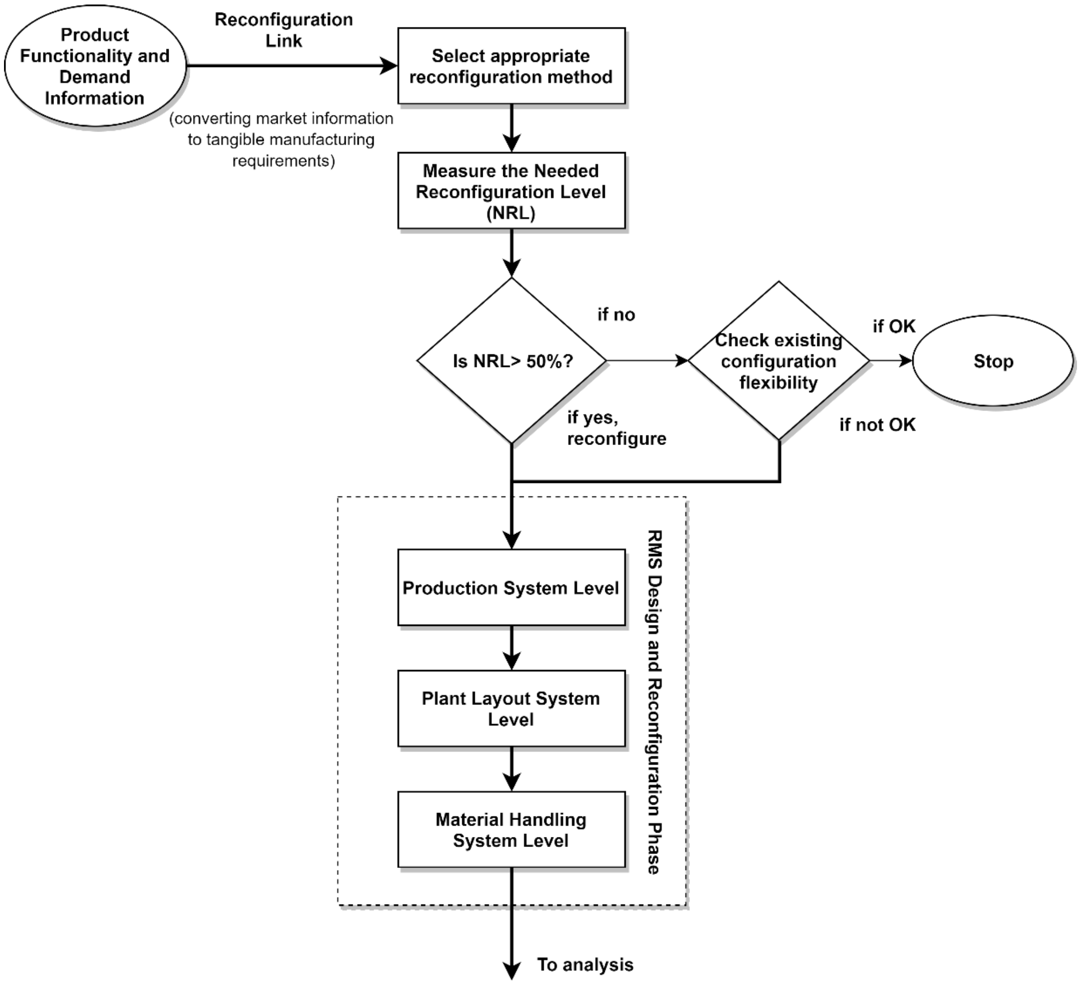

Figure 21 Approach to develop the RMS methodology (Reconfiguration Process)

Concerning the essential reconfiguration characteristics, scalability, convertibility and customisability, an improvised reconfiguration process is developed, as shown in the Figure 21*. Firstly, the Product Functionality and Demand Information will be acquired, which is the market requirements. These market requirements will be converted into tangible manufacturing requirements, such as for determining the number of manufacturing equipments, assigning the operations and scheduling the operations on the RMS configuration as explained in section* 5.3.1. Reconfiguration Link*Subsequently, based on this information, an appropriate reconfiguration method, as explained in section* 5.3.2. Reconfiguration Modes*, will be selected. This reconfiguration method is the guide to (re)configure the reconfigurable manufacturing system based on either the capacity and or the functionality requirements. Succeeding, to ensure if a reconfiguring an existing configuration is required, the measure of the reconfiguration effort, i.e. Needed Reconfiguration Level, as explained in section* 5.3.3. Needed Reconfiguration Level*will be measured relative to the existing system configuration. If the NRL is greater than 50% or as per the management preferences, the current configuration will be reconfigured to a new reconfiguration design. The next step is redesigning the system.*

The redesign is performed by designing a modular and scalable production system, as explained in section 5.2.1. Production System Design*, by determining the base machines and module positions on each base machine. Subsequently, after determining the production system resources, the next step is (re)designing the plant layout system and material handling system, as explained in section* 5.2.2. Plant Layout System and Material Handling System Design*A symmetric configuration design with cross-over* *material handling connection system will be designed. The system will be designed around a product part family, ensuring that the system flexibility is around the product family, which can anticipate the future functionality and capacity requirements within the same product family. Lastly, the available (re)configuration designs will be analysed further based on manufacturing objectives, which is explained in next section* 5.4. Implementation

5.4. Implementation

After performing the reconfiguration process for designing or reconfiguring a RMS system, there will be many candidate (re)configurations designs (cell layouts) available. These configurations are required to analysed based on the manufacturer's preferences and the configuration's performances. With this approach, an ultimate configuration design can be proposed based on the satisfying performance measures involving minimum reconfiguration effort. To do so, the methods available on the analysis of the RMS configurations are researched and selected.

5.4.1. RMS Configuration Analysis

A RMS involves numerous candidate configurations. These configurations include symmetric and asymmetric configurations, as explained in above section 5.2.2. Plant Layout System and Material Handling System DesignA symmetric configuration must be selected. But, one of the major aspects and a pre-requisite is to check whether these symmetric configurations are balanced or not. An unbalanced configuration means that it will have bottlenecks in any of the production stages and will not be able to fulfil the daily production volume. The machines and modules are considered with similar reliability and availability rates. But, in a real manufacturing environment, it is obvious that the machines and the modules will have different reliability and availability rates, thus, checking the system balance is an important aspect.

The inputs required for line balancing are the cycle time of machining tasks, task precedence and setup constraints for each operation. The term "cycle time" in this context means the tool-to-tool time, i.e. the time taken to produce a product from one machine tool to another. This cycle time consists of the time taken by a cutting tool from being installed the spindle, to finishing the machining cycle and the tool being returned to the tool pallet. With evaluating the configurations with the system cycle time and the production stage cycle time, the remaining RMS configurations are analysed based on the performance measures (Freinheit T. W., 2007)

A brief overview of the performance measures of the RMS is presented. In order to evaluate the RMS configurations, one must evaluate the configurations based on the throughput, scalability, quality and number of product variations that can be produced and system conversion time between the products. These measures have a profound effect on the configuration and can influence the life cycle cost of the system (Koren Y. J., 1998). Based on this information, the system's throughput with reliability less than 100% is the most important factor to evaluate the RMS configuration (Koren Y. S., 2011). Along with, other factor such as Investment Cost, Scalability-the smallest increment gained of production capacity by adding a machine and floor space should be considered. With this information, the configuration analysis approach is developed, as shown in Figure 22. The candidate configurations will be analysed subjective to high throughput rate, high scalability percentage, low investment cost and low floor space. These factors are further explained in detail.

The *"throughput rate"* of a manufacturing system is defined as the long-run average production of a system, which is the number of units produced over a given period of time. When examining the throughput rate, the system cycle time is determined, which is the ratio of the daily units to the available machining time per day. With this the bottlenecks in the stages are examined, if the stage cycle time is high in comparison with the system cycle time.

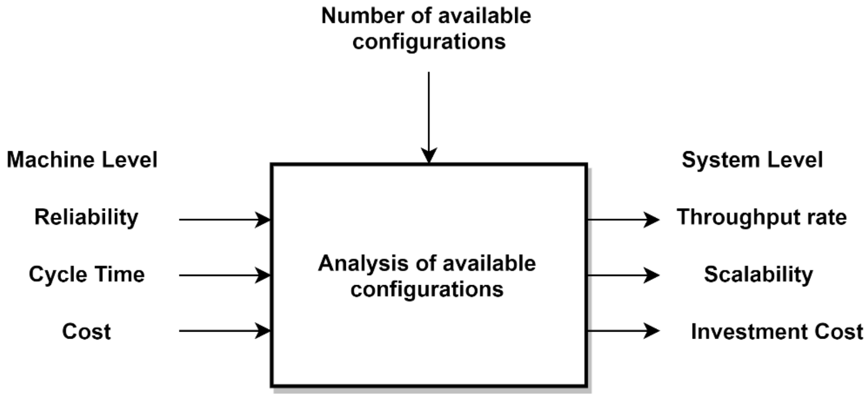

Figure 22 Configuration Analysis Approach

To adapt the throughput of the RMS to the fluctuations in product demand, the system capacities must be adjusted quickly and cost-effectively (Wang, 2012). Capacity scalability of RMS is a necessary characteristic needed for rapidly adjusting the production capacity in discrete steps, allowing thereby a given systems' throughput to adjust from one yield to another to meet the changing demand requirements. This scalability is defined as:

$$Scalability = 100 - smallest\ incremental\ capacity\ in\ percentage$$

If the minimal capacity increment by which the system output can be adjusted to meet the new market demand is small, then the system is said to be highly scalable (Wang, 2012). The rest of the factors are the investment cost, which is the total cost of the manufacturing equipments in the system and the material handling costs, and floor space, which is the area of the configuration length and breadth.

Theoretically, the above factors are important to make a wise decision for analysing the configurations. But in a practical case, the investment costs should also include the labour, tooling, utility, floor space, operating costs, etc. (Wang, 2012).

5.4.2. RMS Reconfiguration Analysis

Implementing an existing configuration from the set of possible configurations is a critical issue. Analysing the configurations based on their performance is important but it becomes necessary to know how easily and quickly one can perform reconfiguration activities to see how rapidly the system can become stable. Due to highly changing conditions in the manufacturing environment, it is necessary to choose a system such that the system can be made rapidly responsive in terms of ramp up time. Thus, during the reconfiguration of the RMS system, it is necessary to indicate the manufacturer to choose a RMS configuration with respective to Ramp Up time and Reconfiguration Time and Reconfiguration Cost.

One can analyse the available configuration based on the reconfiguration analysis. A similar approach related to reconfiguration analysis was found. This paper presented a methodology to design economical reconfigurable machining systems (Son, 2000). This methodology generates a configuration path for the changing demand as well as cost for each demand period. This method utilises a Genetic Algorithm (GA) approach based on the level of similarity index between any two configurations. This similarity index defines the common resources among two configurations, and defines precedence relationship between operations and subsequently assigns operations to the stations. Thus, it rather changes the machining operations on a Reconfigurable Machine (RM) rather than providing any information of reconfiguration effort required or reconfiguration strategy on the whole system level and the objective of minimising this effort. Later, *Moon et. al*. suggested that one must develop a "*reconfigurability index*" (Moon, 2006). But, this suggestion was valuable only around a Reconfigurable Machine Tool (RMT's), which is again just at the machine level. Supporting to Moon et. al methodology, a reconfiguration analysis methodology was presented (Mittal, 2014). This method presents a solution regarding different operations that can be performed for different auxiliary modules for a machine configuration while carrying out reconfiguration planning. Yet again, this method just focussed on the reconfiguration effort required at the machine level and did not considered the reconfiguration effort required at the system level.

From these above methodologies presented, it can be strongly reflected that the reconfigurability index or the reconfiguration of the RMS system is not only associated with the machine level but also at the complete production system level, plant layout system and material handling system level. This is because, the RMS system is designed is such a manner that each individual machine in a production stage are internally connected to each other and with the material handling system. Any reconfiguration activities performed on the machine level, will also include performing reconfiguration activities at the system level and material handling system level. Thus, the reconfiguration planning should be associated at the complete level, i.e. production system level, plant layout system level and material handling system level to change an existing configuration to a new configuration. Performing reconfiguration activities can involve huge amount of reconfiguration effort. Moreover, the manufacturer must know how to reconfigure the system. For e.g. from which stage the machine should be removed, which machine should be reconfigured and the objective of minimising this effort.

Youssef et. al. presented a method of how to reconfigure the system and how to measure the reconfiguration effort (Youssef, 2006). A Reconfiguration Smoothness Value (RS) was developed to measure the effort required to change one configuration to another. This RS value associated to three different levels of reconfiguration, the market-level reconfiguration smoothness, system-level reconfiguration smoothness and the machine-level reconfiguration smoothness. Further, these metrics are associated with weights reflecting to the cost, time and the effort required to perform the reconfiguration activities in the reconfiguration process. Generally, all the soft and hard reconfiguration effort at the levels of the reconfiguration are considered which are involved in a real manufacturing environment. Hence, this metric developed can potentially be a powerful relative assessment tool for the transitional smoothness between the configurations.

Following this approach evaluates the closeness between two configurations and can assist a manufacturer to select the configurations based on the amount of reconfiguration effort involved at the beginning of each reconfiguration period. Thus, this approach is considered to evaluate the effort and select the reconfiguration design based on the reconfiguration smoothness value.

5.4.3. Proposing a RMS configuration

After the design or reconfiguration analysis of the available RMS configurations, the next step is to propose a desired configuration layout based on low Reconfiguration Smoothness Value along with other objectives such as the configuration high throughput rate and high scalability rate. The RS value should be much emphasised. This is because the RS is a relevant measure respective to cost, time and effort required. The low the RS value, the lower will be the ramp up time, thus making the system to be rapidly responsive. Responsiveness in RMS should be given high priority. Performing more reconfiguration activities can make the system take much time to be responsive to meet the market requirements. This will make the system involve more time to meet the market requirements and hence losing the market grip. Thus it is important to select the configuration which has less time, and can eventually reduce the ramp up time of the system, further minimising the production wastage

Although the candidate configurations designs will be analysed respective to the Reconfiguration Smoothness Value and throughput rate, it is also important to calculate the real daily production phase costs and production time to monitor the daily requirements. This is because, the RMS system is designed for multiple product families. Additionally, the machines are reconfigurable in the nature and offer varied functionalities in their different configurations. Choosing the number of different machines with different configurations can make it complex to assign the operation to the machines and schedule the operations in order to minimise the completion time and cost of the entire schedule.

Moreover, due to the dynamic product and market changes, the products is sometimes requested quickly to satisfy the market. For example, when a new phone is launched, the market becomes excited. Although the price is high, the customers want the phone quickly. But after sometime the market becomes steady, the demand reduces and proportionally the prices also reduce. It is obvious that when the market demand is high, all the machines in the system are working at high capacity, which leads to high product costs. But in case of multiple product part families with variable demand sizes, it is important to monitor the product manufacturing costs and its manufacturing time. Concerning, it makes the user to select different machines in the system with different module configurations such that a fast production system with high production costs or a slow running production system with averagely production costs can be selected. Thus, to enable these requirements, the production phase cost and time is required to be determined so that a manufacturer can know the cost of the set of machines selected to manufacture particular product families.

Bensmaine et. al. (Bensmaine, 2013) proposed an approach of machine selection based on the assignment of each operation and the scheduling of operations. These objectives are minimisation of total cost of the production phase and total completion time of a product. The total cost emphasised on production cost, reconfiguration cost, tool changing cost and tool usage cost while the total completion time emphasised the machine usage time, tool usage time, configuration change time and tool change time. This proposed technique can give a manufacturer to select a desirable configuration as well as it can also potentially make a manufacturer to decide which machines should be selected based on the process plans of the products. Although the approach is for machine selection through developing a simulation model, it is reframed analytically and attempted to select the desired configuration from the set of configurations. As the number of machines and tools determined are according to the product functionality and the demand requirements, the manufacturer can select all the machine and tools in the configuration or can select set of feasible machines required if in future, respective to product functionality or demand changes.

With this approach, the reconfiguration process approach is developed. Figure 23 *shows the reconfiguration process. After the (re)design of the production system, plant layout system and material handling system, the available candidate (re)configurations will be analysed based on the Reconfiguration Smoothness value along with the other performance measures such as the high throughput rate, high scalability percentage, low investment cost and low floor space, as explained in section* 5.4.1. RMS Configuration Analysis*and* 5.4.2. RMS Reconfiguration Analysis *Based on the configuration satisfying these objectives, a configuration will be proposed with the total cost and time based on the products operations assigned, as explained above. With this approach, the reconfiguration process is developed, presented in the next chapter.*

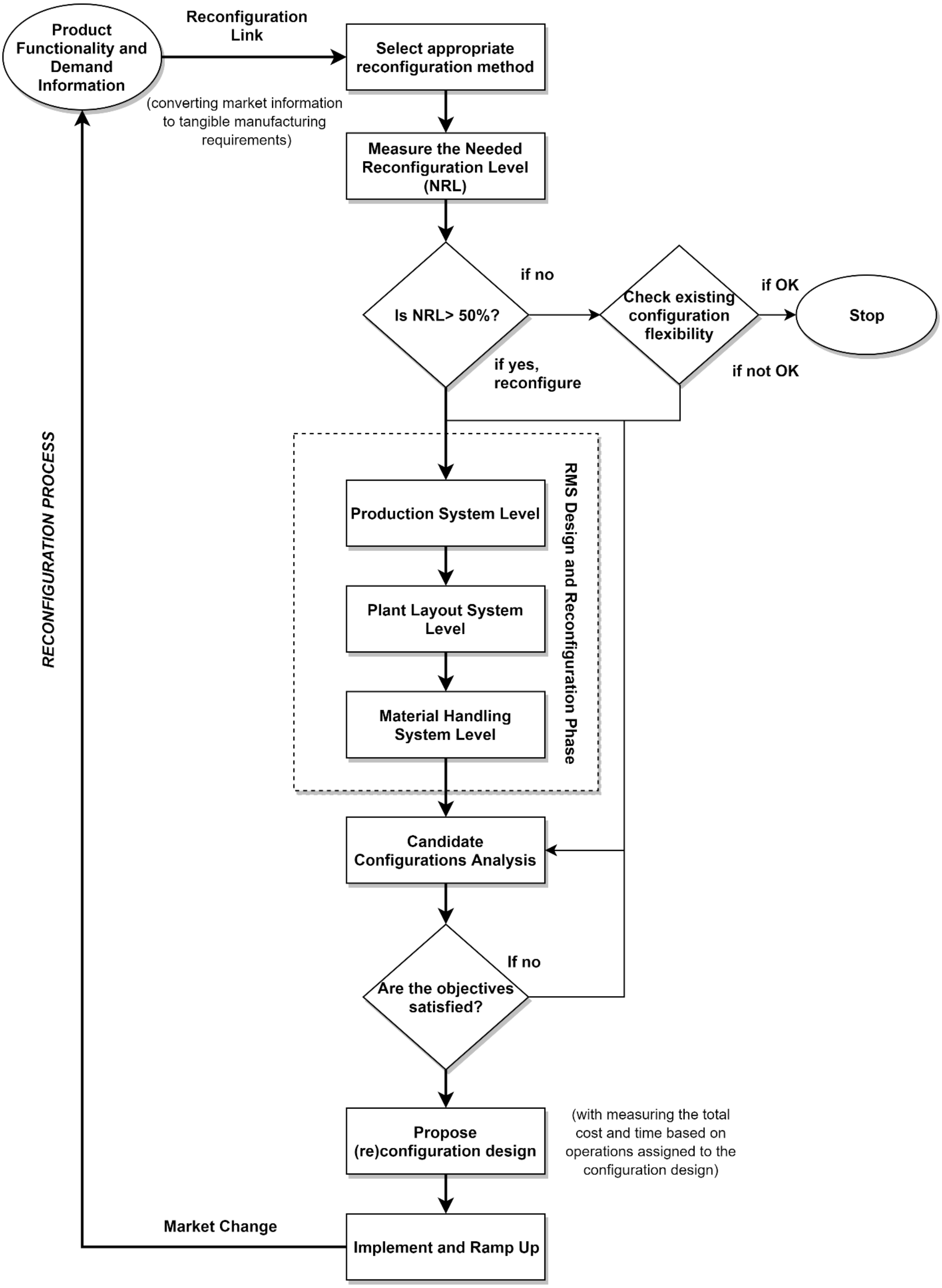

Figure 23: Approach to develop RMS methodology (Reconfiguration Process)

5.5. Conclusion

To develop a methodology to design the RMS, it is important to consider the (re)design aspects, operations management and life cycle costs around a product part family with respective to the changing market requirements. The life cycle cost analysis can provide justification if investing in RMS system is suitable for current needs in comparison to traditional manufacturing systems. The system should be designed considering modularity and integrability, i.e. independent base machines and modules which will act as configuration drivers. To (re)configure the RMS system, a reconfiguration link is important to connect the reconfigurable manufacturing system environment and market environment. This will closely monitor the market needs, configure the product-process design and will assist in reconfiguring the system respectively. Thus, a RMS can be reconfigured be measuring the Needed Reconfiguration Level (NRL), and an existing configuration can be scaled, converted and customised to the new market requirements. Succeeding, the candidate (re)configurations designs will be analysed based on the Reconfiguration Smoothness value (RS), which is a relative measure of the reconfiguration time, cost and ramp up time and other system performance measures. Finally, the candidate configurations with low RS value, high throughput rate, high scalability rate, low investment cost and low floor space will be proposed.

Chapter 6: Reconfiguration Process

This chapter presents the decision support methodology to design the Reconfigurable Manufacturing Systems (RMS). This methodology is called as Reconfiguration Process. As explained the procedure in previous chapter 5, section 5.1., in this chapter Section 6.1. presents a quantitative approach to develop the methodology for Life Cycle Economic Analysis Model (LCEAM). Subsequently, according to the procedure explained in previous chapter 5 Section 5.2, Section 5.3. and Section 5.4, a qualitative and quantitative approach in section 6.2. is presented to develop the Reconfigurable Manufacturing System Design Model (RMSM), i.e. the reconfiguration process.

This chapter answers the following research question:

1. *When and how a Reconfigurable Manufacturing System should be designed and reconfigured?*

6.1. Life Cycle Economic Analysis Model

The Life Cycle Economic Analysis is an economic justification to decide if a RMS is a right investment for the required market requirements. Three technological solutions such as Dedicated Manufacturing Lines (DML), Flexible Manufacturing System (FMS) and Reconfigurable Manufacturing System (RMS) are considered to manufacture a product family. The first one is the DML, where each product requires a particular dedicated line. For each new product introduced, a new line must be built. This system operates at its maximum capacity, and if additional capacity is required, again an additional line might require. Secondly, a FMS is considered, which consists of general purpose machine able to perform all the technological operations required to produce wide variety of products. Thirdly, a RMS is considered, which consists of shells (machine blocks independent of modules) that hold particular module configurations able to produce a product family.

The objective, in this subsection, is to compare these three systems from an economic point of view, emphasising the traditional Net Present Value (NPV) and the expansion cost to increase the capacity of the system at a certain time of investment. Further assisting a manufacturer by providing an understanding of the economic convenience and to suggest under what circumstances a RMS is preferable.

The Life Cycle Economic Analysis model is designed with solving simple static allocation models as explained in previous section 4.1., which determine the manufacturing elements, such as the number of minimum lines in DML system, number of minimum CNC machines in FMS systems and number of minimum shells and modules in RMS system. To begin with the model, the following are the notations used in common for all the three systems;

- S System index representing DML, FMS and RMS;
- i product index varying from 1 to I;
- j production period index varying from 1 to J;
- r capital interest rate for each period;
- A number of time units available for manufacturing within each period j;
- D_{ij} market demand for the product i in the period j;
- WL_j^S work load of the system for manufacturing the product I over DML;
- CM contribution margin of the products, i.e. the selling price per unit minus the variable cost per unit;
- V_{ij}^S production volume of the product i in the period j, for the system S;

For a DML system, the capacities and the cost of each particular line, according to the product it is manufacturing is assumed (Amico M. A., 2006). Each line here consists some set of machines with particular modules on it required to produce one particular product.

DML	Sub-system 1	Sub-system 2	Sub-system 3
Yearly throughput(parts/year)	48,000	32,000	20,000
Cost of one line (Euros)	300,000	250,000	200,000

Table 6 Capacities and Costs of DML lines

In order to plan the DML investment over J periods, the following mathematical formula is used, with the objective of maximising the NPV (Bruccoleri, 2006):

$$NPV^{DML} = \sum_{j=1}^{J}\sum_{i=1}^{I}\frac{-L_{ij}^{DML}\,.\,C_i^{DML}+V_{ij}^{DML}\,.\,CM}{(1+r)^{j-1}} \quad (6.1.1)$$

Where,

- DML_i the specific dedicated line for producing product i;
- C_i^{DML} the investment cost for purchasing DML_i;
- L_{ij}^{DML} the number of DML lines purchased in the period j;

Under the following constraints:

$$(\forall i,j)\ V_{ij}^{DML} \le D_{ij}, \quad (6.1.2)$$

$$(\forall i,j)\ V_{ij}^{DML} \le L_{ij}^{DML}.Cp_i^{DML} \quad (6.1.3)$$

Where,

- Cp_i^{DML} is the maximum number of product a DML line can manufacture in the period j, when the number of units available for manufacturing in period j and the maximum machining time at the bottleneck station is known.

The decision variables are the L_{ij}^{DML} and V_{ij}^{DML} respectively. Hence, it is straightforward that the optimal volumes are $V_{ij}^{DML} = \min\{D_{ij};\ L_{ij}^{DML}.Cp_i^{DML}\}$, and therefore the decision variables are just the L_{ij}^{DML}.

To assume the capacities and the machine costs in FMS and RMS systems, a parametric approach is introduced. The parametric approach lies on the attempt to formalise FMS and RMS capacities and cost factors on the basis of DML system's capacity and costs. In order to make a parametric approach, two technological factors are introduced (Bruccoleri, 2006) (Amico M. A., 2006) :

- $\boldsymbol{\alpha^s}$ is a technological factor relating FMS and RMS to a DML from the ***"processing point of view."*** This technological factor takes into account that a more flexible machine requires longer machining times to perform the same technological operations. This implies that the throughput of a flexible system is lower than that of a dedicated line.
- $\boldsymbol{\beta^s}$ is a cost factor relating FMS and RMS to a DML from *"**investment cost point of view**."* This cost factor takes into account that more the flexible the machine is, the higher is the investment cost.

As discussed in previous chapter section 5.1., different constraints are presented in two literature articles. *Bruccoleri et. al*. (Bruccoleri, 2006) highlighted the NPV of a FMS system by considering the α^{FMS} within $0 < \alpha^{FMS} \le 1$ and β^{FMS} within $0 < \beta^{FMS} \le 1$ in comparison with DML. And for RMS,

α^{RMS} within $0 < \alpha^{RMS} \leq 1$ and β^{RMS} within $0 < \beta^{RMS} \leq 0.5$ in comparison with DML. Through these constraints, it can be understood that, as higher the capacity or the functionality of a machine in an FMS system, the proportional will be its cost. Moreover, as higher the capacity or the functionality of a machine in an RMS system, it is not necessary that the cost will be as high as the functionality. It can be assumed that this relation is defined based on the number of base machines and the number of modules on it, where the costs will be less due to its reconfigurability and reusability.

In another article, Amico *et. al.* (Amico M. A., 2006), defined different constraints ranges. For capacity factor, the capacities for the machines in the FMS system (CNC machines) and the base machines in the RMS system, the α^{FMS} and α^{RMS} are by considering the capacity factors in comparison with DML within $0 < \alpha^{FMS,RMS} \leq 1$. And in case of cost factor, for β^{FMS}, the cost factor was constrained within $0.5 \leq \beta^{FMS} \leq 1$. This is due to the reason that to manufacture the same mix of products, the investment cost of a more flexible system is higher than the maximum cost of a single DML line and lower than the summation of all the DMLs investment costs. Additionally, the cost factor for the RMS, $\beta^{FMS}$is constrained within $0 \leq \beta^{RMS} \leq 1$. This is due to the reason that, in case of a RMS, the cost of a base machine can be easily be lower than the cost of a DML. Thus, this work varied the parametric values within the constraints and just proposed the highest NPV value irrespective of a reasonable parametric relationship values between both, the FMS and RMS systems. Based on this approach, it is hard to conclude the NPV of the systems. For example, proposing the NPV at $\alpha^{S} = 1$ and $\beta^{S} = 0.5$ because it shows highest NPV (Amico M. A., 2006). But it can be reflected that the throughput rate (capacity) of any manufacturing system, in general, is proportional to its cost. The more the capacity of a machine, the higher is its purchasing cost. Thus, with no parametric relationship defined among the RMS and FMS systems, new relationship is defined and the approach is improvised.

To determine the NPV of the RMS and FMS systems, the manufacturing equipments required in the RMS system will be determined. This will be determined by the Reconfiguration Manufacturing System Design Model (RMSM) explained in the next section. Acquiring the design variables (manufacturing equipments) from the Reconfiguration Design Model, these variables will be used as an input to Life Cycle Economic Analysis model to determine the correct NPV values of the RMS and FMS systems.

Feeding the design variables, we get the α^{RMS}, i.e. the capacity rate of each machine. We use this value to determine the NPV of the RMS system. Figure 24 shows the methodology to determine the NPV of the RMS system.

For RMS system, we put the acquired α^{RMS} in the following equation:

$$C^{RMS} = \alpha^{RMS}.C_i^{DML} \quad (6.1.4)$$

Where,

- C^{RMS} is the capacity of the RMS system in relative to the capacity of the DML system;

To note, that the α^{RMS} is acquired by giving the design variables, i.e. the manufacturing equipments obtained from the Reconfiguration Manufacturing System Design Model (RMSM) which is explained in the next section. This α^{RMS} is the capacity factor of the RMS obtained in relative to the capacity of a DML system.

Now, determining the value of β^{RMS}, it is considered:

$$\beta^{RMS} = \alpha^{RMS}$$

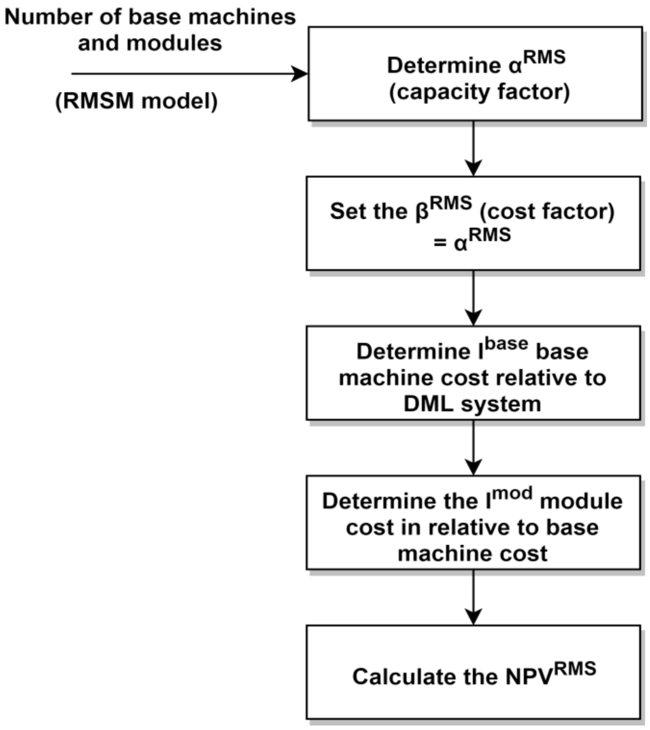

Figure 24 LCCA methodology for RMS

This is the new improvised relationship. The β^{RMS} is set equal to the α^{RMS}. This is because, it is assumed that in a practical case, the higher the throughput rate (capacity) or functionality of a Reconfigurable Machine the proportional will be the cost at the initial period. Thus, with this new definition, the cost factor is determined in the similar way,

$$I^{base} = \beta^{RMS} . \sum_{i=1}^{I} I_i^{DML} \qquad (6.1.5)$$

Where I^{base}, i.e. the investment cost of a base machine determined relatively to the cost of the sum of the DML lines. The cost of each module I_i^{mod} for product i, is assumed to be 60% of the base cost.

With this relation, we calculate the NPV of the RMS system depending on the α^{RMS} and β^{RMS} values,

$$NPV^{RMS} = \sum_{j=1}^{J} \frac{-L_j^{base} \, . \, I^{base} + \sum_{i=1}^{I}(-L_{ij}^{mod} \, . \, I_i^{mod} + V_{ij}^{RMS} . CM)}{(1+r)^{j-1}} \qquad (6.1.6)$$

This is to be noted that the NPV formula for the FMS and the NPV for the DML differs from each other. This is because, in case of DML, the NPV is calculated considering the cost of each line and the product produced on it. Whereas in RMS, it is considered that the RMS machines will be capable of producing all the products on the machine. Additionally, the NPV formula for the RMS is calculated considering the number of base machines and modules in the RMS system.

Where,

- L_j^{base} is the number of RMS base machines required to manufacture $\sum_{i=1}^{I} V_{ij}^{RMS}$ products in the period j (acquired from RMSM model);
- L_{ij}^{mod} is the number of modules required to manufacture V_{ij}^{RMS} products i in the period j (acquired from RMSM model);
- I^{base} is the cost of purchasing one base machine;

- I_i^{mod} is the cost of purchasing one module (tool);

under the following constraints:

$$(\forall i,j)\ \alpha^{FMS} = \beta^{FMS} \quad (6.1.7)$$

$$(\forall i,j)\ WL_{ij}^{RMS} \leq L_{ij}^{mod}.A \quad (6.1.8)$$

$$(\forall i,j)\ V_{ij}^{RMS} \leq D_{ij}, \quad (6.1.9)$$

$$(\forall j)\ L_j^{base} \leq \sum_{i=1}^{I} L_{ij}^{mod} \quad (6.1.10)$$

Where equation (6.1.7) is the parametric constraint, equation, (6.1.8) is the capacity constraint, (6.1.9) is the demand constraint, and equation (6.1.10) expresses that in each period, the number of required base machines can be equal to or less than the sum of the required modules. Thus, the decision variables are the L_j^{sh}, L_{ij}^{mod} and the V_{ij}^{RMS}.

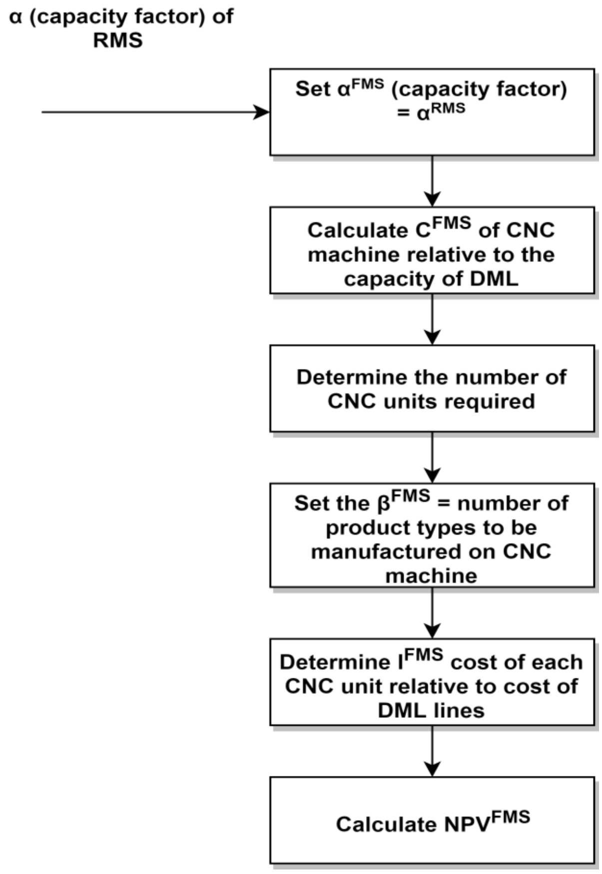

Figure 25 LCCA methodology for FMS

Figure 25 shows the methodology for determining the NPV of the FMS system.

For a FMS system, it is assumed that the throughput of CNC machine is lower than the throughput of a DML line. Thus, the throughput rate of the FMS unit is set the same as that of a Reconfigurable Machine in the RMS. Thus, a new relationship is defined, which is:

$$\alpha^{FMS} = \alpha^{RMS} \quad (6.1.11)$$

This value of α^{FMS} is used in the following equation:

$$C^{FMS} = \alpha^{FMS}.C_i^{DML} \quad (6.1.12)$$

With this equation, the number of CNC units required in the FMS system relative to the DML system is determined.

Whereas, from the investment cost point of view, it is assumed that the investment cost of purchasing one CNC unit will be equal to or lower than the investment cost of the total lines in DML. But to define the relationship between the cost of CNC unit and an RM unit, it is assumed that:

$$\beta^{FMS} = 0.1 \times number\ of\ product\ types\ in\ the\ system \quad (6.1.13)$$

This is because in RMS, a manufacturer can buy individual base machine, which comes without modules and required modules. But a CNC come with pre-defined general modules with functionality to produce all the product features on the machine. Thus, a new relationship is defined that the cost of each CNC machine will be dependent on the flexibility of the CNC machine by its capability of how many product types it can produce. Putting this β^{FMS}, we get the investment cost of a CNC unit relative to DML line;

$$I^{FMS} = \beta^{FMS}.\sum_{i=1}^{I} I_i^{DML} \quad (6.1.14)$$

With this relation, we calculate the NPV of the FMS system depending on the number of CNC units required and the investment cost of the CNC units;

$$NPV^{FMS} = \sum_{j=1}^{J} \frac{-L_j^{FMS}\ .\ I^{FMS} + \sum_{i=1}^{I} V_{ij}^{FMS}.CM}{(1+r)^{j-1}} \quad (6.1.15)$$

Again, the NPV formula for FMS is different as compared to the DML. Because, each CNC machine can produce all the product types, thus NPV is calculated with respective to period j.

Where,

- I^{FMS} is the investment cost of purchasing one unit of FMS machine;
- L_j^{FMS} is the number of general purpose machines purchased in period j;
- CM contribution margin of the product i in the period j;

Under the following constraints:

$$(\forall i, j)\ \alpha^{FMS} = \beta^{FMS} \quad (6.1.16)$$

$$(\forall i, j)\ \beta^{FMS} = 0 \leq \beta^{FMS} \leq 1 \quad (6.1.17)$$

$$(\forall i, j)\ V_{ij}^{FMS} \leq D_{ij}, \quad (6.1.18)$$

$$(\forall j)\ WL_j^{FMS} \leq L_{ij}^{FMS}.A \quad (6.1.19)$$

Where equation (6.1.16) is the parametric constraint and equation (6.1.17) is the β^{FMS} constraint, equation (6.1.18) is the demand constraint and equation (6.1.19) is the capacity constraint.

The number of flexible machines required in the FMS system is dependent on the ability to manufacture $\sum_{i=1}^{I} V_{ij}^{FMS}$ products in period j, so that the decision variables are just V_{ij}^{FMS}.

By this following approach, the NPV of all the systems can be determined.

6.2. Reconfiguration Manufacturing System Design Model

The following section presents the approach and steps framed to design the reconfiguration process. Based on the reconfiguration process, a quantitative reconfiguration design model is attempted. This section is the answer to the following research question: 5. *When and how a Reconfigurable Manufacturing System should be designed and reconfigured?*

6.2.1. Needed Reconfiguration Level

Before reconfiguring the RMS system, it is determined whether there is a need to reconfigure the system or the existing system can be utilised. If reconfiguring the existing system is essential, it is important to know till what extent the reconfiguration process should be applied. Thus, the metric Needed Reconfiguration Level (NRL) is presented.

As explained in section 5.3.3, an Analytical Hierarchical Process (AHP) is framed. The AHP framework comprises of the Needed Current Agility Level (NAL), status of the manufacturing systems design (MSD) and New Circumstance (NC). The NAL comprises the agility level of Technological Infrastructure (TE), People Infrastructure (PE), Management Infrastructure (MA) and Manufacturing Strategies Infrastructure (M). The status of MSD consists of Production System Size and Functionality (PSS & F), Plant Layout System (PLS) and Material Handling System (MHS). The NC consists of New Product (NP), Product Development (PD) and Changing Demand (CD). Figure 26 shows the complete framework of the AHP model to measure the manufacturing firm's reconfiguration. This model breaks down the complex structure of the decision process into hierarchical sequence in order to determine the relative importance of each manufacturing issue through pairwise comparison.

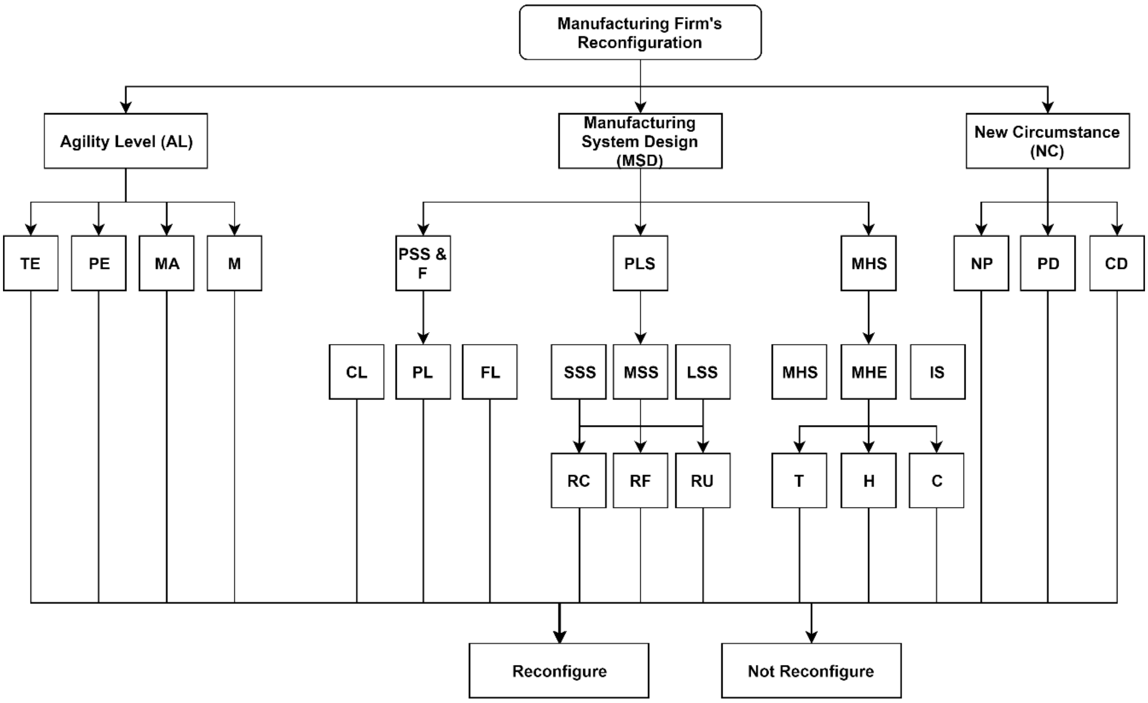

Figure 26 AHP framework for Manufacturing Firm's Reconfiguration

Following are the steps to determine the NRL:

Step 1: Set the strategic objective analysis which is to accept or not to accept the reconfiguration. if the NRL is greater than 50%, the reconfiguration should be accepted otherwise not.

Step 2: Structure the decision hierarchy for estimating the Needed Agility Level required for the configuration alternative (NAL), status of the Manufacturing System Design (MSD) and New Circumstance (NC).

Step 3: Determine the weight or importance of each attribute with the support of the firm's upper level management.

Step 4: Check the consistency of the attribute weights determined.

Step 5: Calculate the elements Needed Agility Level (NAL), status of Manufacturing System Design (MSD) and the New Circumstance (NC)

i. To estimate the NAL, the first step is to determine the current agility of the technology infrastructure (TE), people infrastructure (PE), Management Infrastructure (MA) and Manufacturing Strategies Infrastructure (M)
ii. After estimating the current agility level, the next step is to determine the needed agility level. The Needed Agility Level (NAL) is set to 1. This decision depends on the current systems agility level and the required system agility level to reconfigure the system.

$$(\forall i, j) NAL = w_{TE}\,(NAL_{TE}) + w_{PE}\,(NAL_{PE}) + w_{MA}\,(NAL_{MA}) + w_M(\,NAL_M) \qquad (6.2.1)$$

Where,

- $NAL_{TE}, NAL_{PE}, NAL_{MA}, NAL_M$ are the agility level required for TE, PE, MA and M for configuration;

The symbols w_{TE}, w_{PE}, w_{MA} and w_M are relative weights of TE, PE, MA and M respectively. These values vary depending on the companies and on the manufacturer's preferred preferences. These values are estimated using AHP. The relative weights can be determined by AHP and can be changed frequently depending on the circumstances. Pair-wise comparisons are used for a particular manufacturing system design (Garbie I. , 2014)

iii. To determine the status of the Manufacturing System Design (MSD). MSD comprises of the following elements, the production system size and functionality (PSS & F), plant layout system (PLS) and material handling system (MHS). The general equation to measure the MSD is:

$$(\forall i, j) MSD \;= w_{PSS\,\&\,F}(Attributes\ of\ SSS, MSS, LSS, RC, RF, RU, PPL, MS\ \&W) + w_{PLS}(\,Attributes\ of\ CL, PL, FL) + \ w_{MHS}(Attributes\ of\ MHE, MHSS, IS) \qquad (6.2.2)$$

where

- $w_{PSS\,\&\,F}$ is the relative weight of production system size and functionality;
- w_{PLS} is the relative weight of the plant layout system;
- w_{MHS} is the relative weight of the material handling system;

Whereas, SSS is the small-sized manufacturing system, MSS the medium sized manufacturing system, LSS the large-sized manufacturing system, RC the resource capacity, RF the resource flexibility, RU the resource utilisation, PPL the physical product limitations, MS & W the machine size and weight, PLS the plant layout system, CL the cellular layout, PL the product layout FL the functional layout or process layout, MHE the material handling equipment, MHSS the material handling storage system and IS the identification system.

These attributes are evaluated based on the effort required to reconfigure them. The explanation and determination of each attribute is explained in detail in next chapter, section 7.4.2.

iv. Respectively, to estimate the New Circumstance (NC):

The New Circumstance (NC) is related to the New Product (NP), Product Development (PD) and Changing Demand (CD).

$$(\forall i,j) NC \ = f[NP\ , PD\ , DC\ ] \quad (6.2.3)$$

These attributes can be evaluated based on the reconfiguration effort required if there is a new product introduced in the system, if a current existing product's functionality is changed (product development) or if the products demands varies. These are again explained in detail in chapter 6, section 6.4.2.

$$(\forall i,j) NC \ = \ w_{NP}[NP\ ] + w_{PD}[PD\ ] + w_{DC}[DC] \quad (6.2.4)$$

Where,

- NP is the attribute value of New Product i at period j;
- PD is the attribute value of developing a product i at period j;
- DC is the attribute value of changing demand of product i at period;

whereas, $w_{NP}, w_{PD}\ and\ w_{DC}$ are relative weights of new product, changing demand, respectively.

Step 6: Calculate the Needed Reconfiguration Level (NRL).

The NRL(t) at any time t is determined by the equations (6.2.1), (6.2.2) and (6.2.4) as a function of all the issues in a manufacturing system, i.e., business and manufacturing issues.

$$(\forall i,j) NRL \ = f\ [\ NAL\ , MSD\ , NC\ ] \quad (6.2.5)$$

$$(\forall i,j) NRL \ = \ w_1[NAL\ ] + w_2[MSD\ ] + w_3[NC\ ] \quad (6.2.6)$$

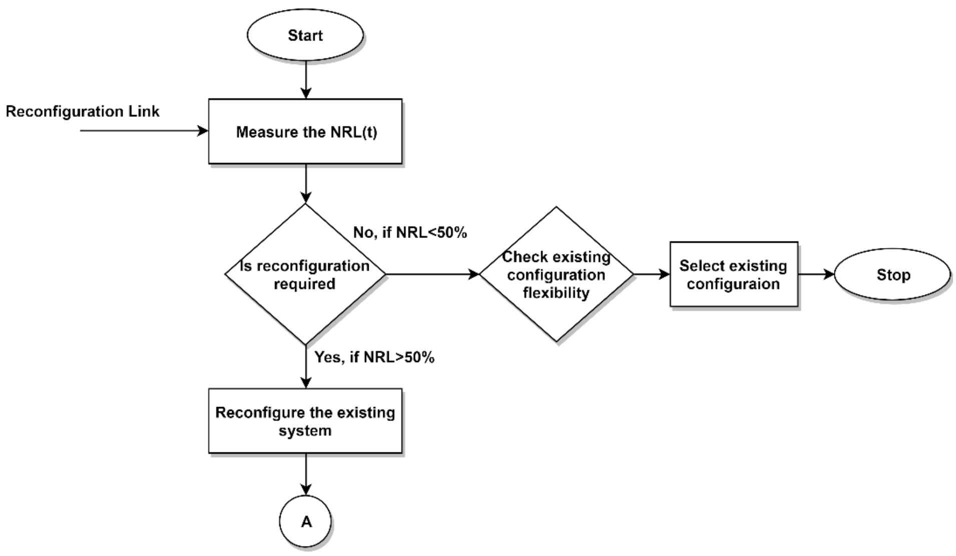

Figure 27 Approach for Reconfiguration Process

With equation (6.2.6), the NRL can be measured. Figure 27 show, if the NRL>50%, the NRL value should be accepted and the existing system should be reconfigured. Based on this analysis, the reconfiguration process is developed as follows.

6.2.2. Production System Level

The production system level consists of the design and reconfiguration at the system and the machine level. The objective is to determine the number of base machines and number of modules to meet the product and market requirements. The system and machine level is designed incorporating the RMS characteristics, modularity, scalability, convertibility and customisability, thus making it reconfigurable in nature.

If a new RMS system is required to be designed, start from Step 7, if an existing system is required to be reconfigured, follow Step 1.

Step 1: Select an appropriate (re)configuration mode.

As explained in chapter 5, section 5.3.2, the reconfiguration drivers and the reconfiguration method are presented based on the market and manufacturing uncertainties. Based on the reconfiguration driver, i.e. need of functionality changes or capacity changes, select an appropriate reconfiguration method.

Subsequently, as explained in section 5.3.4, the reconfiguration process is developed.

Step 2: Estimate the Resource Work Load (RWL) of all the existing machines at time t

The resource work load represents how much is the work load of the products to be produced with a demand for a given time period.

$$(\forall i, j)\ RWL_j(t) = \sum_{i=1}^{I} D_{ij} \times T_{c_{ij}}(t) \qquad (6.2.8)$$

Where,

- D_{ij} is the demand or production volume of product i at period j;
- $T_{c_{ij}}$ is the total processing time of the product i at period j;

After determining the work load of the current production phase requirements, the next step is to determine the number of base machines with allowed module positions on each machine.

Step 3: Determine the number of base machines required to meet the Resource Work Load

The base machine is the machine without any modules on it. This is determined based assuming a perfectly balanced system (Koren & Shpitalni, 2011).

$$(\forall i, j)\ n_o = \sum_{i=1}^{I} \frac{D_{ij} \times T_{c_{ij}}}{Min\ day\ available \times machine\ reliability} \qquad (6.2.9)$$

Where,

- n_o is the number of machines required to fulfil the market requirements;
- I is the number of products i in the system;
- D_{ij} is the demand of product i at period j;
- $T_{c_{ij}}$ time to produce single product i at period j;

Determining the base machine is not enough, as one must know the production capacity of each base machine in the system. To enable the capacity changes, the base machine should be designed with scalable architecture. Determining the number of modules positions allowed on each scalable machine is a key design parameter such that it can further influence convertibility and customisability of the system. It is advantageous to design the machine to hold many modules. This is because the cost of adding modules should be less than starting again with another machine base. Contrarily, with more mechanical hardware on the machine, a machine might fail. Moreover, this affect the machine's availability, and therefore its productivity gains, become smaller with each additional module. This creates a trade-off between the productivity advantages of additional modules and productivity losses due to decreased availability (Spicer, 2005). Thus, the number of cost-optimal module a base machine can allow, i.e. *"number of optimal module positions"* is determined. Figure 28 Architecture of scalable machinesshows the architecture of a Reconfigurable Machine.

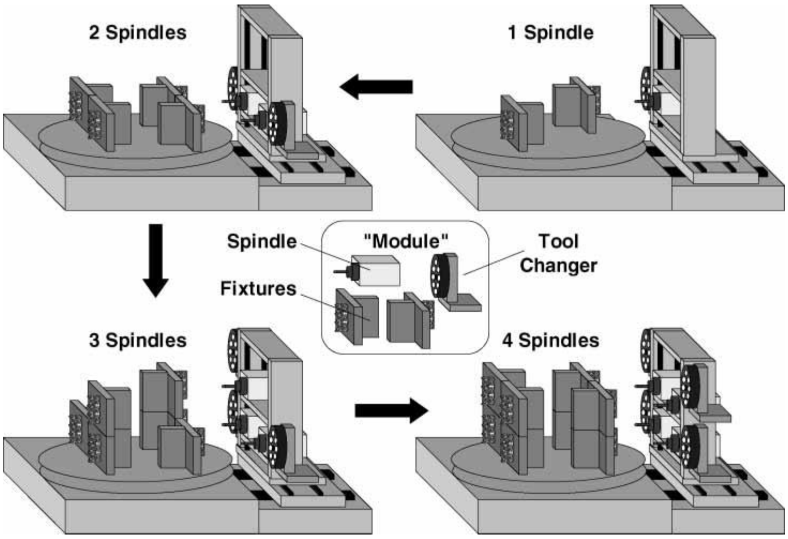

Figure 28 Architecture of scalable machines

Step 4: Determine number of module positions on base machine

Module positions is an indication of how many modules (tools) each base machine can have. To determine the number of module positions each machine base can allow, the optimal number of module positions on each base machine should be determined. To determine the module positions, the equations governing machine production rates are described. These equations are the base to derive the equations of optimal module positions and maximum module positions (Spicer, 2005)

The following equation gives the production rate of a RM excluding the machine failures:

$$P_n = (n)(P_m) \quad (6.2.10)$$

where

- P_m is the production rate of the module;
- P_n is the machine production rate as a function of n;

Additional information such as machine availability and module availability is considered to see the effect of additional modules on the overall machine availability. This is quantified by equation:

$$A_{Machine} = (A_B)(A_M)^n \quad (6.2.11)$$

Where,

- n is number of modules;
- A_B is the probability of the base machine available to run;
- A_M is the probability of the module available to run, together resulting the probability of the machine ($A_{Machine}$) that is available to run.

Combining equations (6.2.10) and (6.2.11), the production rate of the machine adjusted for availability can be determined, given by equation:

$$P_n = (n)(P_m)(A_B)(A_M)^n \tag{6.2.12}$$

Where

- P_n is the production rate of the machine concerned with machine and module availability;

Practically, the number of modules on the RM can be greater than or equal to one and the availability rate of the module to run is less than one. This implies that the production rate determined from equation (6.2.12) gives the maximum production rate. With this available information, the number of modules than can provide maximum production rate can be determined. This is performed by differentiating equation (6.2.12)with respect to the function of n, setting it to zero, and solving for n_{max}, the number of modules that offer maximum production rate (n_{max}) is determined.

$$\frac{dP}{dn} = (A_B)(P_m)(A_M)^n \, [(n)\ln(A_M) + 1] \tag{6.2.13}$$

Equating $\frac{dP}{dn}$ for 0 and solving for n_{max}, we get:

$$n_{max} = -\frac{1}{\ln(A_M)} \tag{6.2.14}$$

Where,

- n_{max} gives the exact point when additional modules will no longer increase the production rate of the machine;

Although equation (6.2.14) provides an important information when the production rate will no longer increase, this information alone is not sufficient to make a decision on the number of module positions on a RM, as it is not a cost beneficial number of module positions. To determine the cost-optimal number of module positions, it is important to determine when the production rate per unit cost of a scalable machine is maximum. If the production rate surpasses after this point, a new machine is required. To determine the cost optimal solution, one must know the cost of the base machine.

$$K_n = C_B + (n)C_M \tag{6.2.15}$$

where

- C_B is the cost of the base machine;
- C_M is the cost of a module;
- n is the number of modules;

Consequently, dividing equation (6.2.12) and (6.2.14), i.e. P_n with K_n, the production rate per unit of cost of a machine with n modules is obtained.

$$G_n = \frac{P_n}{K_n} = \frac{(n)(P_m)(A_B)(A_M)^n}{C_B + (n)C_M} \tag{6.2.16}$$

where,

- G_n gives the maximum production rate for n modules.

Equating equation (6.2.16) with respect to n, the number of cost-optimal module positions, n^*, can be determined.

$$\frac{dG}{dn} = \frac{A_B P_M (A_M)^n [C_M(n) + C_B)(n) \ln(A_M) + C_B]}{(C_M(n) + C_B)^2} \quad (6.2.17)$$

Setting equation (5.2.17) to zero, a quadratic equation is obtained, which is given by:

$$C_M(n^*)^2 + C_B(n^*) + \frac{C_B}{\ln(A_M)} = 0 \quad (6.2.18)$$

Finally, solving equation (5.2.18)for n^*, we get,

$$n^* = \frac{-C_B \pm \sqrt{C_B^2 - 4C_M\,(\frac{C_B}{\ln(A_M)})}}{2C_M} \quad (6.2.19)$$

Where $\boldsymbol{n}^*$ **is the optimal number of modules.** Equation (6.2.19) gives two values. The negative value should be truncated and the positive root must be chosen where the value must be an integer and greater than or equal to 1.

Equation (6.2.14) and (6.2.19) gives the maximum number of module positions and optimal number of module positions that can be allowed on the base machine. With this approach, the RM is designed to be scalable and can facilitate a manufacturer to decide the number of modules on each RM.

Step 5: Determine the production rate of the machine

After determining the module positions, the manufacturer can decide to put the modules on the base machine. With this number of modules as an input, the production rate of the machine can be determined using equation (6.2.12).

Step 6: Determine the Resource Capacity (RC) (production capacity)

From the production rate of the individual machine, the resource capacity available in the system can be determined. This is done by multiplying the total production rate with number of available machines in the system.

$$(\forall i, j)\ RC = \sum_{i=1}^{I} P_r \times n_o \quad (6.2.20)$$

Where, - RC is the capacity of the resource for all the products at time period j;

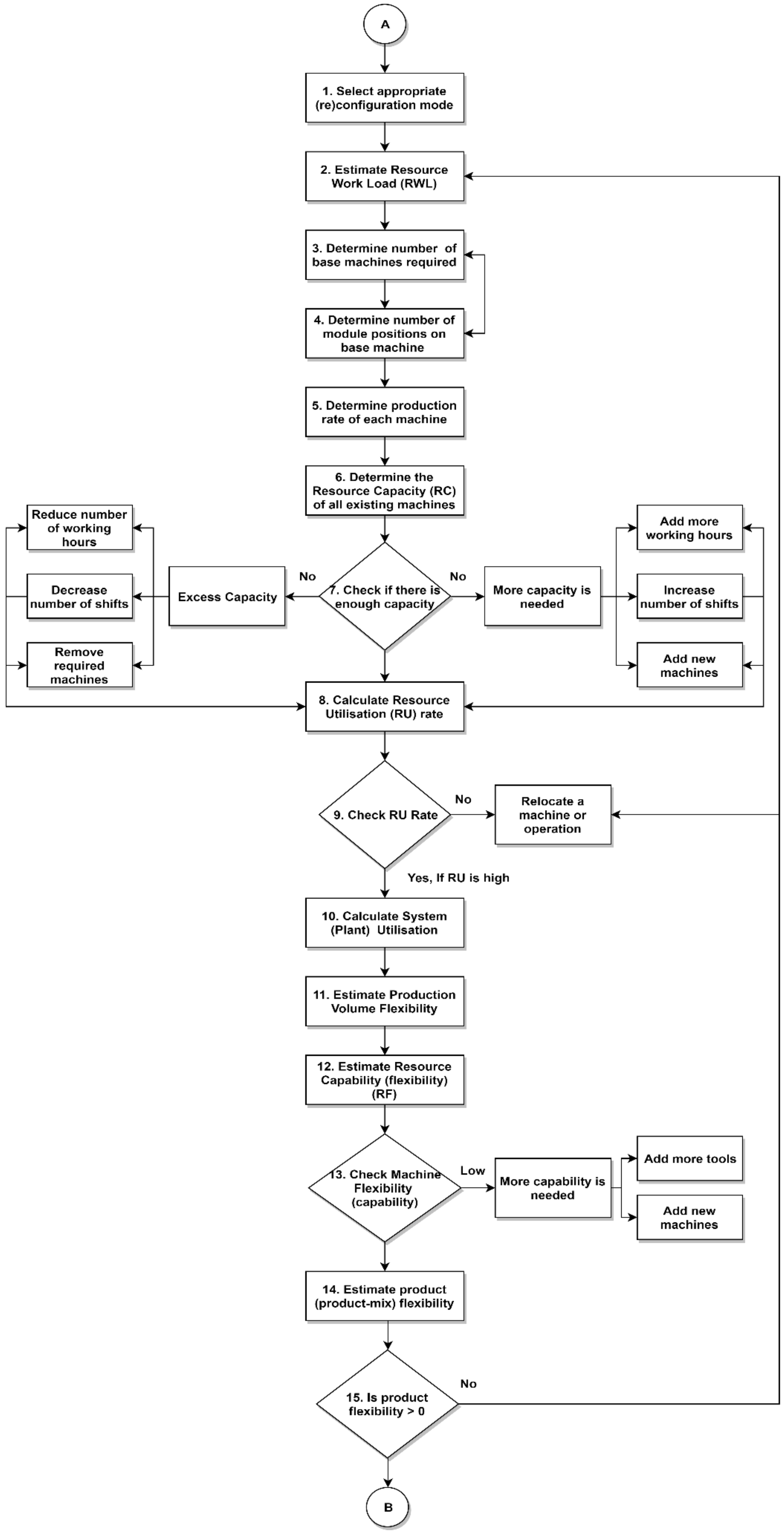

Figure 29 Approach to design and configure the RMS production system

Step 7: Check the Resource Capacity

The Resource Capacity (RC) of the system is checked with the Resource Work Load (RWL). From equation (6.2.8) and equation (6.2.19), if equation (6.2.19) is greater than equation (6.2.8), i.e. if RC > RWL, calculate the resource utilisation rate. If not, more capacity is required. This can be either done by increasing the work hours or adding an additional working shift for a period of time, adding extra modules if the module positions are available on the Reconfigurable Machine (RM) or adding an extra machine. Contrarily, if RC is more than sufficient, the manufacturer can either remove the working hours, modules or machines.

Step 8: Calculate the Resource Utilisation (RU) rate

The Resource utilisation rate (RU_i) is evaluated as the ratio of the RWL and RC. This is obtained by dividing equation (5.2.8) with equation (5.2.20).

$$(\forall i, j) RU = \frac{RWL}{RC} = \sum_{i=1}^{I} \frac{D_{ij} \times T_{c_{ij}}}{P_r \times n_o} \quad (6.2.21)$$

Step 9: Check the Resource Utilisation rate

If the utilisation rate is high, go to next step. If not, relocation of machine or operation is required.

Step 10: Calculate the plant or System Utilisation (SU) rate.

The plant or system utilisation rate is determined by:

$$(\forall i, j) SU = \frac{1}{n_o} \sum_{k=1}^{n_{ok}} RU \quad (6.2.22)$$

Where

- n_{ok} is the number of available machines in the system at period j;

This refers to the actual amount of output of a production facility relative to its theoretical capacity. For example, the machines can have different utilisation rates and sometimes only few set of machines are selected from the set of available machines. Thus, this formula is governed on the sum of the utilisation rates of the number of machines selected in the production facility.

Production system Flexibility

The production system flexibility comprises of Production Volume Flexibility (PVF), Resource Flexibility (RF) and Product (product-mix) Flexibility (PF). A little flexibility around the product part family is essential to have in the system. This reserved flexibility can be useful in adapting the daily production changes as well as can act as a proactive decision to reconfigure the production system. This can provide an insight in checking the scalability, convertibility and customisability of the system.

Step 11: Estimate the production volume flexibility (PVF).

The production volume is the system ability to transform or quickly accommodate variations in the production volumes. Production volume flexibility (PVF) relates to the slack capacity in the system. Slack capacity is the capacity which remains unused due to machines left idle. This is due to insufficient demand relative to what the economy is capable of producing. This attribute can be defined by following equation (Garbie I. , 2014):

$$(\forall i, j) PVF = 1 - RU \quad (6.2.23)$$

Equation 6.2.23 can be used if all the machines are selected in the system. But, in case of different product types, sometimes a set of machines can be allocated to produce particular product types in the system. Then to check the PVF, following is the formula that can be used:

$$(\forall i,j) PVF = \frac{1}{n_{oi}} \sum_{oi=1}^{no_i} \frac{SRC}{RC} \qquad (6.2.24)$$

Where,

- SRC Is the slack in resource capacity at period j;
- n_{oi} is the number of machines that can be used to produce product i at time period j;

Where $(\forall i,j)\ SRC = RC - RWL$ (6.2.25)

This gives the production volume flexibility from the number of machines selected from the available set of machines available. By this, the production volume flexibility can be monitored when there are number of products in the system and if specific set of machines are assigned to the particular products.

Step 12: Estimate the resource capability (flexibility)(RF) in all existing resources

The Resource Flexibility (RF) can be estimated by the number of operations a machine can perform relative to a give set of product family, by how well it can perform the operations and how well it can switch operations. This is given by:

$$(\forall i,j) RF = \frac{o_i}{O_{i_{max}}} \qquad (6.2.26)$$

Where

- RF is the resource flexibility (or capability) of resource at time period j;
- o_i is the number of operations that can be done on resource at time period j;
- $O_{i_{max}}$ is the maximum number of operations available at resource at time period j;
- O is the subscript of operations;

Step 13: Check for machine flexibility or capability

If there is enough capability, go to the next step. Otherwise the capability can be increased by adding new tools or magazines or adding new machines.

Step 14: Estimate the product (product mix) flexibility

New product flexibility will be evaluated by checking the capability of all manufacturing facilities needed in the plant. Product Flexibility can be used to evaluate the ability of a plant to accept a new product. This is given by:

$$PF_{ij} = \frac{1}{n_{ij}} \sum_{i=1}^{n_{ij}} \sum_{o=1}^{o_i} \frac{SRC}{RC} \times \frac{SRF}{O_{i_{max}}} \qquad (6.2.27)$$

Where,

- n_{ij} is the number of machines that can be used to produce product i at time period j;

By this, one can determine if the reserved flexibility and the capacity in the system is sufficient to accept a new product in the system. If the production system flexibility values are greater than 0, and around the product family in the system, then go to the next step, (re)designing the plant layout system and material handling system.

6.2.3. Plant Layout and Material Handling System Level

To design the plant layout system (configuration), we now know the number of machines required to meet the product demand and functionality requirements. Based on this output, a configuration design is planned.

Step 15: Plan number of production stages required

The number of stages can be determined from the reconfiguration link. The reconfiguration link defines the product variety and its demand based on its process similarities and defines them into appropriate families. This information can be translated into technical requirements and thus, with this information and the management decision, the number of stages can be planned in a way that the manufacturing resources are efficiently utilised.

Step 16: Calculate the number of configurations available.

With decided number of production stages (m), and with the number of machines (N) determined in the production system, the RMS configurations can be calculated, if the machines N are arranged in exactly m stages, which is given by (Shpitalni, 2010):

$$K = \frac{(N-1)!}{(N-m)!(m-1)!} \qquad (6.2.28)$$

Where,

- K is number of possible configurations with N machines arranged in exactly m stages.

Step 17: Check the configurations

As explained in Chapter 5, section 5.2.2, the calculated configurations will have symmetric configurations as well as asymmetric configurations.

Step 18: Select Symmetric Configurations

The configurations should be evaluated based on the symmetric axis, and symmetric configurations should be selected.

Step 19: Analyse Symmetric Configurations

As the production system design approach is based on the perfectly balanced system. Some symmetric configurations will have bottlenecks in the stages. These configurations should be eliminated. Symmetric configurations with no bottleneck stages and satisfying the system cycle time should be selected.

Note: Step 16, Step 17, Step 18 is only possible if a programming algorithm is used to design the configurations and then select symmetric configurations. Thus, in this case, the symmetric configurations and the material handling systems are designed manually, arranging the machines in particular production stages. Further ensuring that there are no bottleneck stages in the configuration design.

Step 20: Check the operation sequence of the material handling equipment (MHE)

After eliminating the configurations, the configurations should be checked based on the number of stages in the configuration, the number of locations of the machines, the number of locations available for future expansion, the machine size and weight and physical product limitations. This is necessary so that a bi-directional MHE sequence can be planned.

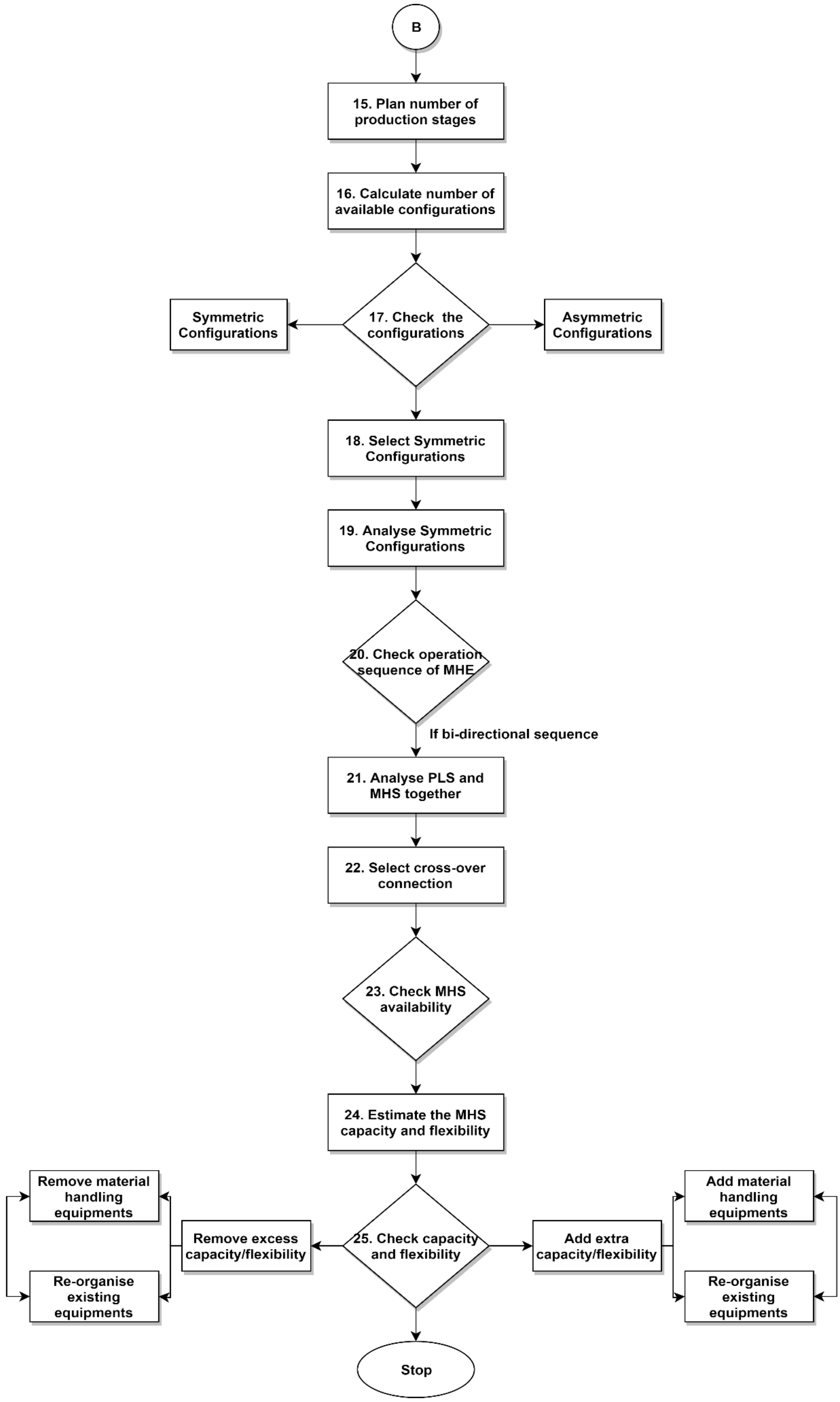

Figure 30 Approach to design and configure the RMS plant layout system and material handling system

Step 21: Analyse PLS and MHS together

Analyse the Plant Layout System and Material Handling System together.

Maintain minimum separation between facilities. The layout be flexible enough to accommodate changes in product design, process design and schedule design. While designing the PLS and MHS, the overall plant layout, the possibility of future expansion, future compression and other changes must be considered (Garbie I. P., 2008).

Step 22: Select the crossover connection (Material Handling System)

As explained in previous chapter 5, section 5.2.2, the Material Handling System should be designed with a crossover connection. The machine in each production stage must be connected to the material handling system in such a way that any machine failure in the stage does not cause the system to fail.

Step 23: Check the Material Handling System (MHS) availability rate

To deal with the continuous production of varying product mixes and the quick changes of production requirements in response to changing demands in the market, the material handling should have high degree of dynamically adjustable flexibility (Ho, 1997).

Check the material handling system for its availability. The material handling availability rate must be higher than the system productivity rate (Freiheit T. K., 2004).

When the MHS availability rate is greater than the minimum required MHS rate and system availability rate, go to the next step.

Step 24: Estimate the MHS capacity and flexibility

Estimate the capacity and flexibility of the MHS based on the fluctuating demand. This can be estimated by considering the number of MHS equipments in the system of type i at time t, maximum unit load quantity factor based on the capacity of the equipment, the normal operating speed of the equipment at time t, equipment loaded travel factor at time t, and the total number of material handling equipments used at time t (Garbie I. , 2014)

Step 25: Check the MHS capacity and flexibility

If sufficient capacity and flexibility are available, go to the next step. Otherwise, more capacity and flexibility can be obtained by adding new equipments or reorganising the existing equipments.

Figure 29 Approach to design and configure the RMS production system and Figure 30 Approach to design and configure the RMS plant layout system and material handling systemshows the steps structured to develop the RMS design methodology.

6.2.4. Implementation

After performing the steps at production system level, plant layout and material handling system level, the next steps are to analyse the available RMS configurations based on configuration performance measures and manufacturer's preference. To select and propose one configuration design among the RMS configurations, the configurations should be analysed based on the following criterion,

1. Reconfiguration Smoothness Value (RS)
2. System throughput less than 100%
3. Total Investment Cost
4. Scalability, i.e. increment of production capacity that can be gained by adding a machine

5. Floor Space.

This factors are ranked according to their importance. In case of designing a new RMS system, the configurations should be analysed based on factors 2-5, whereas in case of reconfiguring an RMS system, the re-configurations should be analysed based on all the five factors, paying much attention to Reconfiguration Smoothness Value (RS). Figure 31 shows the methodology steps to implement the RMS configuration.

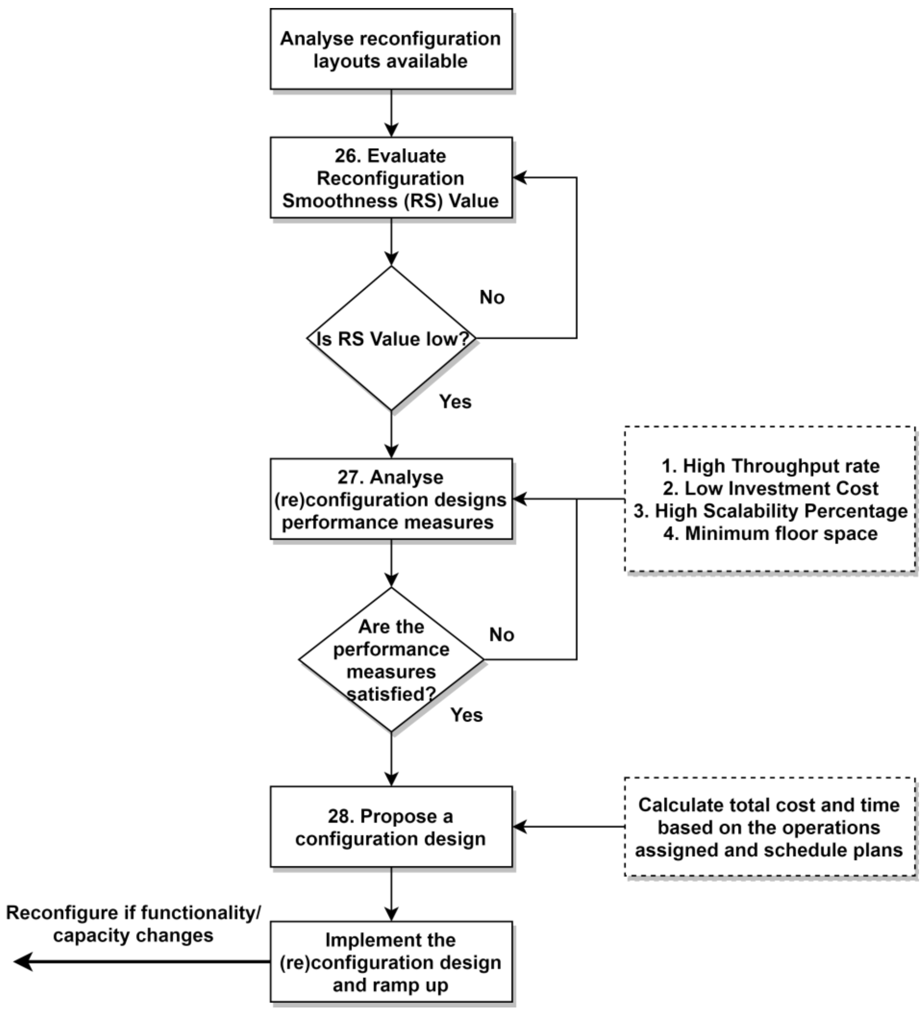

Figure 31 RMS Implementation Methodology

Step 26: Evaluate the Reconfiguration Smoothness Value

If reconfiguration is performed, follow this step. If a new RMS system is designed, go to next step.

To determine the reconfiguration smoothness value (RS), certain rules applies so that the RS metric can be measured correctly. These rules can normally assist the manufacturer to plan the reconfiguration, and accordingly, determine the parameters required to fully define the RS. These rules aims in minimising the reconfiguration effort (Youssef, 2006). Following are the rules for reconfiguration planning in order of application to break the possible ties.

- *Maximise the number of stages types that keep their locations*
- *Maximise the number of machines that keep their locations*
- *Minimise the number of empty stage locations between consecutive stages.*
- *Maximise the number of machines that keep their configurations*

- *Maximise the number of machines that keep their operation clusters setup assignment.*

The first two rules are aimed to minimise the physical activities at the system level. One important aspect to consider is the space limitations, in terms of the available stage locations when applying the first rule. The third rule is aimed to minimise the material handling effort by minimising the distances between consecutive stages. The fourth and fifth rules are concerned with minimising the machine level reconfiguration activities in terms of both hard (machine reconfiguration) and soft activities (change in operation clusters setup assignments).

Now, the RS between any two configurations can be evaluated, which comprises of the Market Level Reconfiguration, System Level Reconfiguration and Machine Level Reconfiguration. The following metrics are described in detail.

- **Market Level Reconfiguration**

The market level reconfiguration smoothness represents changes related to use of machines (TRS_m) and changes related to the use of the machine modules (TRS_d). Changes related to the machines are represented by:

$$TRS_m = \delta \frac{Number\ of\ added\ machines}{Total\ number\ of\ machines} + (1-\delta)\frac{Number\ of\ Removed\ machines}{Total\ number\ of\ machines} \qquad (6.2.29)$$

Changes related to the machine modules are represented by:

$$TRS_d = \delta \frac{Number\ of\ added\ machine\ modules}{Total\ number\ of\ machine\ modules} + (1-\delta)\frac{Number\ of\ Removed\ machine\ modules}{Total\ number\ of\ machine\ modules} \qquad (6.2.30)$$

The total market level reconfiguration is the sum of both the changes:

$$TRS = \varepsilon TRS_m + (1-\varepsilon)TRS_d \qquad (6.2.31)$$

Where ε lies between [0,1].

It is recommended that $\varepsilon > 0.5$ because the TRS activities associated with machines/stations are more cost, time and effort consuming than those associated with machine modules. It is also recommended that $\delta > 0.5$, because, generally, the activities associated with buying/renting are more cost, time and effort consuming than those associated with selling/returning of either machines or machine modules.

- **System Level Reconfiguration**

The system level reconfiguration smoothness is categorised into three types: SRS_s representing changes related to the stages, SRS_m related to the changes regarding the machines and SRS_f regarding the changes related to material handling system.

SRS representing changes related to stages is given by:

$$SRS_s = \pi \frac{Number\ of\ installed\ stage\ types}{Total\ number\ of\ stage\ types} + (1-\pi)\frac{Number\ of\ uninstalled\ stage\ types}{Total\ number\ of\ stage\ types} \qquad (6.2.32)$$

SRS representing changes related to machines is given by:

$$SRS_m = \pi \frac{Number\ of\ installed\ machines}{Total\ number\ of\ machines} + (1-\pi)\frac{Number\ of\ uninstalled\ machines}{Total\ number\ of\ machines} \qquad (6.2.33)$$

SRS representing changes related to material flow paths is given by:

$$SRS_f = \theta \frac{Number\ of\ added\ material\ flow\ paths}{Total\ number\ of\ material\ flow\ paths} + (1 - \theta) \frac{Number\ of\ removed\ \ material\ flow\ paths}{Total\ number\ of\ material\ flow\ paths} \quad (6.2.34)$$

The total SRS is represented by the changes related to the stage, machines and the material flow paths is given by:

$$SRS = \lambda SRS_s + \varphi SRS_m + \Phi SRS_f \quad (6.2.35)$$

where $\varphi + \Phi + \lambda = 1$

It is recommended that $\varphi > \Phi > \lambda$ as these weights reflect the amount of cost, time and effort for performing activities corresponding to the SRS components. Practically, activities associated with changes related to stages are the most expensive ones as they involve both hard-type and soft-type reconfiguration concerning the type of material handling equipment used and soft-type reconfiguration concerning the number of operators assigned.

It is recommended that $\pi > 0.5$ because activities associated with adding a new/relocated stage is more cost, time and effort consuming than those because of removing, because adding involves calibration, setup and ramp up activities. Whereas, $\theta > 0.5$ because increasing the number of flow paths between stages is obviously more complicated with regards to material handling design and installation than decreasing them.

- **Machine Level Reconfiguration**

MRS is divided in two components namely: MRS_d representing the changes related to utilisation of machine tools and MRS_o representing the changes related to operational clusters. MRS is defined as follows:

The MRS at representing the changes related to the machine modules is given by:

$$MRS_d = \sigma \frac{Number\ of\ added\ machine\ modules}{Total\ number\ of\ machine\ modules} + (1 - \sigma) \frac{Number\ of\ Removed\ machine\ modules}{Total\ number\ of\ machine\ modules} \quad (6.2.36)$$

MRS representing changes related to the operation cluster assignments is represented by:

$$MRS_o = \sigma \frac{Number\ of\ OS\ assignments\ added\ to\ machines\ keeping\ their\ configurations}{Total\ number\ umber\ of\ OS\ assignments\ for\ machines\ keeping\ their\ configurations} + (1 - \sigma) \frac{Number\ of\ OS\ assignments\ removed\ to\ machines\ keeping\ their\ configurations}{Total\ number\ umber\ of\ OS\ assignments\ for\ machines\ keeping\ their\ configurations} \quad (6.2.37)$$

The total MRS is given by:

$$MRS = \nu MRS_d + (1 - \nu) MRS_o \quad (6.2.38)$$

Where ν lies between [0,1].

It is recommended that $\nu > 0.5$ because the MRS activities associated with machine reconfiguration (adding/removing of modules) already encompass the activities associated with changes in operation cluster assignments and more. It is also recommended that, $\sigma > 0.5$ because, the activities associate with adding either machine modules or operation cluster assignments are more cost, time and effort consuming than those associated with removing of either machine modules or operation cluster assignments.

The weights to be assigned for the various metric components can be left on the manufacturer to decide based on the practical situations. The above weights cannot be generalised to accommodate all the practical situations. It also depends on how modular the system architecture is, both hardware and software components. For e.g., it is easier to relocate a machine if it is designed to be modular.

The proposed reconfiguration smoothness metric is the summation of the all the above three metrics: market level reconfiguration smoothness, system level reconfiguration smoothness and machine level reconfiguration smoothness. Accordingly, the reconfiguration smoothness between the configurations is defined as follows:

$$RS = \alpha TRS + \beta SRS + \gamma MRS \qquad (6.2.39)$$

Where $\alpha + \beta + \gamma = 1$ and the three components, TRS, SRS and MRS all lie between 0 and 1. If the reconfiguration smoothness is 0, the configurations can be said identical. It is recommended that $\beta > \gamma > \alpha$ as these weights reflect the relative amount of cost, time and effort performing the activities to the three components associated with the reconfiguration process. System level is the most expensive reconfiguration process as it involves both hardware and software activities. Followed by, machine level activities, which also involves hard-type and soft-type activities but relatively less than the system level and market-level activities mostly involve soft-type activities like buying/selling of machines.

Step 27: Analyse the performance measures of the (re)configuration

After measuring the RS value, the next step is to analyse the system throughput, investment cost, scalability and floor space of the configurations.

- The system throughput rate, i.e. the number of products can be produced. This is determined by the total daily time available divided by the maximum cycle time in a RMS production stage at reliability less than 100%.
- The investment cost is the cost of the total machines, modules and the material handling system in the system.
- The scalability is the increment of the production capacity that can be gained by adding a machine, i.e. to change the system throughput to match the new demand.
- The floor space is the space acquired by the configuration. This is simply measured by the configuration length with configuration breadth.

Step 28: Propose a configuration

Based on the performance measures, one configuration is proposed. Now, the objective consists of to achieve all the necessary operations to accomplish the desired product while minimising the time and costs incurred during the production.

Note: This step is just to highlight the problem associated with assigning the number of operations on the machine and to schedule these operations in order to minimise the daily demand completion time and cost of the entire schedule. Additionally, for the simplification and the understanding of this step, the machines and the modules are considered to be identical. This is due to the reason it will become complex to use these formulas, as a simulation model is required to compute the daily completion time and costs. Thus, the goal is to just ensure that the total demand produced is less than the daily available time and to highlight their costs. These steps are further discussed and recommended for future work.

- **Total Cost**

It is the sum of all the costs incurred during the production phase. This cost is mainly divided into four major costs.

1. Machine Usage Cost (MUC)

The MUC is the cost of using a particular machine for carrying out an operation on the product. It depends on the processing time of a particular operation and the type of operation. This is expressed as:

$$MUC = \sum_{i=1}^{I} \sum_{oi=1}^{O} CM\ [M_j(OP_o^i)] \times PrTime\ \left[[M_j(OP_o^i)]\ [C_l^j\ (OP_o^i)]\right] \quad (6.2.40)$$

Where,

- $CM\ [M_j(OP_o^i)]$ is the cost of using a particular machine M_j for a particular set of operational features OP_o^i for the products i with the operational features o in the system;
- $PrTime\ [M_j(OP_o^i)]$ is the processing time of a particular machine M_j to produce particular set of operational features OP_o^i;
- $[C_l^j\ (OP_o^i)]$ is a configuration of a machine to produce the particular set of operational features OP_o^i;

2. Tool Usage Cost (TUC)

The tool (module) usage cost is the cost of using a particular tool. It depends on the type of the tool used, the processing time of the product and the type of the product.

$$TUC = \sum_{i=1}^{I} \sum_{oi=1}^{O} CT_j\ \left[T\ (OP_o^i)\ \right] \times PrTime\ \left[[M_j(OP_o^i)]\ [C_l^j\ (OP_o^i)]\right] \quad (6.2.41)$$

Where,

- $CT_j\ \left[T\ (OP_o^i)\ \right]$ is the cost of using a module for producing the particular set of operations OP_o^i;

3. Configuration Change Cost (CCC)

Configuration Change Cost is the cost of changing a particular machine configuration to a required configuration based on the number of operations and the products in the system. This is expressed by:

$$CCC = \sum_{o=1}^{O} CCCost_j\ [C_l^j(u)][C_{l'}^j(u')] \quad (6.2.42)$$

Where,

- $C_l^j(o)$ is the current machine configuration for the set of the operations o;
- $C_{l'}^j(o')$ is the new machine configuration for the set of new operation o';

4. Tool Change Cost (TCC)

The TCC is the cost incurred by changing the tool as different operations may require different kind of tools. This cost varies from one machine to another.

$$TCC = \sum_{o=1}^{O} TCCost_j\ [T_j^r(o)][T_{j'}^r(o')] \quad (6.2.43)$$

Where,

- $T_j^r(o)$ is the current tools on the machine to produce the set of operations o;
- $T_{j'}^r(o')$ is the set of new tools on the machine to produce the set of changed/new operations o';

- **Total Time**

Since the aim of the RMS is to be cost-effective and responsive, it is important to consider the total time of the production. This will give a manufacturer the information about the amount of time required to meet the daily demand based on the process plan. The total time consists of:

1. **Processing Time of a particular operation (PT)**

The processing time is the time required for the machine to perform a particular operation. It depends on the machine, its configuration and the type of operations to be performed. With this information, the total processing time of the products in the system is determined by the equation,

$$PT = \sum_{i=1}^{I} \sum_{o=1}^{O} PrTime\left[M_j\left(OP_o^i\right)\right]\left[C_l^j\left(OP_o^i\right)\right] \quad (6.2.44)$$

Where,

- $PrTime\left[M_j\left(OP_o^i\right)\right]$ is the processing time of a particular machine M_j to produce particular set of operational features OP_o^i;
- $\left[C_l^j\left(OP_o^i\right)\right]$ is a configuration of a machine to produce the particular set of operational features OP_o^i;

2. **Tool Changeover Time (TCT)**

The tool changeover time is the time required to change the tool of a particular machine depending on the set of operations assigned to the particular machine and the modules used. This is given by:

$$TCT = \sum_{o=1}^{O} TCTime_j\left[T_j^r(o)\right]\left[T_{j'}^r(o')\right] \quad (6.2.45)$$

Where

- $TCTime_j$ is the tool change time from a particular tool $T_j^r(o)$ to $T_{j'}^r(o')$ depending on the sequencing of the operations to be performed.

This depends on the number of tools accommodated on a machine and the size of the automatic tool changer.

3. **Configuration Change Time (CCT)**

It is the time required to change from one configuration to another. For e.g., adding or removing the modules from a particular machine, modifying the movement axis to change the system functionality, adjustments in the machining fixtures and positioning systems and other hard and soft reconfiguration activities required to be performed to meet the new operational and process plan requirements.

$$CCT = \sum_{o=1}^{O} CCTime_j\left[C_l^j(o)\right]\left[C_{l'}^j(o')\right] \quad (6.2.46)$$

Where,

- $CCTime_j$ is the machine configuration change time $C_l^j(o)$ to a new configuration $C_{l'}^j(o')$;

With this mathematical formulations, the total production time and the cost, based on the ability of the machines to schedule and perform all the operations can be calculated. Additionally, with this information, a manufacturer can select set of machines from the system, to select a fast production system or an averagely running production system based on the manufacturing conditions and the management preferences.

6.3. Summary

Two methodologies are presented. A Life Cycle Economic Analysis Methodology is developed to determine the Net Present Value of the RMS in comparison with DML and FMS. Secondly, a methodology to design and (re)configure the RMS is developed. The RMS should be designed when a new product family is introduced in the system. A RMS should be reconfigured when the Needed Reconfiguration Level is greater than 50%. The RMS should be reconfigured based on the new circumstances, and respectively, an appropriate reconfiguration mode should be selected to reconfigure the system either in functionality requirements or capacity requirements. Based on these two methodologies, a Life Cycle Economic Analysis Model (LCEAM) and Reconfigurable Manufacturing System Design Model (RMSM) are developed, which are shown in the next chapter.

Chapter 7: Case Study

This chapter presents the application and validation of the Life Cycle Economic Analysis Model (LCEAM) and Reconfigurable Manufacturing System Design Model (RMSM) developed from the steps presented in previous chapter. The focus is on the segment of an automotive cylinder head product family. The data used of the automotive cylinder head is approximately based on the actual data. Other required data is assumed based on reasonable approximation of what a major power-train manufacturer might consider. *Section 7.1. describes the design of the new RMS system, section 7.2. describes the incrementing the production capacity of the existing RMS system, section 7.3. describes reconfiguring the existing RMS configuration.*

7.1. Designing a new RMS

The rough machining of an automotive V6 cylinder head family is selected for this study, shown in Figure 32 . (Freinheit T. W., 2007). There are 141 features of this cylinder head, which can be grouped into 43 machining tasks. Due to its complexity, a cylinder head is ideal for this study because it permits many solutions for different configurations design.

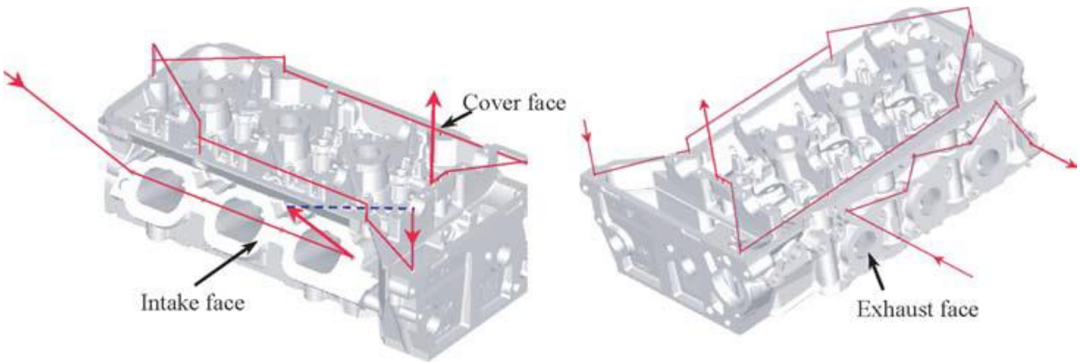

Figure 32 Automotive Cylinder Head

7.1.1. Reconfiguration Link (Product and Market Information)

Due to the excessive number of machining operations, only 6 machining operations are considered to show the behaviour of the RMS respective to different product and market scenarios. The 6 operations are required to be performed on three faces of the cylinder head, where 1 operation on Intake Face, 4 operations on Cover face and 1 operation on exhaust face. It is assumed that each face will be produced on a particular production stage. This is because each face requires separate fixturing and positioning as well as same group of machining operations can be accommodated to each respective stage. Figure 33 shows the number of operations, individual operation times and operation sequence of the Intake face, the cover face and the exhaust face. The total time needed for the rough machining of these 6 operations are considered to be 13.9 minutes, 13.2 minutes and 15.7 minutes respectively.

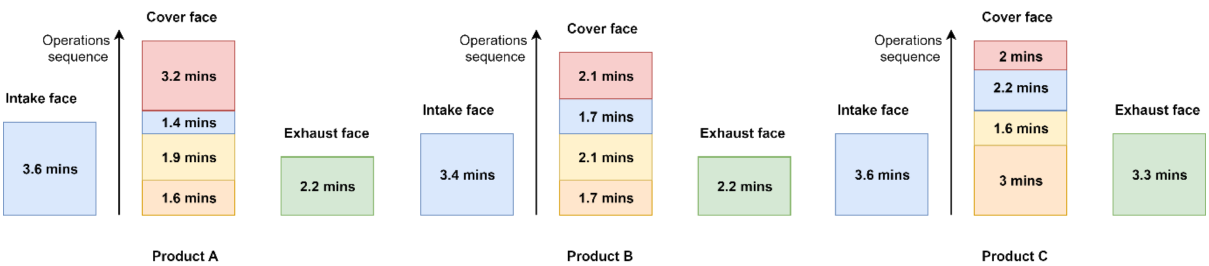

Figure 33 Processing times of the automotive cylinder head

Product Demand Information						
Period	**0**	**1**	**2**	**3**	**4**	**5**
Product A	40000	39000	39000	55000	56000	56000
Product B	44000	44000	46000	66000	68000	68000
Product C	59400	60000	60000	77000	77000	77000
Annual Demand	143400	143000	145000	198000	201000	201000

Table 7 Product Demand Information

Table 7 shows the demand of the products for life span of 6 years. The demand topology is stable and increases at period 3. Period 0 is considered to design the RMS. The daily production volume for Product A, Product B and Product C is 180 units, 200 units and 270 units respectively. The daily production volume is determined by the annual product demand divided by the annual working days. The product and market information is fed to reconfiguration link. Based on the product features and its demand, the products can be classified based on the process similarities. Based on the process similarities, each product will be defined based on the group of similar set of operations. For each set of operations, and the number of product faces, a manufacturer can plan tangible manufacturing elements required so that the manufacturing elements are utilised efficiently and the system and machine capability is planned around the product family. With this information, the manufacturer can plan the machine configurations and tools required on each machine and can also plan the number of production stages required in the configuration.

7.1.2. Production System Level Design

Initially, the RMS system will be designed based on the initial capacity and functionality requirements according to year 0 in Table 7. The production system level design consists of determining the number of modular base machines and the number of optimal module positions each base machine can allow subjective to our product features and its volume.

To begin with the production system level design, reasonable approximation production system assumptions are considered. The base machines in the system are identical. Each machine can allow tools up to a certain limit. Each base machine will accommodate different machine and tool configuration depending on the task and its location in the system. The Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR) of these machines are assumed to be 193 minutes and 16.7 minutes respectively. For our simplification, the availability rate of each module in the system is considered to be 90% and the production rate of each module is considered to be 400 units/day (Spicer, 2005). This following information is used in our RMSM, and the following information are acquired:

Product Demand Scenarios			
	Product A	Product B	Product C
Demand (Units/day)	180	200	270

Processing Time for total operations for product			
	Product A	Product B	Product C
Processing Time (mins)	13.9	13.2	15.7
Total time (mins)	13.9	13.2	15.7

Number of Operations			
	Product A	Product B	Product C
No. of operations	6	6	6

Assumptions	
Machine reliability	92%
Working time actual (mins)	1080
Working time available (mins)	1200

Machine Input Information		
Cost of Base machine	€	2,00,000
Cost per Module	€	50,000
Availability of base machine	92%	
Availability of a module	90%	
Production rate of module	400	

System Level Outputs

		Extra machine
Base Machines required	10	0
Resource Work Load	9381	
Machine Capacity Check	OK	

Machine Level Outputs

Number of modules	4
Max module positions	12
Optimal module positions	4
Machine Production Rate	966
Total Production Rate	9658
Resource Utilisation Rate	0.97
System Utilisation Rate	0.97
Slack Resource Capacity	277

Production System Flexibility

Production Volume Flexibility	0.03
Resource Flexibility	0.10
Product Mix Flexibility	0.05

Input
Output
Calculations
User Input

Figure 34 RMSM results at Production System Level

Figure 34 shows the data of the production system design. It shows the number of manufacturing elements determined. From Figure 34 RMSM , it is clear that the number of base machines required are 10. The base machines are modular can allow up to 4 module positions. Thus, each base machine will accommodate a pallet with 4 module positions. As the calculation of the number of base machines and the number of module positions in the system required are inter-related, a further clarification is provided to check how many modules can each base machine allow. Figure 35 a. Production Rate vs number of modules. b. Production rate per unit cost shows the production rate vs number of modules and production rate per unit cost. It is obvious that the production rate will increase as the number of modules (tools) on each base machine increases till a certain point. But, practically, one must check and ensure that the point where the production rate per unit cost is maximum. It is clear that the production rate per unit cost is maximum at 4 modules, and subsequently reduces as the number of modules increases, as shown in Figure 35 a. Production Rate vs number of modules. b. Production rate per unit costb. With this information, we decide that each machine will accommodate only 4 modules. Adding more than 4 modules on each machine can increase the complexity of the module configuration and thus can affect the tool performance (Spicer, 2005). Moreover, it will affect the customisability of the tool and the machine configuration. Hence, the pallet on the base machines will have 4 module positions, where each machine can accommodate maximum 4 tools.

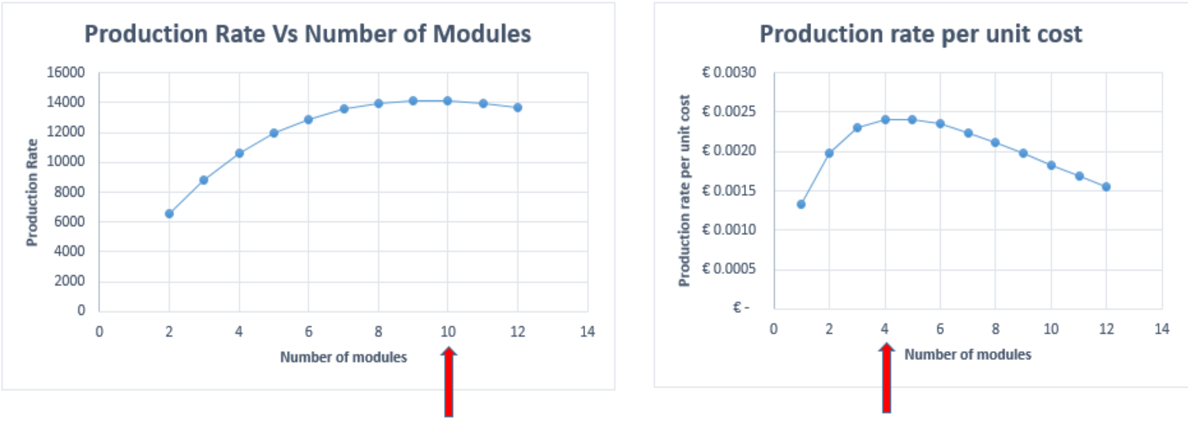

Figure 35 a. Production Rate vs number of modules. b. Production rate per unit cost

Figure 34 RMSM results at Production System Level also shows the Resource Utilisation (RU) rate, System Utilisation (actual output capacity relative to the theoretical capacity) (SU) rates and the Production System Flexibilities rate which is also essential to incorporate along with the decisions on the number of base machines and number of module positions. From the Figure 27, it can be observed that the RU and SU rate are 97%. The SU rate is same equal to the RU rate, as all the machines are considered to meet the production requirements. Moreover, the Production Volume Flexibility (PVF), Resource Flexibility (RF) and Product Mix Flexibility are 3%, 10% and 5% respectively. With high utilisation rate and nearly no flexibility, the system will resist any internal changes of any product functionality or demand change. Thus, to provide some flexibility to compensate the internal changes in the system, we decide to put an additional machine.

Product Demand Scenarios			
	Product A	Product B	Product C
Demand (Units/day)	180	200	270

Processing Time for total operations for product			
	Product A	Product B	Product C
Processing Time (mins)	13.9	13.2	15.7
Total time (mins)	13.9	13.2	15.7

Number of Operations			
	Product A	Product B	Product C
No. of operations	6	6	6

Assumptions	
Machine reliability	92%
Working time actual (mins)	1080
Working time available (mins)	1200

Machine Input Information		
Cost of Base machine	€	2,00,000
Cost per Module	€	50,000
Availability of base machine	92%	
Availability of a module	90%	
Production rate of module	400	

System Level Outputs

		Extra machine
Base Machines required	10	1
Resource Work Load	9381	
Machine Capacity Check	OK	

Machine Level Outputs

Number of modules	4
Max module positions	12
Optimal module positions	4
Machine Production Rate	966
Total Production Rate	10624
Resource Utilisation Rate	0.88
System Utilisation Rate	0.88
Slack Resource Capacity	1243

Production System Flexibility

Production Volume Flexibility	0.12
Resource Flexibility	0.53
Product Mix Flexibility	0.23

Input
Output
Calculations
User Input

Figure 36 Updated RMSM results at Production Level

Figure 36 shows the new RU, SU and Flexibility rates after adding one extra machine. The new RU and SU rate are 88%. The PVF rate is 12%. The RF is the machine capability which is 53%. This is because it is assumed that the machines in the system are capable of handling 8 operations, whereas currently it handles 6 operations. Whereas, the Product Mix Flexibility is 23%. This implies that the system's capability of accepting any new product within the family is just 23%. This is because we have assumed that only one machine in the system can allow a little flexibility to accept the new product.

Thus, with production system flexibility just around the product family and values greater than 0, we consider 11 machines with 4 modules ideal to meet our current production requirements. This elements act as an input to design our RMS cell configuration.

7.1.3. Plant Layout and Material Handling System Design

After determining the manufacturing elements from the reconfiguration model, now we design the plant layout system and the material handling system is designed concurrently. The focus is just on the cell design and its material handling connection.

Now we have the information that 11 machines are required in the system. This 11 machines are now to be arranged in a RMS (cellular) configuration. These machines are required to be arranged in appropriate production stages, where each production stage will perform similar set of operations. The products will be produced partially on each stage until all the tasks are performed. As the product has three different machining faces which require an appropriate machine configuration (fixturing and positioning) and module (tool) configuration (based on the operations accommodated on the stage), we decide that atleast three production stages should be considered. This will eliminate the need to change the machine configuration as long as the current product family is required to be manufactured.

For three stage configurations, 45 configurations are available. These configurations include symmetric as well as asymmetric configurations. We only consider symmetric configurations and eliminate asymmetric configurations. Also, the material handling system should be connected with each other machine (cross-over connection) in the system and should have a bi-directional sequence. We further eliminate these symmetric configurations depending on if the system is perfectly balanced and can meet the daily demand of 650 units. Thus, we check for the configurations having bottlenecks in the system. The available three stage configurations are presented in Figure 37.

To determine the bottleneck in the system, the cycle time must be known. The cycle time is the average time between completion of units. The total production time available per day is 1080 minutes, i.e. 2 shifts of 9 hours each. The total daily demand is 650 units. (for Product A is 180 units, Product B is 200 units and Product C is 270 units). The Cycle Time is $1080 \div 650 = 1.66\, mins$. Based on this information, the remaining configurations are evaluated. The processing times of each operation is already given in Figure 37 three stage configurations. The product with highest total processing time is considered to analyse the bottleneck in the configurations.

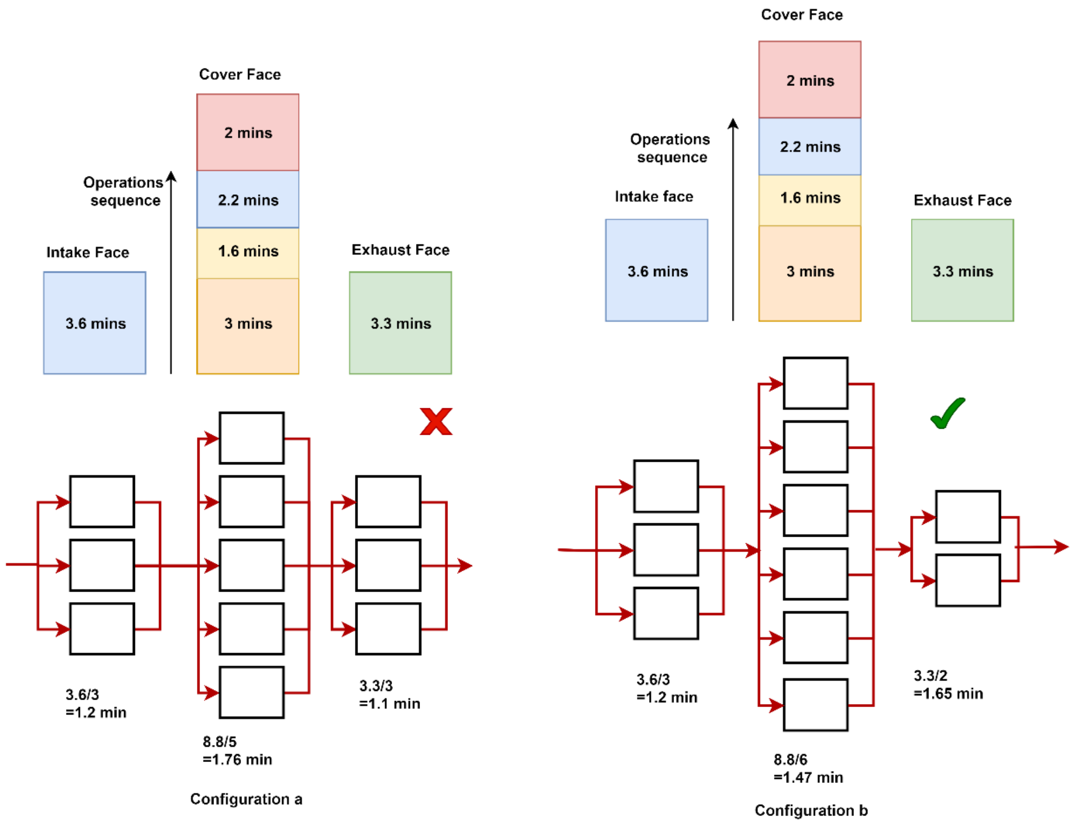

Figure 37 three stage configurations

Ultimately, two configurations are available, Configuration a and Configuration b as Figure 37. Configuration a has 3 machines in first stage, 5 machines in second stage and 3 machines in third stage. In stage 1, one part is produced in every 1.2 minutes, in stage 2 every 1.76 minutes and stage 3 every 1.1 minutes. Stage 2 is a bottleneck stage as it indicates that the maximum cycle time is t_{max} = 1.76 minutes which is greater than the system cycle time 1.66 minutes. Thus, this configuration a is unacceptable as it will not be able to meet our daily production requirements. Also, the daily throughput is 1080/1.76 = 613 units, less than the daily average demand of 650 units. For configuration b, the maximum cycle time is in stage 3, which is of 1.65 minutes, less than the system cycle time. Thus, this configuration can be accepted.

For four stage configurations, 120 configurations are available. Out of these 120 configurations, we eliminate asymmetric as well as the configurations having bottlenecks. Now, we have two configurations, configuration c and configuration d available as Figure 38. Out of 120 configurations, we have shown only 2 configurations as all 120 configurations cannot be analysed. Configuration c and configuration d have t_{max} of 1.65 minutes which is less than system cycle time 1.66.

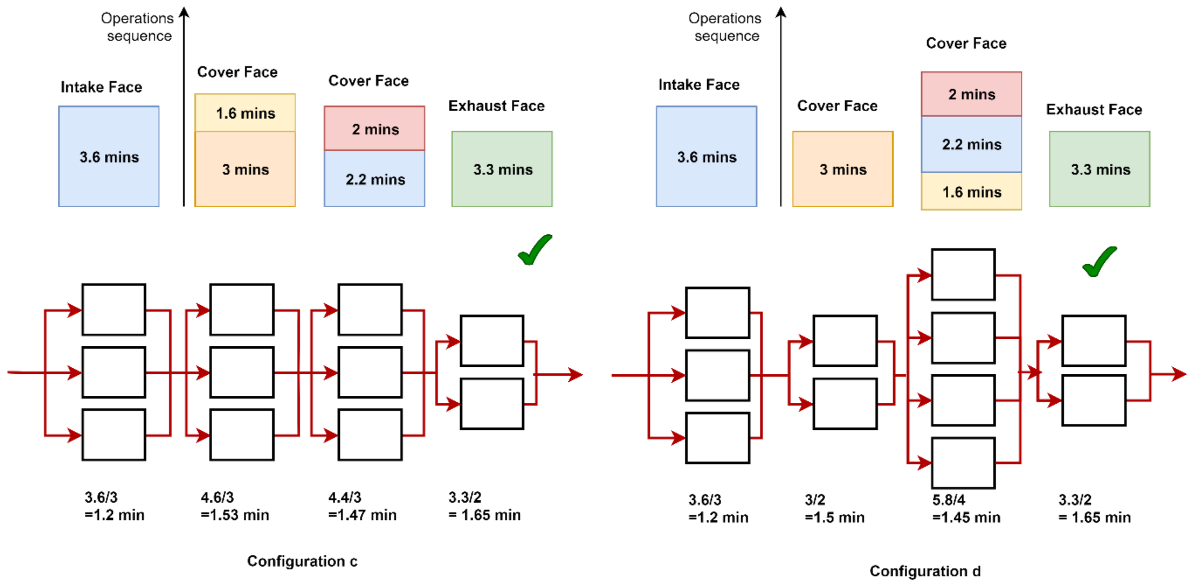

Figure 38 Four stage configurations

For 3 and 4 stages, out of 165 available RMS configurations, only 3 configurations are shown which do not have bottleneck in the system. These configurations are balanced configurations and can be further analysed based on their performance measures and other manufacturing preferences.

7.1.4. Performance Analysis

Now, out of 3 configurations available, one configuration has to be considered. This selection is further narrowed down on the basis of the following factors: System throughput at reliability less than 100%, Investment Cost, Scalability, i.e. the smallest increment of production capacity gained by adding a machine and Floor Space (ranked accordingly). Table 8 presents the measures of the following elements:

Performance Measures	**Configuration b**	**Configuration c**	**Configuration d**
System Throughput at R=92%	655 units	655 units	655 units
Investment cost	45,00,000 Euro	45,50,000 Euro	45,50,000 Euro
Scalability	90	90	90
Floor Space	15 m2	16 m2	12 m2

Table 8 Configuration Analysis

From Table 8 Configuration Analysis, a final choice is to be made from available configuration b, configuration c and configuration d. Configuration b, c and d meet the daily average demand and their throughput rate is 655 units. The second important factor is the investment cost. Since the machines has been fixed at 11, and as they are assumed identical, the investment costs are almost same. The only difference in the investment costs are the material handling costs associated with each configuration. For configuration b, the total investment cost is 45,00,000 Euro and configuration c and configuration d costs 45,50,000 Euros. Adding an additional production stage increments little productivity of the system. But on the other hand, it also increases the material handling costs and transportation time which can affect the daily production costs and time. Thus, a wise compromise has to be made analysing all the evaluation parameters.

Thus, configuration b is proposed which have throughput rate of 655 units at system reliability rate 92%. The total investment cost is 45,00,000 Euros with Scalability of 90% and floor space of 15m2.

7.1.5. Proposed RMS Design

The proposed configuration design is shown Figure 39 Proposed configuration design, with number of machines 11. The tools considered on each machine is 4.

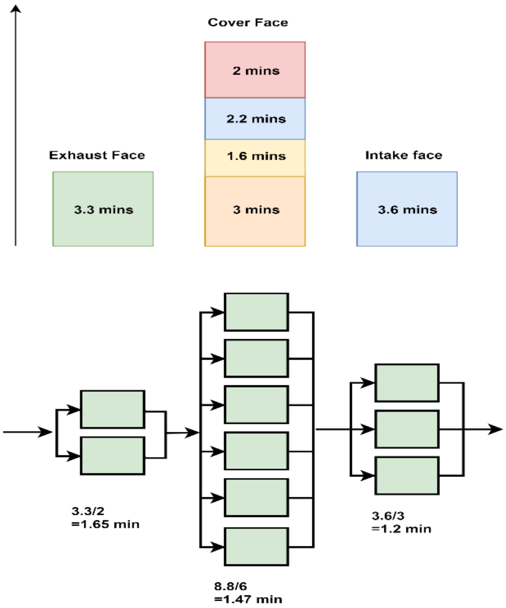

Figure 39 Proposed configuration design

For the proposed configuration, our ultimate objectives, the daily production cost and daily production time to meet our daily volume requirements are determined.

Market and Product Information			
Number of Products	3		
Product Demand	180	200	270
Number of Operations on each product	6		

System Design Input Information	
Number of machines	11
Number of modules	4
Number of stages	3

Cost Information Input		
Cost of a machine	€	2,00,000
Cost of a module	€	50,000
Cost of Material Handling System	€	50,000
Cost of using a machine	€	7
Cost of using a module	€	3

Time Information Input	Product A	Product B	Product C
Total Processing Time of product i	13.9	13.2	15.7
Setup time of product i	0.2	0.15	0.2
Tool changeover time	0.05	0.06	0.07

Reconfiguration Input		
Number of machines added/removed	0	
Number of tools reconfigured	0	
Machine Reconfiguration Cost	€	6,000
Module Reconfiguration Cost	€	200
Total Reconfiguration Time	0	

Total Investment Cost

Machine Investment Costs	€	22,00,000
Module Investment Costs	€	22,00,000
Material Handling Investment Costs	€	1,50,000
Total Investment Cost	€	45,50,000

Total Production Phase Cost (Euro)

Machine Usage Cost	€	3,296
Tool Usage Cost	€	5,650
Machine Configuration Cost	€	-
Tool Change Cost	€	-
Total Cost	€	8,945

Total Production Time (mins)

Processing time of a particular operation	864
Tool changeover time	47.52
Configuration Change time	0
Total Time	911

Legend
Input
Output
Calculations
User Input

Figure 40 Daily Production Phase cost and Time Results

Figure 40 Daily Production Phase cost and Time Results shows the total investment cost, total daily production phase cost and total production time acquired from the Reconfiguration Model. As all the machines are considered functioning in the system, the total daily production costs are 8,945 Euro. This is determined by assuming the hourly machine usage cost as 7 Euro and Tool usage cost as 3 Euro. Whereas, the total production time is 911 minutes. This total time refers to processing time of daily production volume, tool changeover time and configuration change time. As observed in the Figure 34 the reconfiguration costs and reconfiguration time considered is 0. This is because our system is designed new and no reconfiguration is yet performed.

Subjective to product and market requirements, the RMS system is designed incorporating modularity, scalability and the plant layout system and material handling system is designed incorporating integrability and customisability. The Reconfiguration Model is capable to make decisions and facilitates in making decisions related the number of manufacturing elements required and check how the system will perform. Respectively, to the changing requirements, decisions on selecting a fast production system with high production costs or an averagely running production system with low production costs can be made.

7.2. Life Cycle Economic Analysis

In Life Cycle Economic Analysis, the Net Present Value (NPV) of the RMS is determined in comparison with DML and FMS to justify whether investing in RMS is a right choice for this particular product and demand topology.

From the previous section, the design variables are determined. The design variables are the manufacturing equipments required to meet the initial product and market requirements. With these variables as the input and other assumptions, the NPV of the systems are determined.

Product Demand Information						
Period	**0**	**1**	**2**	**3**	**4**	**5**
Product A	40000	44000	39000	41000	41000	40500
Product B	44000	44000	44000	45000	45000	45500
Product C	59400	60000	60000	60000	61000	61000
Annual Demand	143400	144000	143000	146000	147000	147000

Table 9 Demand Information for NPV

Table 9 shows the annual demands of Product A, Product B and Product C for time horizon of 6 years. The following are the modelling assumptions:

- Number of systems: DML, FMS, RMS
- Number of products: I = 3;
- Number of periods (time horizon): J = 6;
- Capital interest rate: r = 10%;
- Product contribution margin (Units of Money), CM= 20 Euro

The following are the NPV determined for DML, RMS and FMS.

For DML, as clarified in previous chapter, each line will produce only one product at the maximum planned capacity of the DML line. Table 10 Capacity and Cost Information the capacity (throughput/year) and costs assumed for each of the line.

DML Capacity and Cost Information		
DML	Capacity	Cost
Line 1	48000	€ 3,00,000
Line 2	32000	€ 2,50,000
Line 3	20000	€ 2,00,000

Table 10 Capacity and Cost Information

Knowing the capacity of each line and the annual demand of each product, the number of lines determined are presented in Table 11 DML equipments required

Number of Lines Required				
Product	Demand	DML Line	Lines Required	Additional Lines
Product A	39600	Line 1	1	0
Product B	44000	Line 2	2	0
Product C	59400	Line 3	3	0

Table 11 DML equipments required

Table 11. shows that 1 line is required for Product A, 2 and 3 lines for Product B and C respectively. The NPV determined for DML system is ***7,162,124 Euros***.

For RMS, we already know the number of base machines and modules required from the production system level design in previous section. From this, we determine the α^{RMS}, the capacity factor and β^{RMS}, the investment factor of the RMS.

Figure 41 LCEA Model Results shows the α^{RMS} parameter value obtained is 0.1. Thus, we equate, $\beta^{RMS} = \alpha^{RMS} = 0.1$. From this, we get the base machine cost, the module cost and the capacity in relevance with DML cost and capacity assumptions. The base machine cost is 75,000 Euro and individual module costs is 37500. The module cost is considered to be 50% of the base machine. The base machines and the modules are determined respectively to produce the products features depending on the location of the machine and tools.

RMS System Input Information

RMS Capacity Information		
α^{RMS}	C^{DML}	C^{RMS}
0.1	100000	3333

RMS Cost Information				
β^{FMS}	I^{DML}	Base Machine Cost	Module factor	Module Cost
0.1	750000	75000	50%	37500

Number of RMS shells and modules required			
Base Machines	Modules	Extra BM	Extra Module
11	43	0	0

Figure 41 LCEA Model Results for RMS

With these parametric relationship of RMS comparison with DML, the NPV of the RMS system is ***2,191,683 Euros.***

For FMS system, the technological factor α^{FMS} is assumed equal to the α^{RMS}. The machines assumed in FMS system are general purpose CNC machines able to produce all product features on each CNC machine. Thus, the high the functionality of the CNC machine, the higher is the investment cost of purchasing the machine. With this, we assume that β^{FMS} =0.3, which is the investment factor. The investment factor is considered dependent on how many products a CNC can produce. Thus, with 3 products on the system. the β^{FMS} =0.3, i.e. the cost of each CNC machine will be 3 times that of the base machine of the RMS. Figure 42 shows the results obtained for FMS.

FMS System Input Information

FMS Capacity Information		
α^{FMS}	C^{DML}	C^{FMS}
0.1	100000	10000

FMS Cost Information		
β^{FMS}	I^{DML}	I^{FMS}
0.3	750000	225000

Number of FMS units required			
Demand	Capacity	Units Required	Extra Units
143000	10000	15	0

Figure 42: LCEAM Results for FMS

With this relation, the NPV of the FMS system determined is ***-2,299,680 Euros.***

Table 12 System configurations and NPVs shows the system configuration and their NPVs. To meet the current product and market requirements, total 5 sub-DML lines are required. One sub-system for Product A, 2 sub-systems for Product B and 3 sub-systems for Product C. The NPV is 7,162,124 Euros. For a FMS system, 15 general CNC machines are required. The NPV of the FMS system is -2,299,680 Euros. For RMS, 11 base machines with total 43 modules are required in the system. The NPV is 2,191,683 Euros.

System	System Configuration	NPV (euros)
DML	(1,2,3)	7,162,124
FMS	15	-2,299,680
RMS	(11,43)	2,191,683

Table 12 System configurations and NPVs

From Table 12*, it is concluded that the NPV of the DML is the best option for this product and market information. This is due to the stable market demand and high throughput rate of the lines, DML performs better in this situation. RMS is the second best option. Although the initial investment cost is high, the modular structure of the base machines and the modules can be reutilised in the production requirements. Thus, reconfigurability can bring value. The FMS has a very high investment costs because of its high functionality. Due to the low capacity and high functionality, the FMS units required are high. Thus, investing in this system is not a right choice.*

7.3. Changing the existing RMS capacity

In the previous section, a new RMS system based on the initial market requirements is designed. Now, let us suppose, that in period 4 as shown in Table 7, the demand increases. Based on this demand information, the daily production volume estimated is 900 units/day, which is for Product A as 250 units, Product B as 300 units and Product C as 350 units per day. The existing RMS design configuration, as proposed in previous section, can only produce maximum 650 units/day. Thus, the existing RMS configuration is unable to meet the current increased demand requirements and thus, the system is required to be incremented to increase its resource capacity (production capacity).

To increment the capacity, there are three choices: increase an additional working shift, increase number of tools or increase the number of machines. Generally, increasing an additional work shift for the particular year. Assuming 20 employees working in the plant and their average wages as 20 Euro/hour will cost us 704,000 Euros. Secondly, we can either put an additional module on the machine in the stage which forms the bottleneck after the increased demand. As the demand is increased, the new cycle time is 1080/900 = 1.2 minutes. With the existing configuration design, Figure 39 Proposed configuration design, Stage 1 and stage 2 does not satisfy this cycle time, as the maximum time is 1.65 minutes and 1.47 minutes respectively. Thus, additional modules can be put on the machine in stage 1 and stage 2. But currently, as the base machines have pallet with only 4 module positions and all the positions have a tool accommodated, there is no choice rather than adding extra machines. Thus, the new requirements of the production system level are determined by the RMSM.

Product Demand Scenarios			
	Product A	Product B	Product C
Demand (Units/day)	250	300	350

Processing Time for total operations for product			
	Product A	Product B	Product C
Processing Time (mins)	13.9	13.2	15.7
Total time (mins)	13.9	13.2	15.7

Number of Operations			
	Product A	Product B	Product C
No. of operations	6	6	6

Assumptions	
Machine reliability	92%
Working time actual (mins)	1080
Working time available (mins)	1200

Machine Input Information	
Cost of Base machine	€ 2,00,000
Cost per Module	€ 50,000
Availability of base machine	92%
Availability of a module	90%
Production rate of module	400

System Level Outputs

		Extra machine
Base Machines required	13	2
Resource Work Load	12930	
Machine Capacity Check	OK	

Machine Level Outputs

Number of modules	4
Max module positions	12
Optimal module positions	4
Machine Production Rate	966
Total Production Rate	14487
Resource Utilisation Rate	0.89
System Utilisation Rate	0.89
Slack Resource Capacity	1557

Production System Flexibility

Production Volume Flexibility	0.11
Resource Flexibility	0.48
Product Mix Flexibility	0.21

Legend: Input; Output; Calculations; User Input

Figure 43 RMSM results at production system level

Figure 43 RMSM results at production system level shows the new requirements determined. Based on the new demand considered as input to the Reconfiguration Model, 15 number of machines with 4 modules are required. This implies that 4 additional machines are required in the existing configuration. Moreover, the Resource Utilisation rate is checked and is 89%. As observed, the Production Volume Flexibility (PVF), Resource Flexibility and Product Mix Flexibility rates are 11%, 48% and 21%. This meet out criteria. Thus, it is decided to put additional 4 new machines in the existing system.

Adding the extra machines requires careful planning so that the performance of the existing configuration does not gets affected, no bottlenecks are formed and the system configuration gives the highest throughput rate. Moreover, the adding the new machines should have minimise effort and has to be connected with the material handling system. Considering this information in account, it can be noticed, Figure 44, only stage 3 satisfies the system cycle time of 1.2 minutes (shown in green). Stage 1 and stage 2 have bottleneck (shown in red) as T_{max} is 1.65 minutes and 1.47 minutes respectively. Thus, to avoid these bottlenecks and balance the system, we will add the additional machines in stage 1 and stage 2. Utmost care should be taken that the process plan is not required to be changed and the sequencing of the machining tasks remain the same. Thus, taking in to account the following conditions, one machine is added in stage 1, 2 machines in stage 2 and 1 machine in stage 3. Doing so, the existing configuration satisfies the system cycle time and also provides high throughput rate of 982 units per day.

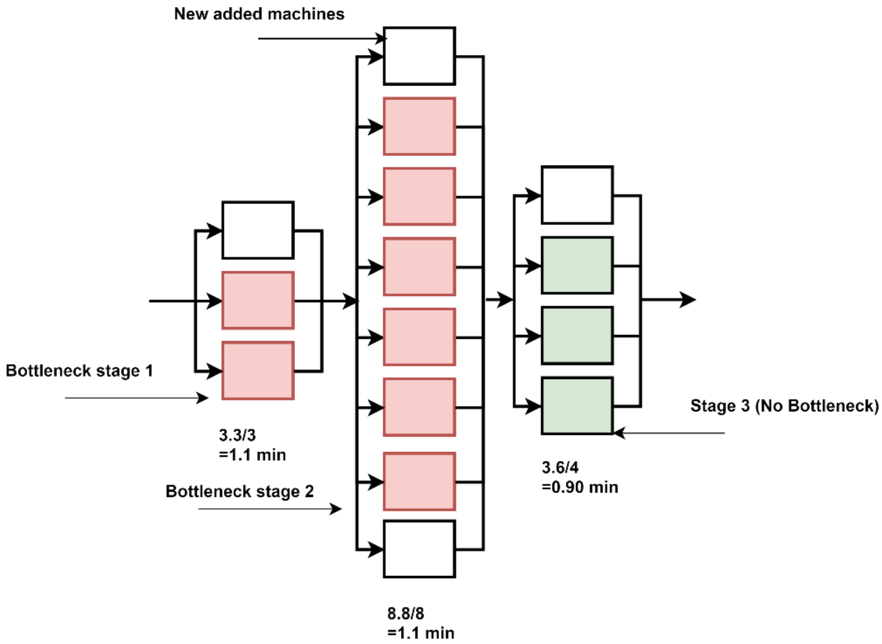

Figure 44 New Configuration

The existing system is scaled up to meet the new production requirements. Thus, modularity of the system highly influences the scalability in the system and make the RMS systems scalable adaptable in nature.

The RMS can be reconfigured to meet the changing functionality and demand requirements. The expansion cost for this scenario, for adding 4 base machines is 300,000 Euros. Whereas in case of DML, the expansion cost is 1,050,000 Euros, i.e. adding an additional line for each of the products. Further justifying the investment choice, RMS have low expansion cost in comparison with DML. Thanks to the modular and scalable architecture, the RMS can be easily converted and scaled subjectively in comparatively low costs.

7.4. Reconfiguring existing RMS system

Let us suppose that after a certain time horizon, the current product family, i.e. automotive cylinder head family is slowly phasing out from the market and a new product family is decided to be manufactured on the existing system. The priority now is to fulfil the new market requirements of the new product family introduced and meanwhile continue to manufacture the existing product family, the automotive cylinder head family as long as it completely phase outs from the system. The new product part family is the power transmission case of the automotive cylinder head (Bole RP & Co., Ltd., 2016), as shown in Figure 45. For the understanding, the existing product family, the automotive cylinder head is named as Family A and the new product family, the power transmission case as Family B.

Figure 45 Powertrain head

7.4.1. Reconfiguration Link (Product and Market Information)

Family B consists of three similar power transmission cases for the Product Family A. The demand of Family A reduces from 900 units/day to 300 units/day whereas the demand for Family B is 530 units/day, where Product A is 160 units/day, for Product B 180 units/day and for Product C is 190 units/day. Total 8 number of operations are required to be performed on the Product Family B. The individual processing times of each operation are Figure 46. whereas the total time is 15.6, 14.8 and 14.6 minutes respectively.

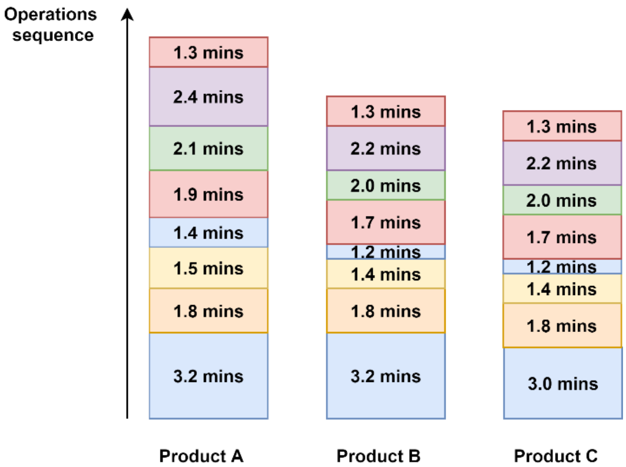

Figure 46 Processing times of each operation

These operations are majorly finishing operation grouped into milling, drilling, boring, spot facing and tapping. Based on the common functionality of the both the families, the manufacturer can decide whether the existing tools can be reutilised for the new product family B or new modules are required. In this case, it is considered that only one machining face where the machining tasks is required to be performed. Based on the product functionality and the demand, the manufacturer can further plan the resources and also can plan the number of production stages.

As a new product family is introduced in the current system (reconfiguration driver), thus it is necessary reconfigure the existing RMS system in capacity as well as functionality (reconfiguration mode). Subsequently, the reconfiguration process is performed.

7.4.2. Needed Reconfiguration Level (NRL)

As, we are reconfiguring the existing system, the new Needed Reconfiguration Level (NRL) is determined before reconfiguring the existing system. Based on NRL measure, the reconfiguration process is performed.

The NRL is measured from the Agility Level required for configuration, status of Manufacturing System Design and New Circumstance. The agility level is divided into four categories: Technology (TE), People (PE), Management (MA) and Manufacturing Strategies (M). The TE, PE, MA and M agility levels are assumed to be 75%, 90%, 90% and 35%. The needed agility level, i.e. the agility level required to configure the system is determined by calculating the relative weights for TE, PE, MA and M as shown in fig xx. The relative weights are determined by Analytical Hierarchical Process (AHP) which is estimated as 0.13,0.42, 0.23 and 0.22. The detailed explanation of the calculation of relative weights are further explained in the appendix.

Recommended Attribute Values			
Main Element	**Attribute**	**Range of Value**	**Attribute Value**
Production System Size	Small-sized system	0.1-1	n/a
	Medium-sized system	1.0-2.0	1
	Large-sized system	1.0-2.0	n/a
Resource Capacity (Reliability)	Resource Capacity	0.1-1	0.1
	Resource Flexibility	0.1-1	0.24
	Resource Utilization	0.1-1	0.89
Product Size and Limitations	Physical product & limitations	0.1-1	0.5
Machine Size and Weight	Small Size	0.5-1	n/a
	Medium Size	1.0-2.0	1
	Large Size	3.0-6.0	n/a
Plant Layout System	Cellular Layout	1	1
	Product Layout	1	1
	Functional Layout	3.0-5.0	n/a
Material Handling System	Material Handling Equipment	1.0-5.0	3
	Material Handling storage system	1.0-3.0	1
	Identification system	1.0-2.0	1
New Circumstance	New Product	1	1
	Product Development	1	1
	Changing Demand	1.0-2.0	1

Not applicable
Acceptable
Not acceptable

Figure 47 Recommended and Feasible values

To determine the configuration required for the Manufacturing Systems Design, the attributes Production System Size and Functionality (PSS & F), Plant Layout System (PLS) and Material Handling System (MHS) are evaluated.

For the attribute PSS and F, it can be suggested that the feasible and recommended attribute values are presented in Figure 47. These values represent how much effort is necessary to reconfigure each component in the manufacturing system. Now, as our production system size is medium-sized with 15 number of machines in the system. Thus we assume not much reconfiguration effort will be required, as practically, the number of machines to be configured may be less than 15. Thus from Figure 47, for Production System Size, we select Medium-sized system. With the recommend value from 1-2, we select 1. Similarly, the attributes of PSS & F are Production System Size, Resource Capacity, Resource Flexibility, Resource Utilisation and Physical Product size and limitations, we consider the values to reconfigure the particular attribute as 1, 0.7, 0.9, 0.50, 0.3 and 1. This values are considered because as the new product introduced has changed functionality, the resource capability (flexibility) will require high reconfiguration effort. This implies that the machines will require rearrangement of the tools. Followed by, enough effort is required to change the system capacity. With all these values, ($1 \times 0.7 \times 0.9 \times 0.5 \times 0.3 \times 1 = 0.09$) we determine the attribute value for PSS & F as 0.09, as shown in Figure 48.

Current Agility Level		
Attributes	Relative Weight	Attribute Value
Technology Infrastructure (TE)	0.13	75%
People Infrastructure (PE)	0.42	70%
Management Infrastructure	0.23	90%
Manufacturing Strategies Infrastructure	0.22	35%

Status of Manufacturing Systems Design		
Attributes	Relative Weight	Attribute Value
Production System Size & Functionality (PSS & F)	0.5	0.09
Plant Layout System (PLS)	0.25	1
Material Handling System (MHS)	0.25	3

New Circumstances		
Attributes	Relative Weight	Attribute Value
New Product	0.25	1
Product Development	0.25	1
Changing Demand	0.5	1

Figure 48 Relative Weights and attribute values of each elements

For the Plant Layout System, the cellular layout is considered which will require high reconfiguration effort. Thus, the attribute value is taken as 1. For Material Handling System (MHS), high reconfiguration effort is required. This is because the machines in the system will require rearrangement and thus the material handling equipments will also require reconfiguration. Thus, this value is taken as 3. The Material Handling storage system and the Identification System is assumed to be same and assume it will require not much changes. Thus the attribute value is considered as 1 for each. With this information, the status of Manufacturing Systems Design is determined presented in Figure 48.

Finally, for the New Circumstance, as the product is new with new changed demand requirements and change functionality, we have considered the attribute value for each as 1.

Figure 47. shows all the attribute values considered. Figure 48 shows the relative weights and the attribute values for each element. The relative weights are explained in detail in appendix. With this, we measure the NRL. The NRL is given in Figure 49.

Level of Reconfiguration		
Attributes	Relative Weight	Attribute Value
Needed Agility Level	0.4	0.32
Status of Manufacturing System Design	0.4	1.05
New Circumstances	0.2	1

Level of Reconfiguration
74.87%

Reconfiguration is required

Figure 49 Needed Reconfiguration Level

With this, the NRL measured is 74.87%. The level of reconfiguration is greater than 50%, thus we accept that the reconfiguration is required. The Manufacturing System' Design implies that the reconfiguration effort required is 41.89%, with Needed Agility Level of 12.98% and New Circumstances (NC) of 20%. Thus, it is recommended that the MSD should be configured at production system level, plant layout system and material handling system level. The MSD is related to the NC. In case of just product change or functionality change, the reconfiguration effort require to MSD will be less.

7.4.3. Production System Design

While reconfiguration, the production system design requires careful planning, so that the manufacturing resources can be reutilised to manufacture both the product families, Family A and Family B at the system. The new data required are determined with the Reconfiguration Model, as shown in Figure 50 Reconfiguration results from RMSM.

Product Demand Scenarios			
	Product A	Product B	Product C
Demand (Units/day)	160	190	180

Processing Time for total operations for product			
	Product A	Product B	Product C
Processing Time (mins)	15.6	14.8	14.5
Total time (mins)	15.6	14.8	14.5

Number of Operations			
	Product A	Product B	Product C
No. of operations	8	8	8

Assumptions	
Machine reliability	92%
Working time actual (mins)	1080
Working time available (mins)	1200

Machine Input Information	
Cost of Base machine	€ 2,00,000
Cost per Module	€ 50,000
Availability of base machine	92%
Availability of a module	90%
Production rate of module	400

System Level Outputs

		Extra machine
Base Machines required	9	0
Resource Work Load	7918	
Machine Capacity Check	OK	

Machine Level Outputs

Number of modules	4
Max module positions	12
Optimal module positions	4
Machine Production Rate	966
Total Production Rate	8692
Resource Utilisation Rate	0.91
System Utilisation Rate	0.91
Slack Resource Capacity	774

Production System Flexibility

Production Volume Flexibility	0.09
Resource Flexibility	0.43
Product Mix Flexibility	0.14

Legend
Input
Output
Calculations
User Input

Figure 50 Reconfiguration results from RMSM

From the Figure 50, we require 9 number of base machines with pallet with 4 module positions on it to meet the new requirements of Family B. The Resource Utilisation rate is 0.91 and the production system flexibility values of Production Volume Flexibility, Resource Flexibility and Product Mix Flexibility are 9%, 43% and 14%. Initially, the system designed for Product Family A had the capability of performing 8 operations. Family A had only 6 operations to be performed, thus the flexibility in the system was sufficient. Now, to manufacture Family B, all the capability is utilised. Thus, the Resource Flexibility of the system was 0. Thus, we recommend that the machines need reconfiguration and the new capability of the system should be designed with 10 operations. With this information, we calculated the RF and is 43%. Now, we perform necessary reconfiguration activities to reconfigure the system to manufacture both product families and balance the system.

7.4.4. Plant Layout and Material Handling System Design

With 9 machines required to manufacture Family B, we assign rest of the machines in the system for Family B. With this approach, a new configuration design is planned.

For Family A, the new cycle time is 3.6 minutes, i.e. actual working time per day divided by number of units to be produced per day (1080/300 =3.6 minutes). The new configuration for Family A is 6 machines arranged in 3 stages, shown in Figure 51: where 1 machine in stage 1, 3 machines in stage 2 and 2 machines in stage 3. No other configurations are available because of the product machining requirements and the system throughput time.

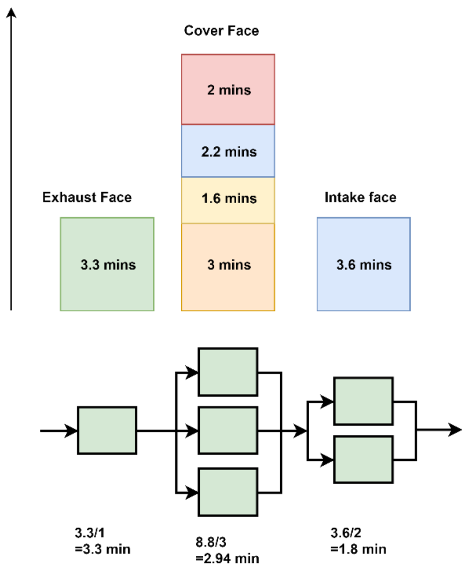

Figure 51 New Configuration design for Family A

For Family B, the number of machines available are 9. To produce Family B, no different fixturing and positioning systems are required. As there is only one face, the machines are assumed identical with same fixturing systems and having required set of modules on each machine to produce the required functionality. Thus, with no restriction of number of stages, the configurations are visualised in 2, 3 and 4 stages. For daily working time of 1080 minutes and 530 units per day, the new cycle time for Family B is 1080/530 = 2.03 minutes.

For two stages, 8 number of RMS configurations are available. Out of 8, symmetric configurations with no bottlenecks are accepted. Only two configurations shown in Figure 52, Configuration a and configuration b meet this criteria, where t_{max} = 1.975, less than the system cycle time of 2.03 minutes.

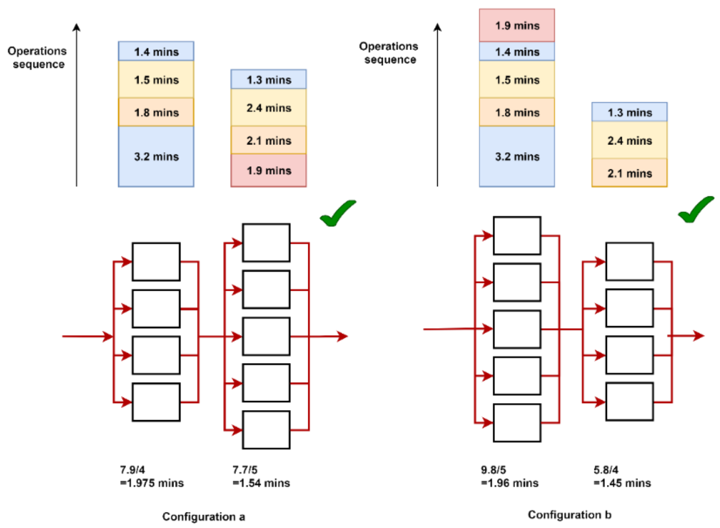

Figure 52 Two stage configurations for Family B

*For three stages***,** 28 RMS configurations are available. Asymmetric configurations are eliminated and symmetric configurations are shown in below Figure 53. Out of 5 symmetric configurations are available. From these configurations, only one configuration, configuration f meets the system cycle time requirement. Others have bottlenecks in the stages and are unaccepted.

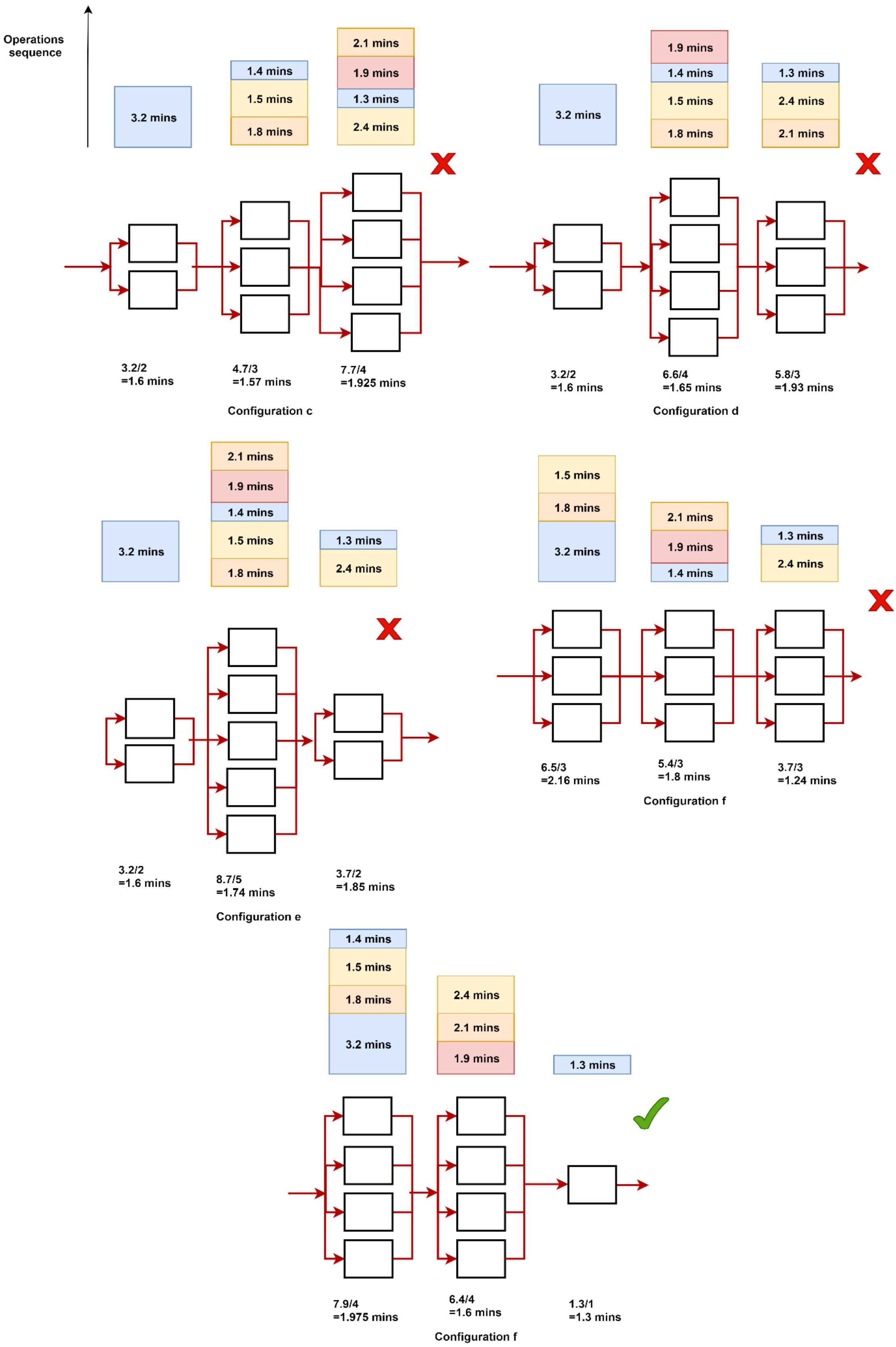

Figure 53 Three stage configurations for Family B

The additional stages are shown just for the representation. But it should be taken into consideration that, as the number of stages increase, the system cost and the material handling cost will increase and the floor space will increase.

7.4.5. Performance Analysis

From the above configuration presented, only 3 configurations are acceptable which do not have bottlenecks in the system. This configurations are further analysed based on their reconfigurability index, i.e. measure of changing to the existing configuration to the new configuration and performance measures, i.e. throughput rate of the system.

To accompolish the planned configuration, we need to choose between the available configurations to change the existing system to the new configuration. Figure 54 shows possible ways to change the existing configuration to required configuration. We analyse these solutions based on the Reconfiguration Smoothness Value (RS) and the throughput rate of the system, as apprarently only deciding based on the throughput of the system is not important. This is because the RS value determines the amount of reconfiguration effort and the ramp up time involved. Thus, the RS values and throughput rates are analysed and represented Table 13 System Throughput and RS values. These RS values are determined based on the Reconfiguration Planning rules as explained in Chapter 5, Section 5.2.4. This planning rules consists of both, the soft and hard type reconfiguration activities required to be performed to achieve the required reconfiguration design. The detailed steps of determining the RS are presented in appendix.

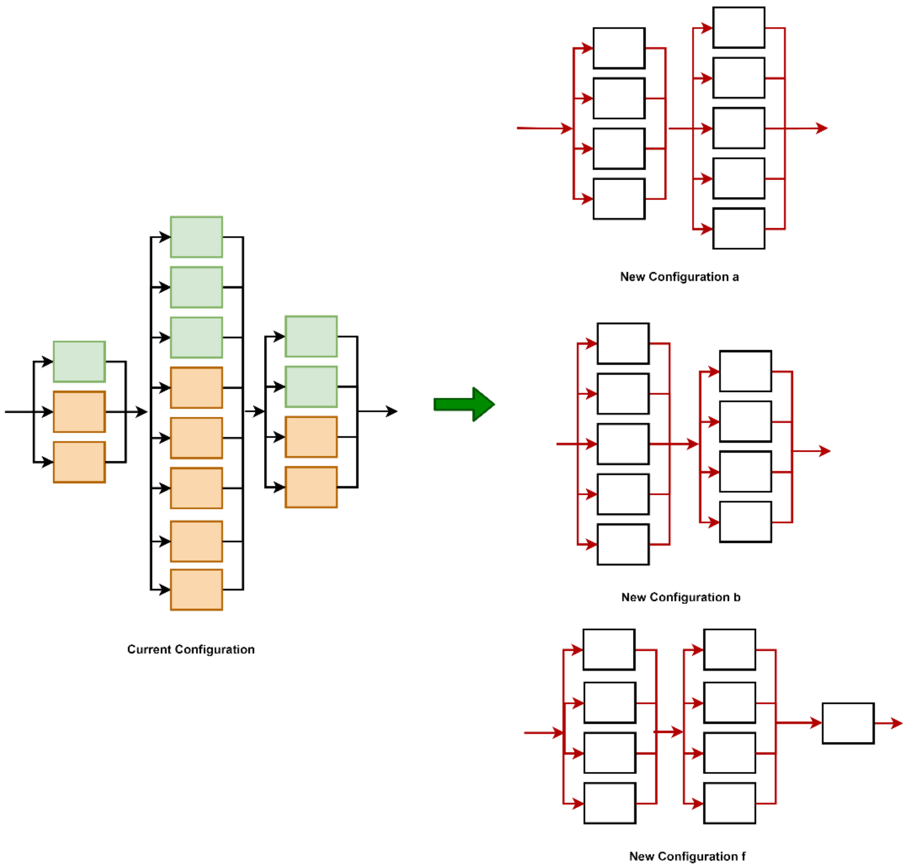

Figure 54 Approaches to configure existing RMS design to required design

Analysing the RS and throughput rate, configuration f is made an ideal choice. This is because the RS value is 0.07. This implies that less reconfiguration activities are required to be performed comparatively in reconfiguring to another configuration.

Configurations	System Throughput	Reconfiguration Effort
Configuration a	547	0.087
Configuration b	551	0.106
Configuration f	547	0.07

Table 13 System Throughput and RS values

Thus, with RS measure of 0.07 and system throughput of 547 units/day, configuration f choice is made. The lower the RS metric, the low is the reconfiguration effort, thus substantially saving the reconfiguration time, reconfiguration cost and reducing the ramp up time.

7.4.6. Proposed RMS Design

Figure 55. represents the new reconfiguration design to produce Product Family A and Family B. The system throughput is 875 units/day, where 328 units/day for Family A and 547 units/day for Family B, meeting the daily production requirements.

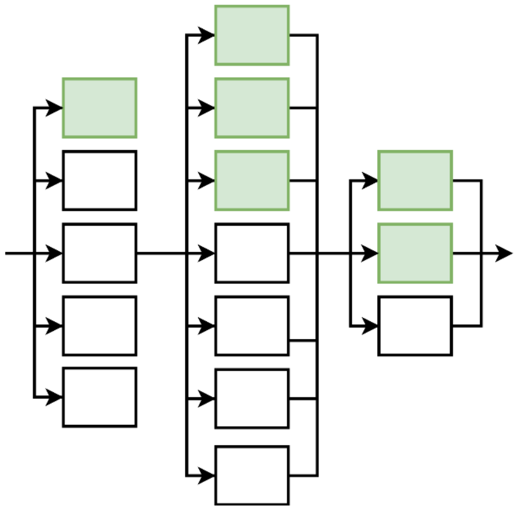

Figure 55 New Reconfiguration Design

Ultimately, now the final objectives, the total production phase cost and total production time is calculated. These costs and times now include reconfiguration costs and time, as reconfiguration is performed.

Market and Product Information			
Number of Products	3		
Product Demand	160	190	180
Number of Operations on each product	8		

System Design Input Information	
Number of machines	9
Number of modules	4
Number of stages	3

Cost Information Input		
Cost of a machine	€	2,00,000
Cost of a module	€	50,000
Cost of Material Handling System	€	50,000
Cost of using a machine	€	7
Cost of using a module	€	3

Time Information Input	Product A	Product B	Product C
Total Processing Time of product i	15.6	14.8	14.5
Setup time of product i	0.2	0.15	0.2
Tool changeover time	0.05	0.06	0.07

Reconfiguration Input		
Number of machines added/removed	2	
Number of tools reconfigured	8	
Machine Reconfiguration Cost	€	6,000
Module Reconfiguration Cost	€	200
Total Reconfiguration Time	480	

Total Investment Cost

Machine Investment Costs	€	18,00,000
Module Investment Costs	€	18,00,000
Material Handling Investment Costs	€	1,50,000
Total Investment Cost	€	37,50,000

Total Production Phase Cost (Euro)

Machine Usage Cost	€	2,829
Tool Usage Cost	€	4,849
Machine Configuration Cost	€	12,000
Tool Change Cost	€	1,600
Total Cost	€	21,278

Total Production Time (mins)

Processing time of a particular operation	891
Tool changeover time	51.84
Configuration Change time	480
Total Time	1422

Input
Output
Calculations
User Input

Figure 56 Total Daily Production Cost and Time

Figure 56 shows the total production phase cost and production time. While performing reconfiguration at the system level, we removed one machine from stage 2 and one machine from stage 3 and added both the machines in stage 1. Additionally, we changed the machine configurations of these 2 machines as the machines are relocated and set according to the machining features in the respective stages. Practically, other machines also require some configuration at the machine level, i.e. changing the module configurations according to the required operations sequence. But for the simplicity, we have just demonstrated the example of reconfiguring two machines. The ramp up time assumed is 480 minutes whereas the reconfiguration cost of one machine is 6000 euros and reconfiguring one module is 200 Euros. This contains both the hard reconfiguration cost and soft reconfiguration cost. The total production phase costs are 21,278 Euro whereas the total production phase time is 1422 minutes, with the ramp up time of 480 minutes.

Chapter 8: Discussions

In this chapter, the results of the research are discussed. First, a discussion of the developed decision support methodology to design the RMS is presented. The gaps in this methodology and the limitations are discussed. Secondly, the results obtained from this methodology are further interpreted and their limitations are discussed.

1. Methodology Discussion

According to the research question 2, what are the characteristics of the RMS, the RMS characteristics are modularity, integrability, scalability, convertibility, customisability and diagnosability. A system which is said to have all these six characteristics is said to have a high level of reconfigurability. *Additionally, according to the research question 3, the relevance of these characteristics on the RMS*, each characteristic is responsible in minimising the reconfiguration effort in the RMS.

According to the research question 3, what are the necessary and sufficient conditions required to develop a decision support methodology to design the RMS, the basic necessary condition is to develop a methodology incorporating all the RMS characteristics. But, diagnosability was not incorporated in developing the methodology.

Diagnosability is the important characteristic to check the system's health, check the product quality, control the RMS in case of disruptions of machine and system failures, etc. Moreover, in a RMS configuration design, due to the cross-over connection, the product travelling routes from one production stage to succeeding production stage are enormous. As the number of routes increases, it may affect the product dimensional quality and can create inconsistencies. Additionally, as the machines used are of reconfigurable nature, i.e. base machines with set of modules accommodated on each base machine according to the set of machining operations assigned to that machines, it can handle the similar machining tasks of different product types. Due to the reconfigurability, i.e. changing the machine hardware and software components, the machine set up changes which can affect the machine controls and can have issues with machine damping, calibrations, etc. Thus, there is a likelihood that the product quality may deteriorate. Due to this limitation of not incorporating the diagnosability, it is hard to convey the quality of the products produced in the RMS. Additionally, diagnosability assists in reducing the ramp up time. Thus, with not incorporating this characteristic, it is hard to confirm the product quality and the ramp up time of the system after reconfiguration.

Design of the Production System Level

Subsequently, one of the major design aspects at the production system level, i.e. at the machine level, is designing the module configurations. As the methodology is developed taking into account the modularity and scalability characteristics, i.e. designing the machines with the approach of base machines with cost-optimal number of tools on it, the module configurations were not taken into account on each machine. As in case of a RMS, the tools used is a Reconfigurable Machine Tool (RMT). In comparison to Computer Numerical Control (CNC) machines, which are general purpose machines (machines with predefined functionality), RMTs are designed for a specific, customised range of operation requirements and can be cost effectively converted when the requirements change. RMT has a customised flexibility that makes it less expensive than general purpose CNCs. Knowing module configurations can assist a manufacturer and the process planner closer to the goal of the operations management in the RMS, by knowing better how to assign and sequence the operations in the RMS system. Additionally, module configurations can let know how an existing module configuration on a base machine can be customised to a new module configuration depending on either functionality or capacity requirements. Thus, with the limitation of not taking into account the module configuration, it is hard to convey the behaviour of the RMS system and the customisability characteristic of the RMS. As customisability is the important characteristic as it synthesises the reconfigurability.

2. Results Discussion

Life Cycle Economic Analysis

It is observed that for the stable demand topology, the DML is the best choice of investment as it shows high NPV value and RMS in this case is the second best option. To provide further insight of the NPV, different demand topologies are assumed. Table 14 shows the shifting demand topology where the demand is shifting for Product A and Product C, and Product B is stable. The NPV determined are for the same parametric values considered in previous chapter.

Product Demand Information						
Period	**0**	**1**	**2**	**3**	**4**	**5**
Product A	29000	39600	39000	98000	98000	100000
Product B	12500	10000	8000	8000	8000	8000
Product C	88000	88000	45000	45000	20000	10000
Annual Demand	129500	137600	135000	151000	126000	118000

Table 14 Shifting Demand Topology

To meet this demand, the new manufacturing system configuration and their NPV's are presented.

System	System Configuration	NPV
DML	(3,1,5)	2,478,571
FMS	12	-156,362
RMS	(10,37)	2,538,455

Table 15 System Configuration and their NPVs

Table 15 shows the system configuration and their NPVs. To meet this demand requirements, the DML requires 3 sub-systems for Product A, 1 sub-system for Product B and 5 sub-systems for Product C. Whereas for FMS, it requires 12 CNC units and for RMS, it requires 10 base machines with 37 modules.

Another demand topology shown in Table 16, where the demand is continuously shifting among the three products is considered.

Product Demand Information						
Period	**0**	**1**	**2**	**3**	**4**	**5**
Product A	54000	60000	0	0	0	0
Product B	0	0	62000	62000	0	0
Product C	0	0	0	0	60000	60000
Annual Demand	54000	60000	62000	62000	60000	60000

Table 16 Continuously shifting demands among the products

To meet this demand, the new manufacturing system configuration and their NPV's are presented.

System	Configuration	NPV
DML	(2,2,3)	-24,52,283
FMS	5	302,419
RMS	(5,17)	841,383

Table 17 System Configuration and their NPV's

Table 17 shows the system configuration and their NPVs. To produce this demand, for DML, 2 subsystems are required to produce Product A, 2 for Product b and 3 for Product C. For FMS, 5 CNC units are required and in case of RMS, 5 base machines and 17 modules are required.

From the Demand Scenario shown in Table 14, the RMS and DML both are the best choice of investment. FMS shows little lower NPV value. It can be concluded that the RMS performs better when there is both throughput and functionality is required. Moreover, DML also shows close NPV value to RMS. But if the demands in any period drops further, the NPV of the DML drastically reduces. FMS can handle the functionality and demand variability. Its high investment cost and low throughput rate performs satisfactory in this scenario. But if the product variety are more and the demand is variably changing, it could be said that the FMS can perform better in this case.

For the Demand Scenario shown in Table 16, RMS again shows the best performance and its NPV is highest. The second best choice of investment is FMS. For just three products with average demand sizes, RMS shows best performance. This is because the RMS can enable its reconfigurability characteristics by switching and reutilising the modules. Also the FMS, handles the product mix variations efficiently as the demand sizes are low. Thus, RMS and FMS both can be a good option. The DML is the least profitable solution in this case, as the lines will run idle in some period than their planned capacities.

The RMS shows a stable NPV range for all the three scenarios. Thus, it is wise to say that RMS can prove to be a profitable choice of investment. This is because due to the modular nature of the RMS, with independent base machines and modules, the RMS can be configured for changing product demand variations. Moreover, the resources can be reutilised, which further reduces the expansion cost of the RMS. Concluding, RMS will be a fruitful choice of investment.

Number of Optimal Module Positions on each base machine

In chapter 6, section 6.2.1, at the production system level, the machines are designed to be modular and scalable nature. A mathematical approach is used to determine the cost-optimal number of modules to be included on a modular scalable machine. This as a design parameter is important because it limits the machine size and the number of module interfaces included in the base machine structure.

According to the results obtained in chapter 7, section 7.2.2, the number of cost-optimal module positions recommended on each base machine is 4. At first it can be argued that the production rate increases as the number of module increases till a specific point. But, considering the capacity gained with respect to the cost, it can be argued that the cost optimal solution is accommodating 4 module positions on a base machine. Additionally, (Spicer, 2005) also recommended that each base machine should allow up to 4 module positions. But from the results, as shown in the Figure 57, it can be interpreted that the cost optimal module positions can be in the range of 3 to 6 modules. This is completely dependent on the module availability rate. If the module availability rate is higher, the number of optimal module positions allowed on a base machine can go up to 6 modules.

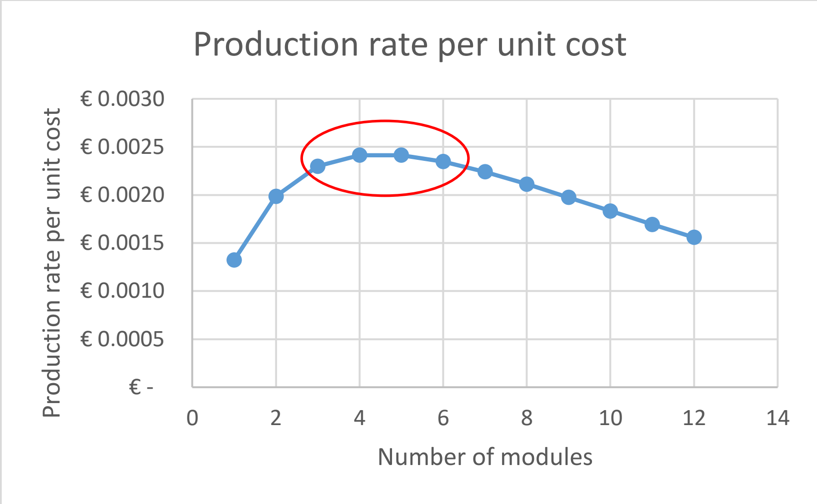

Figure 57 Cost-Optimal Module Positions

Additionally, allowing more than 4 module positions can increase the integrability issues of the module and can increase the complexity of the machine (Spicer, 2005). But knowing the module configurations of the Reconfiguration Machine Tools (RMT's), it can be generally possible to allow additional one or two modules extra on a scalable machine without still affecting much the production rate per unit cost.

Designing a symmetric layout for multiple product families on the same system

In the case study, the system is reconfigured and a new RMS configuration design is proposed. An attempt has been made to integrate an important issue of manufacturing two product part families concurrently on the same system. The configuration design presented in Figure 55, shows two separate configurations arrangements for product Family A and Family B. This is because, as the Product Family A has three different faces to machine, these faces require different positioning and fixturing settings. Thus, a separate set of machines in the configuration are accommodated to produce product Family A.

Practically, in manufacturing cases, further insight is required to check whether more than one product families can be produced on the existing RMS configuration. It is believed, knowing the module configurations, as explained above in the methodology discussion, and from the reconfiguration link, as explained in chapter 5.3.1, it is possible that the same set of operational features of two product families can be associated to the same machine or production stage in the system as long as the module configurations on each machine is same. Thus, knowing the module configurations and from the reconfiguration link, a manufacturer can select a specific production stage and assign appropriate module configurations to the machines in the stage which will be able to produce a group of particular tasks of all the product families.

3. *Model Discussion*

The reconfiguration model is designed for a manufacturer to facilitate an easy making decision at the production system level, the plant layout system level and the material handling system level. Although the level can provide necessary decisions for a RMS in changing market requirements, the model has limitations.

Firstly, the model is developed considering identical set of machines and modules. Thus, the assumptions made are same for all the machines and tools at the production system level. The model works fine at a production system level and give necessary information on the number of manufacturing equipments, i.e. the number of base machines and the number of modules required subjectively to the product demand and functionality requirements. This information is considered as an input to calculate the RMS configurations. After knowing the RMS configurations, the configurations are planned manually, and with respect to the configuration, based on their performance, the total cost and the total time of the production is proposed.

Due to the lack of the data availability of the machining operations, their sequences and the processing times, approximate data is assumed to validate the formulas of calculating the total cost and total time incurred in the production phase. From the results obtained from the formulas of total cost and total time, it is interpreted that based on the information assumed, the configuration design is able to produce the required daily demand in less than the daily available time. But, the formulas should be further validated after designing the module configurations and considering the actual information of the machining tasks, the set of operations assigned to the particular machines, the sequence of the operations, etc.

Chapter 9: Conclusion and Recommendations

The following chapter concludes the research questions and recommends the work to be done further.

9.1. Conclusion

The objective of this thesis was to develop a systematic methodology to design the reconfigurable manufacturing system from the reconfigurability aspects. This objective was met by answering the following questions.

According to the research question what is a Reconfigurable Manufacturing System, A RMS is a system where large variety of products are defined and grouped into families to associate set of similar operation features on a machine which can rapidly change in its architecture by utilising reusable hardware and software components rather than replacing them at a complete plant level, i.e. at the system level, plant layout system level and material handling system level, in order to quickly adjust the production capacity and functionality.

According to the research question *What are the characteristics of a Reconfigurable Manufacturing System,* A RMS system is characterised by its key feature: reconfigurability, which is derived from its configurability characteristics. These characteristics are Modularity, Integrability, Scalability, Convertibility, Customisability and Diagnosability. Also, reusability should be considered as an RMS characteristic.

According to the research question *are these reconfigurability characteristics relevant,* The RMS characteristics are highly relevant to make RMS reconfigurable and reduce the reconfiguration effort. Modularity and Integrability makes the system configurable and helps to reduce the system configuration time and cost. These characteristics act as a supporting role to influence the critical reconfigurability characteristics, i.e. Scalability and Convertibility that leads the system to a capacity or functionality change. These characteristics further lead in reducing the reconfiguration cost and time. Customisation enhances reconfigurability. This unique characteristic makes a system customisable by providing required flexibility just around a product family. Diagnosability allows process diagnostics which shortens the ramp up time.

According to the research question, what are the necessary and sufficient conditions required to develop a decision support methodology to design the reconfigurable manufacturing systems, to design the Reconfigurable Manufacturing System, the necessary conditions are to design the RMS at a production system level, plant layout system level and material handling system level incorporating the RMS characteristics. The RMS should not only be designed from the reconfigurability aspects but also from the operations management point aspects subjective to the changing functionality and capacity requirements around a product part family. A life cycle economic analysis is important to observe how scalability and convertibility can affect the system (re)configuration costs. Modularity and Integrability should be associated to system design decisions, as they make the system reconfigurable and prevent the system from redundancies. Scalability and Convertibility should be associated to the operational decisions as they are bounded to reconfiguration period. Diagnosability should be associated to both design and operational decisions. Customisability evolve the system to meet any physical and managerial changes, thus it should associate to operations planning in RMS.

According to research question, When and how a reconfigurable manufacturing should be designed and reconfigured, A RMS should be designed around a product part family considering the initial functionality and capacity requirements. If there is a new functionality or capacity requirements and the system's flexibility is unable to adapt to these requirements and or the system throughput rate deteriorates, then the existing system should be reconfigured. The RMS system should be designed at the production system level, plant layout system and material handling system concurrently. The production system should be designed for modularity, scalability and customisability with base machines and optimal module positions on it. The plant layout system and the material handling system should be designed for integrability and convertibility by designing symmetric configurations with cross-over material handling connection. The production system should have the flexibility around the product part family and high throughput rate to meet the daily demand request.

According to research question, is investing in Reconfigurable Manufacturing System a right choice in comparison to the traditional manufacturing systems, A Reconfigurable Manufacturing System is profitable when there are varying products with averagely demand sizes, i.e. when there is average functionality changes and averagely higher and varying product volume sizes. Reconfigurability and reusability make the RMS to adapt to the changes quicker and economically. A Dedicated Manufacturing Line (DML) is profitable when there are very less products with very high demand rates whereas a Flexible Manufacturing System (FMS) is profitable when there are large product varieties with averagely varying demands.

According to research question, in case of reconfiguration, which aspects should be considered and how to evaluate various aspects that may be available, in case of reconfiguration, the manufacturing and business aspects should be considered. Aspects such as the Agility Level of the plant, the status of the manufacturing system design and the New Circumstance should be considered. Both these three aspects are important to be considered. The status of the manufacturing system design is the most important aspect. In the Manufacturing System Design, Production System Size and Functionality, the Plant Layout System and the Material Handling System are most important aspects. These aspects should be evaluated in terms of soft and hard reconfiguration activities and should be measured using the Analytical Hierarchical Process.

According to research question, if reconfiguration is required to be performed, how an existing RMS configuration design should be reconfigured to the new required reconfiguration design, a decision should be made associated to the Needed Reconfiguration Level (NRL) measured using the Analytical Hierarchical Process. If the NRL is greater than 50% or if the status of the manufacturing system design involves high reconfiguration effort or if there is a new product family, then the existing system must be reconfigured. Any reconfiguration performed at the system level will require reconfiguration at the plant layout system and material handling system. Thus, if a reconfiguration is required, the existing RMS configuration should not only be configured at the production system level, but also at the plant layout system and material handling system level. In case of reconfiguration, new additional manufacturing should be determined and added in the stage where the cycle time increases. Planning the reconfiguration as low at the system level and reconfiguring the system around the product part family flexibility will substantially save reconfiguration cost, time and ramp up time.

According to research question, *if the reconfiguration is performed, how the candidate configurations should be analysed considering the cost and time,* the candidate configuration designs are analysed on the Reconfiguration Smoothness (RS) Value with considering the reconfiguration effort in terms of soft reconfiguration and hard reconfiguration activities relative to the cost, time and reconfiguration effort. A configuration with low RS value, with high throughput rate at reliability less than 100%, low investment cost, high increment of the production capacity that can be gained by adding a machine and low floor space should be proposed.

9.2. Recommendations

The recommendations are structured relative to the research questions framed.

According to research question, *what are the necessary and sufficient conditions required to develop a decision support methodology to design the reconfigurable manufacturing systems,* the basic pre-requisite is to incorporate *"diagnosability"* to develop the decision-support methodology to design the Reconfigurable Manufacturing Systems. This is because diagnosability is directly associated to the ramp up time of the RMS system. It allows in process diagnostics which can dramatically shorten the ramp up time after the reconfiguration (Shpitalni, 2010). Additionally, diagnosability associates to both configuration and reconfiguration phases and design and operations decisions. Hence, diagnosability should be studied further and should be incorporated in the methodology to further understand the ramp up time involved in the RMS and the ways it can be minimised.

Secondly, at the production system level, it is important to incorporate module configuration methodology in the decision-support methodology to design the Reconfigurable Manufacturing Systems. To do so, it is important to know the machining operations and the sequence of the operations. With this information, the machining operations are transformed into a task matrix, i.e. a homogenous transformation matrix, that contains the necessary motion requirements for the machine tool (Moon, 2006). The functional requirements of the machining operations are used to generate graph representations of candidate machine tools. This generated graph gives the overall topology of the machine tool and structural and kinematic functions are assigned to various portions of the graph. With this information, different tools can be examined from the library of the tools which contain structural and kinematic information. Thus, in this manner, all possible configurations can be determined. These configurations can be further reduced by other criteria such as Degrees of Freedom, static and dynamic stiffness, etc. With this, the characteristic *"customisability"*, to customise the module configurations from existing configuration to new configuration based on the changing functionality or capacity requirements.

Lastly, as presented in chapter 5, section 5.3.2, the reconfiguration methodology is developed for 1. Introduction of New Product Family. 2. Changing Product Demand 3. New Product within the existing product family 4. Introduction of new product family and 5. Improved quality or product requirements. But, one of another important aspect to consider is producing multi-product part families on a configuration design. Practically, it is obvious to have this scenario in an industry. So far no work is discussed regarding the design of a RMS system for multiple product families. Doing so, can help to accomplish a generic configuration design, and can give further insight of how the RMS characteristics can be valuable to minimise the reconfiguration effort.

According to the research question, *is investing in Reconfigurable Manufacturing System a right choice in comparison to the traditional manufacturing systems,* it is recommended that reconfigurability analysis should be incorporated with the Net Present Value (NPV). In chapter 6, section 6.2.4, the reconfigurability index is developed. This reconfigurability index analysis the configurations based on the Reconfiguration Smoothness Value (RS). The RS value is the relative measure to the reconfiguration cost, reconfiguration time and ramp up time involved to change one configuration to another configuration. Assigning economic value to this reconfiguration effort, a new methodology for Life Cycle Economic Analysis using Reconfiguration Analysis can be developed. *Urbani et. al* (Urbani, 2006) has also suggested that a reconfigurability analysis is an important factor to consider with Net Present Value of the RMS system. *Urbani et. al* proposed a conceptual method for Dedicated Manufacturing Systems and Flexible Manufacturing Systems, but so far nothing is found for

Reconfigurable Manufacturing System (RMS). Thus, to understand better the Net Present Value of the RMS during its configurations phases, the reconfigurability analysis should be incorporated.

Also it should be noticed that the comparison between two or more manufacturing systems with different designs have different agility levels. The agility has a certain value associated with it. The value of the agility is a relative concept and it depends on the dynamic uncertainties in the operating environment. Thus, each value of agility has a financial impact of its response to changes in its operating environment (Ramasesh, 2001). This value of agility endowed to a manufacturing system through investments in its resources lies in the financial impact of its response to changes in its operating environment. The value of the agility is a relative concept and it depends on the dynamic uncertainties in the operating environment. For any given system, if the changes take place far out into the future or if the environment is fairly stable, the need for agility and hence its value would be smaller. Also, in changing environment, if the system takes long time to respond or incurs high costs to respond, the value of its agility will be small (Ramasesh, 2001). Thus, agility analysis should also be incorporated to all the systems, i.e. DML, FMS and RMS.

Thus, incorporating the reconfigurability analysis and developing the Life Cycle Economic Analysis further, a manufacturer can decide better on:

- How much change will the system be able to respond?
- How soon will the system be able to respond to the change?
- How much will it cost to respond to the change?
- What is the profit potential from an adequate response to the change?

This kind of analysis can help the manufacturer to make better decisions among the set of alternatives developed to meet expected market scenarios. Thus, developing such methodology will generally provide more insight of RMS in practical manufacturing environment.

General Model Recommendation

Concerning the Reconfigurable Manufacturing System Design Model (RMSM), it is recommended to develop the model further to generate the candidate configuration designs. Although this can be only met with softwares, it is recommended to research configuration design and analysis algorithms with respective to the design and reconfiguration aspects in objective of minimising the reconfiguration effort. Secondly, the formulas for calculating the total cost and total time are calculated based on the number of operations and operations sequence for one product part family. Thus, the research objective of calculating the total cost and total time is met. But it is recommended that this should be further developed so that instead of calculating the total cost and total time, a set of solutions on the process plan can be provided. This can be done by utilising Non-Dominated Sorting genetic algorithm (NSGA-II) (Bensmaine, 2013). Further, the model is designed for just one product family at a time in the system. It is recommended to consider this work further to develop a model for multi-product family case where different types of products are to be manufactured on the same system.

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Appendix

1. Relative Weights for Needed Reconfiguration Level (NRL)

In chapter 6, section 6.4.2, the calculations for measuring the Needed Reconfiguration Level (NRL) is presented. The relative weights considered for each element are calculated by Pair-wise comparison, which is explained here in detail.

The measure of the NRL comprises of Needed Agility Level (NAL), status of the Manufacturing System Design (MSD) and New Circumstance (NC). The relative weights for the NAL is presented:

For Needed Agility Level (NAL),

The NAL is divided into four main infrastructures: Technology (TE), People (PE), Management (MA) and Manufacturing strategies (M). The relative weights are calculated using the pair wise comparison of these elements:

$$A_{NAL} = \begin{bmatrix} 1 & 0.50 & 0.33 & 0.50 \\ 2 & 1 & 3 & 2 \\ 3 & 0.33 & 1 & 1 \\ 2 & 0.50 & 1 & 1 \end{bmatrix}$$

The relative weights of the TE is estimated to be twice as important as PE, thrice as important as MA and twice as important as M. M is estimated to be three times more as compared to PE and equivalent to MA. M is also estimated to be twice as important as PE. With this estimations, the relative weights are calculated which are as follows:

The procedure of the AHP is explained in detail

$$A_{NAL} = \begin{bmatrix} 1/8 & 0.50/2.33 & 0.33/5.33 & 0.5/4.5 \\ 2/8 & 1/2.33 & 3/5.33 & 2/4.5 \\ 3/8 & 0.33/2.33 & 1/5.33 & 1/4.5 \\ 2/8 & 0.50/2.33 & 1/5.33 & 1/4.5 \end{bmatrix}$$

$$w_{TE} = \frac{\frac{1}{8} + \frac{0.50}{2.33} + \frac{0.33}{5.33} + \frac{0.50}{4.5}}{4} = 0.128$$

$$w_{PE} = \frac{\frac{2}{8} + \frac{1}{2.33} + \frac{3}{5.33} + \frac{2}{4.5}}{4} = 0.421$$

$$w_{MA} = \frac{\frac{3}{8} + \frac{0.33}{2.33} + \frac{1}{5.33} + \frac{1}{4.5}}{4} = 0.231$$

$$w_{M} = \frac{\frac{2}{8} + \frac{0.50}{2.33} + \frac{1}{5.33} + \frac{1}{4.5}}{4} = 0.218$$

The weights for w_{TE}, w_{PE}, w_{MA} and w_M are $0.128, 0.421, 0.231$ and 0.218 respectively. But before selecting these weights for determining the level of configuration, it is important to check if these values are consistent. Checking for consistency clarifies if the decision maker's comparisons are consistent or not.

Checking for consistency:

$$A_w^T = AL \times relative\ weights$$

$$A_w^T = \begin{bmatrix} 1 & 0.50 & 0.33 & 0.50 \\ 2 & 1 & 3 & 2 \\ 3 & 0.33 & 1 & 1 \\ 2 & 0.50 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} 0.128 \\ 0.421 \\ 0.231 \\ 0.218 \end{bmatrix} = \begin{matrix} 0.524 \\ 1.809 \\ 0.973 \\ 0.917 \end{matrix}$$

$$= \frac{1}{4}\left[\frac{0.524}{0.128} + \frac{1.809}{0.421} + \frac{0.973}{0.231} + \frac{0.917}{0.218}\right] = 4.197$$

$$CI = \frac{4.197 - 4}{4 - 1} = 0.065$$

Next step is to compare the value of CI to the random index (RI) for the appropriate value of n, as shown in the below table. (Winston 2003)

n	2	3	4	5	6	7	8	9	10
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Hence, comparing CI value for n = 4, we get 0.072, which is less than 0.10. Hence, the degree of consistency is satisfactory. The same procedure of Consistency Check is done for all the relative weights determined. Hence, the relative weights for w_{TE}, w_{PE}, w_{MA} and w_M are $0.128, 0.421, 0.231$ and 0.218.

For status of the Manufacturing System Design (MSD),

To determine the relative weights for the status of manufacturing systems design, following estimations are made,

$$A_{MSD} = \begin{bmatrix} 1 & 2 & 2 \\ 0.5 & 1 & 2 \\ 0.5 & 1 & 1 \end{bmatrix}$$

For the manufacturing system design, the attributes contain production system size and functionality (PSS & F), Plant Layout System (PLS) and Material Handling System (MHS). From the factors, the PLS and MHS is considered 2 times more important than PSS & F.

$$A_{MSD} = \begin{bmatrix} 1/2 & 2/4 & 2/5 \\ 0.5/2 & 1/4 & 2/5 \\ 0.5/2 & 1/4 & 1/5 \end{bmatrix}$$

$$w_{PSS\ \&\ F} = \frac{\frac{1}{2} + \frac{2}{4} + \frac{2}{5}}{3} = 0.467$$

$$w_{PLS} = \frac{\frac{0.5}{2} + \frac{1}{4} + \frac{2}{5}}{3} = 0.30$$

$$w_{PLS} = \frac{\frac{0.5}{2} + \frac{1}{4} + \frac{1}{5}}{3} = 0.233$$

Hence, the relative weights for $w_{PSS\,\&\,F}, w_{PLS}\ and\ w_{PLS}$ are $0.467,\ 0.30\ and\ 0.233$ respectively. (After Consistency Checked).

For New Circumstance (NC),

To determine the relative weights of the NC, the following estimations are made,

The New Circumstance comprises the attributes such as New Product (NP), Product Development (PD) and Changing Demand (CD). For this scenario, it is assumed a new product is to be produced, with additional demand requirements as produced on DML or FMS. Hence, NP and PD is taken as 1 and CD is assumed to be 0.5. (This parameter can be exactly determined if the previous and upcoming demands are known).

$$A_{NC} = \begin{bmatrix} 1 & 1 & 0.5 \\ 1 & 1 & 0.5 \\ 2 & 2 & 1 \end{bmatrix}$$

As a result from the above procedure, the relative weights are determined for $w_{NP}, w_{PD}\ and\ w_{CD}$ are $0.25, 0.25\ and\ 0.5$ respectively.

For Needed Reconfiguration Level (NRL),

With respect to the weights for the elements of the Needed Agility Level, the status of the manufacturing system design (MSD) and the New Circumstance (NC), the relative weights for these attributes for measuring the NRL is presented,

$$A_{NRL} = \begin{bmatrix} 1 & 1 & 2 \\ 1 & 1 & 2 \\ 0.50 & 0.50 & 1 \end{bmatrix}$$

The relative weights of the NAL is estimated to be as important as the status of the MSD and twice as important as the NC. With this, the relative weights are determined for the NAL, MSD and NC which are 0.4, 0.4 and 0.2 respectively.

These relative weights are estimated and considered to measure the NRL of the existing configuration at a complete plant level.

2. **Reconfiguration Planning and Reconfiguration Smoothness Value Calculations**

As explained in Chapter 6, section 6.4.5, after reconfiguring the existing configuration, three reconfigurations designs are available. From these configurations available, one reconfiguration design is to be proposed. This is calculated by reconfiguration planning, as explained in Chapter 5, section 5.2.3, Step 26.

1. **Changing the current configuration design to configuration a.**

To change the current configuration design to required reconfiguration design a, the reconfiguration smoothness value at the market level, at the system level and at the machine level is calculated. Equations 5.2.29-5.2.39 from Chapter 5, section 5.2. is used.

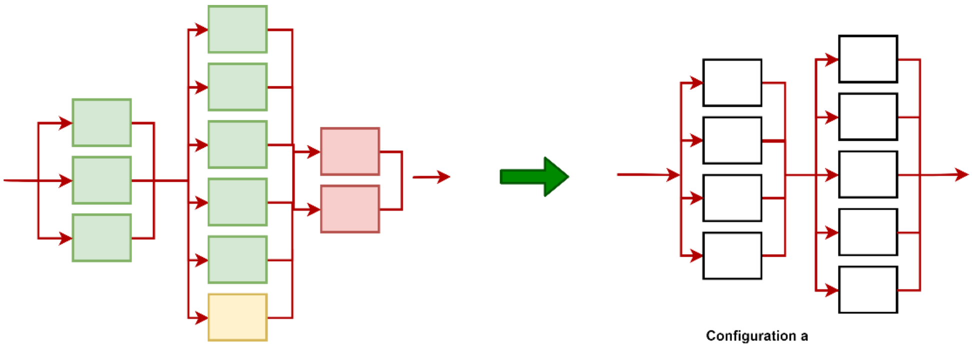

Figure 58 Reconfiguration approach to configuration a

1. Market Level Reconfiguration

At the market level, no machines or the modules are purchased or sold. There are 15 machines in the system. This machines will be reutilised in form of another configuration. Thus, the market level reconfiguration value is determined as,

At machine level,

$$TRS_m = \frac{2}{3}\left(\frac{0}{15}\right) + \frac{1}{3}\left(\frac{0}{15}\right) = 0$$

At module level,

$$TRS_d = \frac{2}{3}\left(\frac{0}{15 \times 4}\right) + \frac{1}{3}\left(\frac{0}{15 \times 4}\right) = 0$$

$$TRS = \frac{2}{3}(0) + \frac{1}{3}(0) = 0$$

2. System Level Reconfiguration

To acquire the desired configuration a, one machine (shown in yellow) from stage 2 is added in stage 1, and two machines from stage 3 (shown in red) is removed. The third stage is completely removed. To calculate the efforts utilised for this configuration, we calculate the market level configuration, system level configuration and machine level configuration. Equations 5.2.30 - 5.2.40 are used.

At the system level,

For stages, no stage is completely removed or added, thus the reconfiguration smoothness value at the system stage level is,

$$SRS_s = \frac{2}{3}\left(\frac{0}{3}\right) + \frac{1}{3}\left(\frac{0}{3}\right) = 0$$

For machines, 2 out of 15 machines are removed from stage 1 and these 2 machines are added in stage 3. Thus, at the machine level,

$$SRS_m = \frac{2}{3}\left(\frac{2}{15}\right) + \frac{1}{3}\left(\frac{2}{15}\right) = 0.133$$

For material handling, the material handling connection for 2 machines are removed from stage 1 and additional material handling system is setup for these two added machines in stage 3. Other material handling equipments are connected together such that the machines are connected. With this, the reconfiguration smoothness value of the SRS_f is determined as:

$$SRS_f = \frac{2}{3}\left(\frac{16}{24+32}\right) + \frac{1}{3}\left(\frac{16}{24+32}\right) = 0.285$$

The total reconfiguration smoothness value at the system level is calculated by:

$$SRS = \frac{3}{6}(0) + \frac{2}{6}(0.133) + \frac{1}{6}(0.285) = 0.117$$

3. Machine Level Reconfiguration

At module level,

as two machines are reconfigured from stage 1 to stage 3, the module configurations are also assumed to be changed according to the machines in the respective stages. Thus, the module level reconfiguration smoothness value is calculated as:

$$MRS_m = \frac{2}{3}\left(\frac{8}{60}\right) + \frac{1}{3}\left(\frac{8}{60}\right) = 0.133$$

At the machine level, the setup changes related to the operation cluster assignments is assumed to be zero. This is due to the unavailability of the required data. With this, it is assumed that no operation clusters assignments are changed. Thus,

$$MRS_o = 0$$

$$MRS = \frac{2}{3}(0.133) + \frac{1}{3}(0) = 0.088$$

Thus, the total reconfiguration smoothness value is calculated as,

$$\boldsymbol{RS = \frac{1}{6}(0) + \frac{3}{6}(0.117) + \frac{2}{6}(0.088) = 0.087}$$

For reconfiguring to configuration a, the total reconfiguration effort is 0.087.

2. Reconfiguration to configuration b.

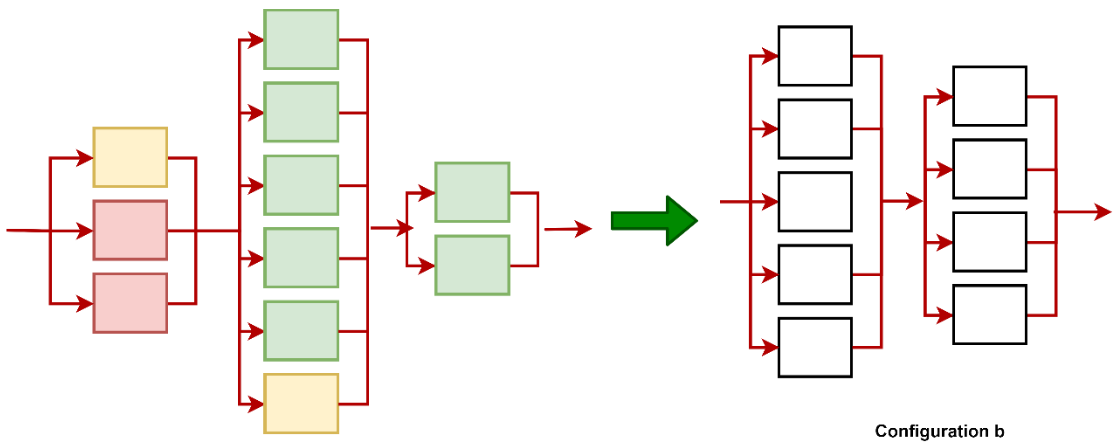

Figure 59 Reconfiguration approach to configuration b

1. Market Level Reconfiguration

At the market level reconfiguration, no machines or modules are purchased or sold. Thus, the market level reconfiguration is,

At machine level,

$$TRS_m = \frac{2}{3}\left(\frac{0}{15}\right) + \frac{1}{3}\left(\frac{0}{15}\right) = 0$$

At module level,

$$TRS_d = \frac{2}{3}\left(\frac{0}{15 \times 4}\right) + \frac{1}{3}\left(\frac{0}{15 \times 4}\right) = 0$$

$$TRS = \frac{2}{3}(0) + \frac{1}{3}(0) = 0$$

2. **System Level Reconfiguration**

For stages, no stages are removed or added. Thus, the stage level reconfiguration is,

$$SRS_s = \frac{2}{3}\left(\frac{0}{3}\right) + \frac{1}{3}\left(\frac{0}{3}\right) = 0$$

For machines, two machines are removed from stage 1 and one machine is removed from stage 2. Correspondingly, three machines are added in stage 3. The machine level reconfiguration smoothness value is calculated,

$$SRS_m = \frac{2}{3}\left(\frac{3}{15}\right) + \frac{1}{3}\left(\frac{3}{15}\right) = 0.20$$

For material handling, the material handling connections of the machines from stage 1 and stage 2 are removed and added in stage 3 for the newly added machines. Thus the material handling reconfiguration smoothness value is calculated as,

$$SRS_f = \frac{2}{3}\left(\frac{21}{24 + 32}\right) + \frac{1}{3}\left(\frac{3 + 14}{24 + 32}\right) = 0.3511$$

$$SRS = \frac{3}{6}(0) + \frac{2}{6}(0.20) + \frac{1}{6}(0.3511) = 0.125$$

3. **Machine Level Reconfiguration**

At module level, three module configurations, two configurations from the stage 1 and one module configurations from stage 2 is changed. Subsequently, three new module configurations are formed.

$$MRS_m = \frac{2}{3}\left(\frac{12}{60}\right) + \frac{1}{3}\left(\frac{12}{60}\right) = 0.20$$

The cluster assignments are assumed to be zero.

$$MRS_o = 0$$

$$MRS = \frac{2}{3}(0.20) + \frac{1}{3}(0) = 0.133$$

The total reconfiguration smoothness value is calculated by,

$$\boldsymbol{RS = \frac{1}{6}(0) + \frac{3}{6}(0.125) + \frac{2}{6}(0.133) = 0.106}$$

For reconfiguring to configuration a, the total reconfiguration effort is 0.106.

3. **Reconfiguring to configuration f.**

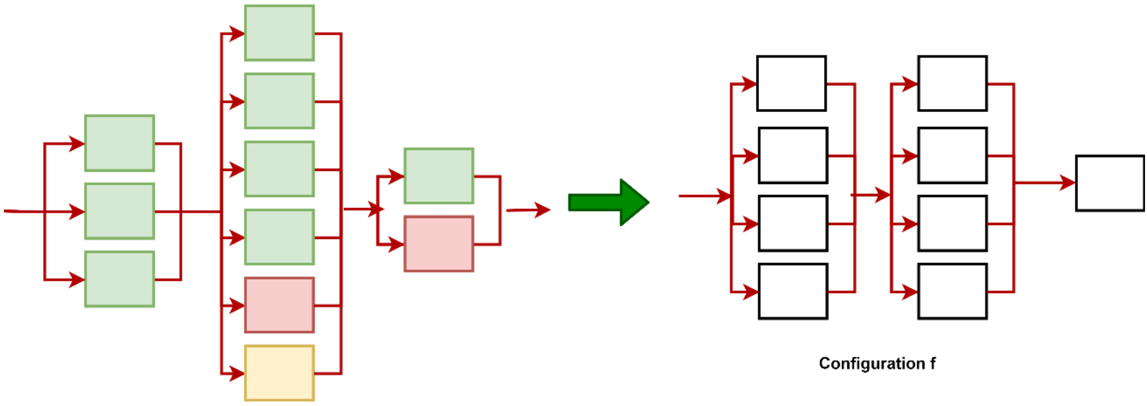

Figure 60 Reconfiguration approach to configuration f

1. Market Level Reconfiguration

At the market level reconfiguration, no machines or modules are purchased or sold. Thus, the market level reconfiguration is,

At machine level,

$$TRS_m = \frac{2}{3}\left(\frac{0}{15}\right) + \frac{1}{3}\left(\frac{0}{15}\right) = 0$$

At module level,

$$TRS_d = \frac{2}{3}\left(\frac{0}{15 \times 4}\right) + \frac{1}{3}\left(\frac{0}{15 \times 4}\right) = 0$$

Thus, the market level reconfiguration is calculated as,

$$TRS = \frac{2}{3}(0) + \frac{1}{3}(0) = 0$$

2. System Level Reconfiguration

For stages, no stages are added or removed, thus,

$$SRS_s = \frac{2}{3}\left(\frac{0}{3}\right) + \frac{1}{3}\left(\frac{0}{3}\right) = 0$$

For machines, one machine is removed from stage 2 and one machine is removed from stage 3. Subsequently, two machines are added in stage 1.

$$SRS_m = \frac{2}{3}\left(\frac{2}{15}\right) + \frac{1}{3}\left(\frac{2}{15}\right) = 0.133$$

For material handling, the material handling connections are removed for the machines in stage 2 and stage 3 and are added in stage 1.

$$SRS_f = \frac{2}{3}\left(\frac{14}{24 + 32}\right) + \frac{1}{3}\left(\frac{3 + 7}{24 + 32}\right) = 0.22$$

The system level reconfiguration smoothness is calculated by:

$$SRS = \frac{3}{6}(0) + \frac{2}{6}(0.133) + \frac{1}{6}(0.22) = 0.081$$

3. Machine Level Reconfiguration

At module level, the module configurations for the two machines removed are changed. Thus, it is given by,

$$MRS_m = \frac{2}{3}\left(\frac{2 \times 4}{60}\right) + \frac{1}{3}\left(\frac{2 \times 4}{60}\right) = 0.133$$

The cluster assignments are assumed to be zero.

$$MRS_o = 0$$

Thus, the machine level reconfiguration smoothness value is calculated as,

$$MRS = \frac{2}{3}(0.133) + \frac{1}{3}(0) = 0.088$$

The total reconfiguration smoothness value is given by:

$$\boldsymbol{RS} = \frac{\mathbf{1}}{\mathbf{6}}(\mathbf{0}) + \frac{\mathbf{3}}{\mathbf{6}}(\mathbf{0.081}) + \frac{\mathbf{2}}{\mathbf{6}}(\mathbf{0.088}) = \mathbf{0.07}$$

For reconfiguring to configuration a, the total reconfiguration effort is 0.07

As for changing the existing configuration to reconfiguration design f has the lowest reconfiguration smoothness value, this reconfiguration design is proposed.