2016

Synthesis of Manufacturing Systems Using Co-Platforming

Mohamed Hussein Mohamed Hassan Abbas
University of Windsor

Synthesis of Manufacturing Systems Using Co-Platforming

by

Mohamed Hussein Mohamed Hassan Abbas

A Dissertation
Submitted to the Faculty of Graduate Studies through
Mechanical, Automotive & Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada

Synthesis of Manufacturing Systems Using Co-Platforming

by

Mohamed Hussein Mohamed Hassan Abbas

APPROVED BY:

____
R. Jiao, External Examiner
Georgia Institute of Technology

____
J. Sokolowski
Mechanical, Automotive & Materials Engineering

____
R. Caron
Mathematics and Statistics

____
W. ElMaraghy
Mechanical, Automotive & Materials Engineering

____
H. ElMaraghy, Advisor
Mechanical, Automotive & Materials Engineering

October 19, 2016

DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is result of joint research of the author and his supervisor Prof. Hoda ElMaraghy. This joint research has been published / submitted to various Journals that are listed below.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from Prof. Hoda ElMaraghy to include that material(s) in my thesis.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

II. Declaration of Previous Publication

This thesis includes 6 original papers that have been previously published / submitted for publication in peer reviewed journals and conferences as follows:

Thesis Chapter	Publication title/full citation	Publication Status
4	ElMaraghy, H., Abbas, M., 2015, Products-manufacturing systems Co-platforming, CIRP Annals-Manufacturing Technology, Vol.64/1, pp. 407-410.	Journal (published)
4	Abbas, M., ElMaraghy, H., 2016, Design Synthesis of Machining Systems Using Co-platforming, Journal of Manufacturing Systems, Vol.41, pp. 299-313	Journal (published)
5	Abbas, M., ElMaraghy, H., 2016, Functional Synthesis of Manufacturing Systems Using Co-platforming, Procedia CIRP, 52/102-107	Conference proceeding (published)
6	Abbas, M., ElMaraghy, H., Functional Synthesis of Manufacturing Systems Using Co-Platforming to Minimize Cost of Machines and System Changes, ASME Journal of Mechanical Design, Ref. No.: MD-16-1616	Journal (submitted)
7	Abbas, M., ElMaraghy, H., Synthesis and Optimization of Manufacturing Systems Configuration Using Co-Platforming, CIRP Journal of Manufacturing Science and Technology, Ref. No.: CIRPJ-D-16-00124.	Journal (submitted)
8	Abbas, M., ElMaraghy, H., Assembly System Synthesis using Co-platforming	Journal (to be sub.)

I certify that I have obtained a written permission from the copyright owner(s) to include the above published material(s) in my thesis. I certify that the above material describes work completed during my registration as graduate student at the University of Windsor.

I declare that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

ABSTRACT

Modern manufacturing environment is characterized by frequent changes within product design in order to satisfy evolving customer requirements. Various strategies are implemented in order to efficiently manage the consequences arising from the product design changes starting from design of the product, planning, manufacturing…etc. This dissertation focuses mainly on the manufacturing phase in which a new concept in manufacturing system synthesis is proposed.

A new concept in manufacturing system synthesis has been introduced and coined as “Co-platforming”. Co-platforming is the synthesis of manufacturing systems through mapping product platform features and components to platform machines on one side, and non-platform product features and components to non-platform machines on the other side, in order to reduce the manufacturing system investment cost and prolong the manufacturing system useful life as product variants evolve and change.

Tools and methods are developed to synthesize the manufacturing system based on Co-platforming within functional and physical levels. At the functional level, the group of platform and non-platform machines and the number of each machine type are determined. A new matrix based mapping model is proposed to determine the platform and non-platform machines candidates. A ranking coefficient is formulated which ranks the platform machines according to their machining capabilities in order to assist manufacturing firms in decision making concerning which type of platform machine to choose. Furthermore, a new mathematical programming optimization model is proposed in order to provide the optimum selection of machine types among machine candidates and their numbers. Moreover, a new mathematical programming model is proposed which synthesizes manufacturing systems taking into consideration machine level and system level changes based on co-platforming.

At the physical level, the manufacturing system configuration is determined which is concerned with determining the number of stages, types of machines in each stage and the number of machines in each stage. A new mathematical programming optimization model is proposed which determines, in addition to the type and number of each machine, the optimal manufacturing system configuration based on co-platforming.

The Co-platforming methodology is being applied in two case studies from automotive industry. The first case study is concerned with machining of automotive cylinder blocks taken from Mitsubishi Heavy Industries and the second case study is concerned with the assembly of automotive cylinder heads taken from ABB flexible automation. The results obtained from the co-platforming methodology indicate that cost reduction can be achieved when synthesizing the manufacturing system based on co-platforming.

DEDICATION

To my father, for his guidance through my life

To my mother, for her infinite and unconditional love through my life

To my wife, for her love and close support during the journey

To my supervisor, for her guidance during the journey

ACKNOWLEDGMENT

The author would like to express gratitude and appreciation to his supervisor Professor Hoda ElMaraghy whom without her guidance, time and effort, this work would not have been accomplished. Professor Hoda ElMaraghy encourages her graduate students to think critically and find the most creative and innovative topics. The author would like to thank the committee members for their valuable comments and feedback through the period of the program especially Professor Waguih ElMaraghy for his fruitful comments, suggestions and feedback during committee meetings as well as Intelligent Manufacturing Systems (IMS) Centre meetings.

Great thanks to Intelligent Manufacturing Systems (IMS) Centre colleagues and researchers for their suggestions and feedback during formal meetings and informal discussions especially Dr. Tarek AlGeddawy, Dr. Sameh Badrous, Dr. Abdo ElZaher, Dr. Mohmmad Hanafy, Dr. Mohamed Kashkoush, Dr. Abdulrahman Seliem, Dr. Javad Navaei, Mr. Ahmed Marzouk, Ms. Jessica Olivares Aguila, Mr. Ashraf Abou Tabl, Mr. Mostafa Moussa and Mr. Boris Novakovic.

In addition, the author would like to thank his M.Sc. advisor Professor Sayed Metwalli for his help, support and paving the road in building the research skills gained by the author and assisted him through his PhD program.

The author would like to acknowledge the research assistance funds provided by Professor Hoda ElMaraghy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

$ASME$	American Society for Mechanical Engineers
$ASRP$	Assembly System Reconfiguration Planning
CNC	Computer Numerical Control
FMS	Flexible Manufacturing System
$IDEF0$	A function modeling language which stands for Icam DEFinition for Function Modeling. Icam stands for Integrated Computer Aided Manufacturing
ISO	International Organization for Standardization
RMS	Reconfigurable Manufacturing System
TAD	Tool Direction Approach

NOMENCLATURE

ae_f	Cutting width (*mm*)
$a^m_{j,t}$	Binary (0-1) element: *1* if machine *j* is added as non-platform machine in production period *t* and *0* otherwise
ap_f	Depth of cut (*mm*)
ap_f	Depth of cut (*mm*)
$axtad_{p,k}$	A binary (0-1) element in the p^{th} row and k^{th} column of the machining axis-tool direction approach matrix
asp_j	Binary (0-1) element *j* of the assembly platform vector
$atime_{f,j}$	Assembly time of component *f* on machine *j*
$A^m_{0,t}$	Base cost of testing and integration in production period *t* ($)
$AxTAD$	Machining axis-tool direction approach matrix
B_m	Total available one time budget ($)
CR_j	Element *j* of candidate ranking coefficient
$ctmass_f$	Elements of component mass vector
CF	Machining capability-product feature matrix
$demand_{i,t}$	Demand of product variant *i* in production period *t*
$D_{f,q}$	Diameter of component *f* inserted in component *q* (mm)
DSM	Design structure matrix
$dsm_{f,q}$	Binary (0-1) element : the f^{th} row and q^{th} column of the design structure matrix
d	Interface complexity factor (constant)
$d\Theta$	Rotational accuracy (*seconds*)
ds	machine linear accuracy (*mm*)

E	Modulus of elasticity (MPa)
$f_{a,b}$	Number of interfaces between machine type *a* and *b*
$fax_{f,p}$	A binary (0-1) element in the f^{th} row and p^{th} column of the product feature-machining axis matrix
fcp_f	Element *f* of product feature-cutting power vector
$fgeo_{f,g}$	Element in the f^{th} row and g^{th} column of the product feature-geometrical tolerance matrix
$fpr_{f,r}$	A binary (0-1) element in the f^{th} row and r^{th} column of the product feature-process matrix
$fsu_{f,r}$	A binary (0-1) element in the f^{th} row and r^{th} column of the product feature surface finish-process matrix
fsz_f	Element *f* of product feature-workpiece size vector
$ftad_{f,k}$	A binary (0-1) element in the f^{th} row and k^{th} column of product feature-tool direction approach matrix
$ftol_f^{max}$	Element *f* of the product feature-maximum dimensional tolerance range vector
$ftol_f^{min}$	Element *f* of the product feature-minimum dimensional tolerance range vector
F	Number of product features
F_j^{ax}	Maximum axial force applied by assembly machine *j* (N)
FAx	Product feature-machining axis matrix
FCp	Product feature-cutting power vector
$FGeo$	Product feature-geometrical tolerance matrix
FPr	Product feature-process matrix
FSu	Product surface finish-process matrix
FSz	Product feature-workpiece size vector
$FTAD$	Product feature-tool direction approach matrix
$FTol$	Product feature-dimensional tolerance vector

H_0	Height of workpiece (*mm*)
$ifax_{f,p}$	Elements of the intermediate product feature-machining axis matrix
I	Number of product variants
$IFAx$	Intermediate product feature-machining axis matrix
I_0^m	Initial investment cost on the platform machines in production period *t=1* ($)
J	Number of machines
k_{xj}	Compliance device stiffness in the x-direction for assembly machine *j* (ib/in)
$k_{\theta j}$	Compliance device torsional spring stiffness in the θ-direction for assembly machine *j* (in.ib/rad)
kf_f	Specific cutting force (*MPa*)
$l_{f,q}$	Length of component *f* inserted in component *q* (mm)
$l_{gripper}$	Length of gripper (mm)
L_0	Length of workpiece (*mm*)
L	Number of stages
$mf_{j,f}$	Element in the j^{th} row and f^{th} column of the machine-product feature matrix
msp_j	Binary (0-1) element *j* of the platform machine vector
$mct_{j,f}$	Binary (0-1) element : the j^{th} row and f^{th} column of the machine-component matrix
$mct_{j,f}^{in}$	Binary (0-1) element : the j^{th} row and f^{th} column of the insert based machine-component matrix
$mct_{j,f}^{payload}$	Binary (0-1) element : the j^{th} row and f^{th} column of the payload based machine-component matrix
$mass_f$	Mass of component *f* (kg)
MCt	Machine-component matrix

MCt_j^{in}	Insert based machine-component matrix
MDR	Number of modular architecture machines
MF	Machine-product feature matrix
MSP	Platform machine vector
$McOp_{j,o}$	Binary (0-1) element: *1* if machine *j* processes operation *o* and *0* otherwise
$nst_{j,l,t}$	Number of machine *j* in stage *l* in production period *t*
$Nst_{j,t}$	Number of machine *j* in production period *t*
NHD	Available number of hours per day
$opst_{i,j,o,l,t}$	Binary (0-1) element : *1* if operation *o* in product variant *i* in production period *t* is assigned to machine *j* in stage *l* and *0* otherwise
O	Number of operations
plf_f	Binary (0-1) element *f* of the product platform feature vector
$ptf_{i,f}$	Binary (0-1) element in the i^{th} row and f^{th} column of the product variant-product feature matrix
$ptime_{o,j}$	Processing time of operation o on machine *j*
$purcost_j$	Purchase cost of machine type *j* ($)
$payload_j$	Payload of machine *j* (kg)
$prec_{i,f,q}$	Binary (0-1) element : *1* if component *q* is assembled before component *f* in product variant *i* and *0* otherwise
$prec_{i,o1,o2}$	Binary (0-1) element : *1* if component *o1* preceeds *o2* in product variant *i* and *0* otherwise
PlF	Product platform feature vector
PtF	Product variant-product feature matrix
$r_{j,t}^m$	Binary (0-1) element: *1* if machine *j* is removed from non-platform machines in prodution period *t* and *0* otherwise

R_a	Centerline average parameter value (μin)
$sellcost_j$	Salvage cost of machine type *j* ($)
tol_f	Dimensional tolerance for product feature *f*
T	Number of production periods
T_0	Initial production period (T_0=1)
vf_f	Table feed (*m/min*)
W_0	Width of workpiece (*mm*)
$x_{f,t}^p$	Binary (0-1) element: *1* if product feature *f* is product platform feature in production period *t* and *0* otherwise
$x_{j,t}^m$	Binary (0-1) element: *1* if machine *j* is platform machine production period *t* and *0* otherwise
$y_{f.t}^p$	Binary (0-1) element: *1* if product feature *f* is non-platform product feature in production period *t* and *0* otherwise
$y_{j,t}^m$	Binary (0-1) element: *1* if machine *j* is non-platform machine in production period *t* and *0* otherwise
$z_{i,t}$	Binary (0-1) element: *1* if product variant *i* is available in production period *t* and *0* otherwise
α_t^m	Ratio between the platform machines types to the sum of platform and non-platform machine types in production period *t*
$\gamma_{f,o}$	Binary (0-1) element: *1* if operation *o* is required by product feature *f* and *0* otherwise
$\delta_{f,t}$	Binary (0-1) element: *1* if product feature *f* is available in at least one product in production period *t* and *0* otherwise
Δ	Fit matrix
$\Delta_{f,q}$	Element in the f^{th} row and q^{th} column of the fit matrix
$\varepsilon_{f,t}$	Binary (0-1) element: *1* if product feature *f* is available within all products and requires operation *o* in production period *t* and *0* otherwise
ϵ_{0j}	Repeatability of assembly machine *j* (mm)
η	Machine efficiency

θ_{0j}	Angular error of assembly machine *j* (rad)
μ	Coefficient of friction
$\upsilon_{i,j,f,l,t}$	Binary (0-1) element : *1* if product component *f* in product variant *i* in production period *t* is assigned to machine *j* within stage *l* and *0* otherwise
$\upsilon_{i,j,o,f,l,t}$	Binary (0-1) element : *1* if operation *o* required for product feature *f* in product variant *i* in production period *t* is assigned to machine *j* within stage *l* and *0* otherwise
$\rho_{i,f}$	Binary (0-1) element: *1* if product feature *f* is available in product variant *i* and *0* otherwise
$\sigma_{o,f}$	Binary (0-1) element: *1* if operation *o* for product feature *f* is available in all production periods and *0* otherwise
σ_f	Binary (0-1) element : *1* if product component *f* is available in all production periods and *0* otherwise
$\varphi_{i,j,f,t}$	Binary (0-1) element: *1* if product component *f* in product variant i in production period *t* is assembled by machine *j* and *0* otherwise
$\varphi_{i,j,o,f,t}$	Binary (0-1) element: *1* if operation *o* required for product feature *f* in product variant *i* in production period *t* is assigned to machine *j* and *0* otherwise
$\psi_{o,f,t}$	Binary (0-1) element: *1* if product feature *f* is available within all products and requires operation *o* in production period *t* and *0* otherwise

CHAPTER 1. INTRODUCTION

1.1 Motivation

The modern manufacturing environment is characterized by diversity and frequent changes in product requirements. This diversity in product requirements arises due to the changes in customer requirements for products, legislation and environmental issues. As a result, manufacturing firms strive to continuously offer a variety of products with minimal investment cost. The continuous offer of product variety requires changes to product design. Such changes in product design are likely to propagate within the different phases of the product lifecycle such as design, planning, manufacturing…etc. One of the critical phases within the product lifecycle is the manufacturing phase, which is characterized by high investment costs in terms of machine tools, controllers, material handling units…etc. Hence, product design changes can have severe impacts on the manufacturing system within manufacturing firms.

Various techniques, methodologies and models have emerged within each phase of the product lifecycle to efficiently manage the product variety in terms of cost and time to introduce to market [1]. Product family architecture [2] and product platforms and families [3, 4] are widely used strategies to manage variety within the design phase. In addition, within process planning phase, master process planning and variant process planning [5] are used in order to generate process plans for different product variants of a product family within pre-defined boundary. Reconfigurable process planning (RPP) [6] is used in the process planning phase to efficiently, in terms of time and cost, produce process plans for new product variants depending on the existing products which supports evolving part families which was first introduced and coined by ElMaraghy [7]. Various manufacturing paradigms have evolved over the years in order to cope with the frequent changes in product design such as flexible manufacturing system (FMS) and reconfigurable manufacturing systems (RMS) [8, 9].

In addition, joint development, co-development or concurrent design of products and manufacturing systems [10] has been a topic of interest for researchers and scholars which simultaneously address the product and manufacturing systems design during the different production periods scenarios. In addition, significant cost reduction can be achieved by using the concurrent approach rather than the sequential approach in which product and manufacturing systems are designed separately [11]. In addition, co-evolution of products and manufacturing systems [12, 13] has been a recent topic inspired from biology to track the features of individual products and their manufacturing system.

Accordingly, this dissertation is motivated from the proliferation of product variants due to the reasons pointed out earlier which requires in return providing methodologies and techniques within manufacturing firms to produce the product variants with least investment cost as well as in a timely manner. The literature is rich with methods discussing the problems arising from product variety as well as strategies and methods used to attenuate their effect on the manufacturing systems. This dissertation exploits the existing methods and builds on newly enhanced techniques and strategies to provide new methods that are useful to scientific and practical knowledge.

1.2 Engineering Problem Statement

Frequent product design changes require reconfiguration of the manufacturing system in order to accommodate the new product design changes. Reconfiguration of the manufacturing system is characterized by high investment cost and constitutes financial burden on manufacturing firms. Hence, it is required to synthesize adaptable manufacturing systems with the least amount of modifications in order to realize the new features and components introduced.

1.3 Objectives

Based on the engineering problem statement, this dissertation is accomplished within two main levels, the functional and physical levels.

In functional synthesis, the type of machines selected as platform or non-platform machines are determined as well as the number of each machine type. This level is further decomposed:

- First, a group of candidate machines are selected as platform or non-platform machines among a pool of available machines (either existing or can be purchased) using a matrix-based model formulation. Only system level is considered in this part.
- Second, after determining the group of candidate platform and non-platform machines, it is required to find the optimum types of platform and non-platform machines and the number of each machine among the candidates determined earlier. Only system level is considered in this part.

- Third, it is required to find the optimum types of platform and non-platform machines and the number of each machine among the candidates determined earlier. However, in this part, machine level (in terms of addition or removal of axes) and system level (in terms of addition or removal of machines) is considered to find the types and numbers of platform and non-platform machines, as well as the axes added or removed from these machines.

At the physical level, after determining the optimum machine types and numbers, it is required to determine the manufacturing system configuration by finding the number of machine stages, the type and number of machines in each stage. This is presented in chapter 7.

1.4 Research Scope

Products types addressed in this dissertation are mechanical and electromechanical products (e.g. automotive engines, household appliances, power tools…etc.). Family of products with variants are considered. Variants within a product family can be either single part product family with several machining features (e.g. cylinder block machining, cylinder head machining) or multi-components product family (e.g. household appliances, automotive engine). Each variant within a product family share commonalities and similarities with other variants within the same family in terms of their components and features. These common components and features are defined as product platforms. The manufacturing system scope of application includes existing and new manufacturing systems. Manufacturing System purpose and function include machining and assembly systems. Manufacturing system types considered are dedicated manufacturing lines, flexible manufacturing system, manufacturing cells and reconfigurable manufacturing system as in Figure 1.1.

The considered manufacturing system components include machine tools and assembly machines (e.g. CNC machines, horizontal milling machines, industrial robots, presses…etc.). Other system components such as material handling units, buffers and human operators are not taken into consideration. System level change (addition or removal of machines) and machine level (adding axes, setup change) are considered. Production volume is based on medium production volume (from 100 to 10,000 units per year) to high production volume (from 10,000 to a million of units per year). Macro process plans, which include operation sequence, setups, type of tools and types of machines and tools performing operations, are considered. Finally, the product features and components considered are the leaf nodes within the bill of material (BOM).

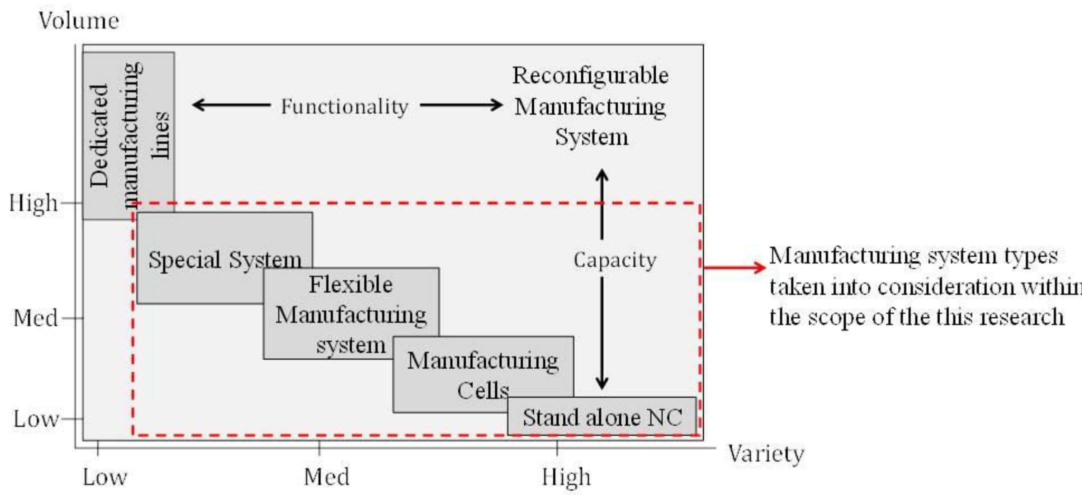


Figure 1.1 Manufacturing system types taken into consideration within the scope of the proposed dissertation

1.5 Research Gaps

Most of the literature considers the manufacturing system synthesis and joint products-systems development from investment and operation costs point of view. In addition, previous research focused on relating individual product features or operational tasks and machines capabilities without considering the notion of mapping and finding relationships between platforms or common components of both products and manufacturing systems.

Table 1.1 provides a summary of the most relevant work in the joint development of products and manufacturing systems as well as manufacturing system synthesis. Detailed literature survey is included in chapter 3.

1.6 Research Plan

This dissertation is presented in nine chapters. A research map is provided in Figure 1.2. This dissertation is mainly oriented towards synthesis of manufacturing systems which an activity within a development/design process. Design is defined as "*the transformation or mapping process from the functional domain to the physical domain which satisfies the stated functional requirements within identified constraints*"[14].

According to Tomiyama et al. [15], Pahl and Beitz defined the steps for product development process as conceptual, embodiment and detailed design. Conceptual design is concerned with finding the solution principles and the output is list of design concepts. This step is analogous to finding the list of candidate platform and non-platform machines within chapter 4. Embodiment design is concerned with finding the structure of system or product and the main output is a preliminary layout. This step is analogous to finding the selected optimum types of platform and non-platform machines as well as their numbers within chapters 5 and 6. Detailed design is concerned with final detailed structure, dimensions, materials (in case of a product) and the main output is the complete specifications of the design. This is analogous to finding the manufacturing system configuration (i.e. number of manufacturing stages, types of machines in each stage and the number of machines in each stage) within chapter 7. The focus of this dissertation is to synthesis manufacturing systems based on mapping of product platforms to machine platform on one side, and non-platform product features to non-platform machines on the other side. Analysis using simulation with different scenarios is out of scope and it is part of the future work.

Table 1.1: Research gaps literature

	Problem Formulation	Product design	System design	Type of solution		Product platform	System platform
				Optimum solution	Feasible Solution		
Hanafy and ElMaraghy 2015 [16]	Baysian Network	x	x		x		
ElMaraghy and Kashkoush 2015 [17]	Mathematical Programming (Optimization)	x	x	x			
Bryan et al. 2013a [11]	Genetic Algorithm	x	x		x		
Bryan et al. 2013b [18]	Dynamic Programming	x	x	x			
ElMaraghy and AlGeddawy 2012 [12]	Cladistics Classification tool	x	x		x		
AlGeddawy and ElMaraghy 2012 [13]	Cladistics Classification tool	x	x		x		
Demoly et al. 2012 [19]	Graph theory	x	x		x		
Gedall et al. 2011 [10]	Theory of technical system	x	x		x		
Michalek et al. 2005 [20]	Mathematical Programming (Optimization)	x	x	x			
De lit et al. 2002 [21]	Functional Entities	x	x		x		
Zhonghui and Ming 2005 [22]	Mathematical Programming (Optimization)	x	x	x			
Michaelis et al. 2015 [23]	Functional means tree	x	x		x		x
Michaelis and Johannesson 2012 [24]	Functional means tree	x	x		x		x

All models provided in this dissertation are intended to be solved sequentially as seen in Figure 1.3. In other words, outputs from the models in the different chapters are considered inputs to successive chapter models. However, in the models introduced in chapters 5 and 7, each model will be solved independently without depending on the previous models. The distinguishing inputs and outputs in each model will be presented and emphasized by an IDEF0 in the beginning of chapters 5 and 7.

1.7 Thesis Hypothesis

> *"Synthesis of an adaptable manufacturing system could be achieved by concurrently integrating common features and components within a product family together with manufacturing system through mathematical modeling which aids in facilitating adaptation and reducing investment cost of the manufacturing system"*

Several terms within this section require clarification. Synthesis, according to Tomiyama et al. [15], is one of the activities in product development/design in which product characteristics are specified and appropriate values are assigned based on functional requirements. The other activity in the product development/design is the analysis in which the behaviour of the product is analysed and studied based on the product characteristics determined within the synthesis activity. The analysis activity is mainly carried out through experiments (e.g. mock-up, prototype, simulation…etc.). In addition, *Synthesis*, according to Ueda et. al. [25], is described as putting together parts or elements so as to form a whole, or the combination of separate elements of thought into a whole, as of simple into complex conceptions, species into genera, individual propositions into systems. In this dissertation, the main concern is directed towards synthesis activity of manufacturing systems. Analysis activity is not included in this dissertation.

Belisario and Pierreval [26] defined *adaptability* as the responsiveness to long term uncertainties and changes unlike agility which is effectiveness to respond to short term changes and uncertainties. Bordoloi et al. [27] defined adaptability as the ability to change within a given state. Keddis et al. [28] described the characteristics and enablers of adaptable manufacturing system as modularity, components loosely coupled, heterogeneity, standardization and interoperability, plug and play and scalability.

	Chapter 4 (Machining)	Chapter 5 (Machining)	Chapter 6 (Machining)	Chapter 7 (Machining)	Chapter 8 (Assembly)
Design Level	Conceptual	Embodiment		Detailed	Conceptual/Embodiment/ Detailed
Functional/ physical	Functional			Physical	Functional/Physical
Machine/system changeover	System level		System and machine level	System level	System level
Purpose	Synthesis of generic candidate machine types	Synthesis of selected machine types and number of machines	Synthesis of selected machine types and number of machines	Synthesis of manufacturing system configuration	Synthesis of functional and physical level of assembly system
Tools	Matrix based mapping model	Optimization using Mixed Integer Linear Programming(MILP)	Optimization using Mixed Integer Linear Programming (MILP)	Optimization using Mixed Integer Linear Programming (MILP)	Matrix based mapping Optimization via MILP
Main Outcomes	Candidate: -Platform machines -Non platform machines	Selected: -Types of platform machine -Types of non platform machine -Number of each machine type	Selected: -Types of platform machine -Types of non platform machine -Number of each machine type	Manufacturing system configuration	-Platform and non-platform machines and their numbers -Assembly system config.

Figure 1.2 Research map

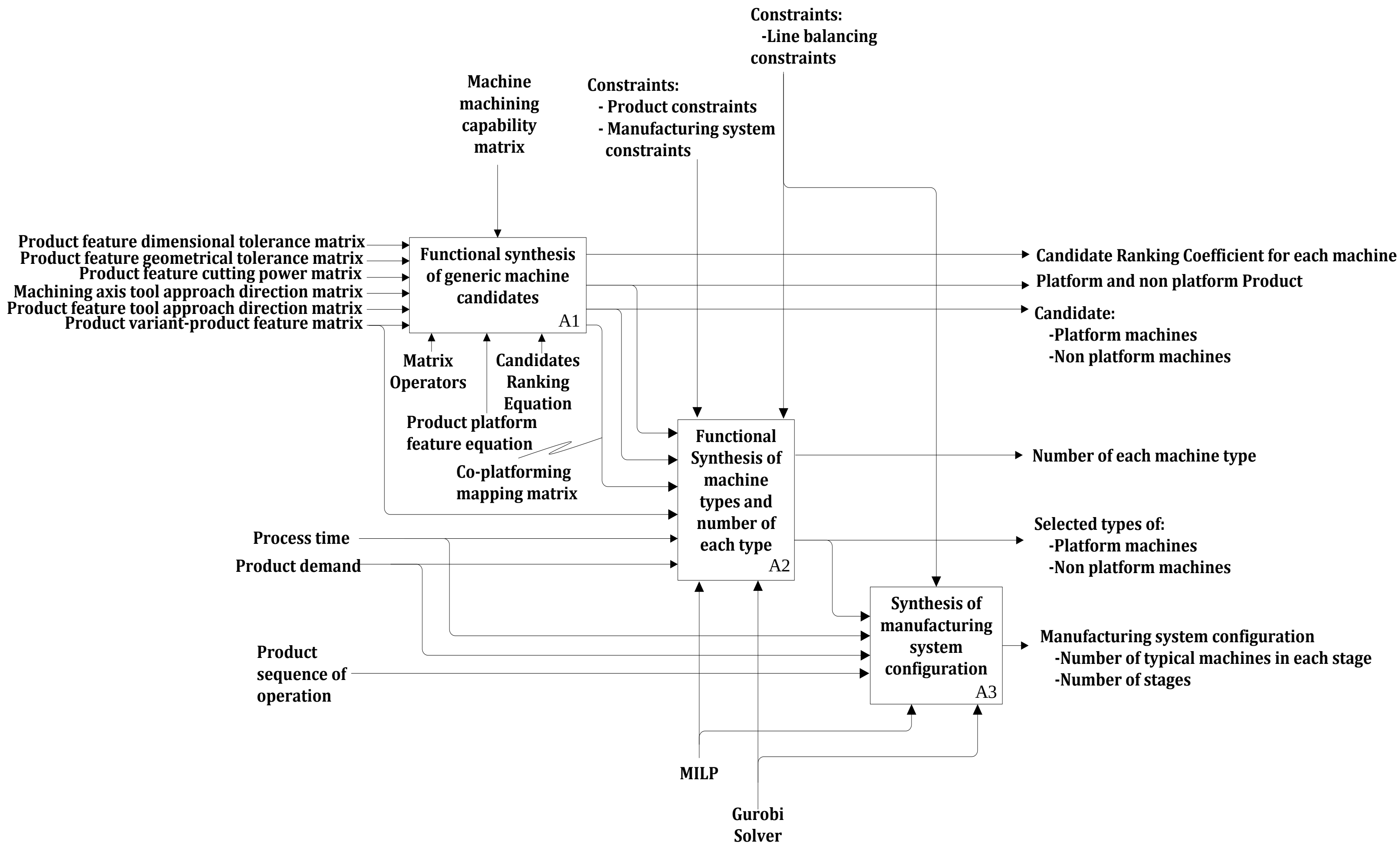


Figure 1.3 IDEF0 of the different models proposed in this dissertation

CHAPTER 2. DEFINITIONS

2.1 Overview

This chapter provides a summary for the different definitions of the important terms used in the dissertation such as product features, machine capability, manufacturing system configuration, product platform and co-platforming.

2.2 Product features

Various definitions exist for the term feature. According to the American Society of Mechanical Engineers ASME [29], the term feature is defined as "*a physical portion of a part such as a surface, pin, hole, or slot or its representation on drawings, models, or digital data files*". Shah and Rogers [30] defined features a set of descriptions used to describe a part. Such descriptions are intended for design, manufacturing, inspection or administrative purposes. ElMaraghy [31] defined features as the building block of components. Features were divided into 2 categories in this case:

- Micro features: form features which are not specific to any application
- Macro features: functional features

More definitions of the term features are available in [32, 33, 34]

2.2.1 Types of features

Shahin [32] proposed that, according to the literature, the feature definition is categorized into two classes; design features and manufacturing features. Design features are defined as the set of geometric entities used to represent shapes and patterns that perform certain functions [32]. In addition, Shahin [32] listed several different features such as functional features, assembly features, analysis features, tolerance features, technological features, material features, precision features, mating features, abstract features and physical features. Definitions of some of these features will be defined within this chapter.

On the other hand, manufacturing features are features related to manufacturing and defined as the regions within a working stock that are formed by metal removal processes [32]. Bernardi et.al [35] differentiated features according to:

- Kind:
    - Geometric (form) e.g. shoulder, groove, protrusion, step…etc.
    - Qualitative features e.g. bars and solid work piece
    - Functional features e.g. rolling bearing bracket, O-ring groove [35], key seats and spline shafts [36]
    - Atomic features e.g. toroid shell, ring, shape tolerance and surface finish
- Application
    - Design features: features related to the early design process
    - Manufacturing features: features related to manufacturing processes

2.2.2 Definition of features types

This section provides the definitions of some features listed earlier in this section.

- Form (Geometric) features: This type of feature is defined as the elements related to nominal geometry of the part model [37]. According to [36], form features are recognizable shapes and entities such as lines, points and surfaces that cannot be further decomposed. This type of feature can be specified as positive (protrusions) or negative (depression) [33] as shown in Figure 2.1.

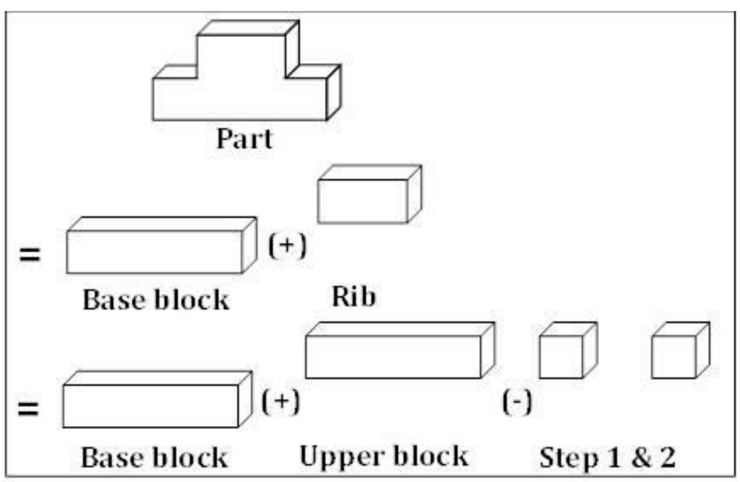


Figure 2.1 Illustration of form feature (adopted from [33])

- Manufacturing features: it is a group of geometric elements analogous to specific manufacturing processes [38]. The classification of the manufacturing features according to STEP AP224 standard is shown in Figure 2.2. The manufacturing features are divided into three main divisions. The first division is machining features which includes features such as thread, knurl, multi-axis features…etc. The multi-axis features are further divided into hole, planar face, slot, pocket…etc. The second division is transitional features which includes chamfer and fillets. The third division is the replicated features which can be in the form of array (circular and rectangular pattern) as well as general patterns. Machining feature is defined within point (c). In this dissertation, manufacturing features, such as boss, slot, hole and planar face, will be used to describe the features within parts due to their relevance in manufacturing processes [39] since this dissertation focuses on finding relationship between product features and manufacturing system components. In order to provide manufacturing features description, a features library based on STEP AP224 standard will be adopted [40] which is an ISO STEP protocol for manufacturing information [41] and is included in Figure 2.2.

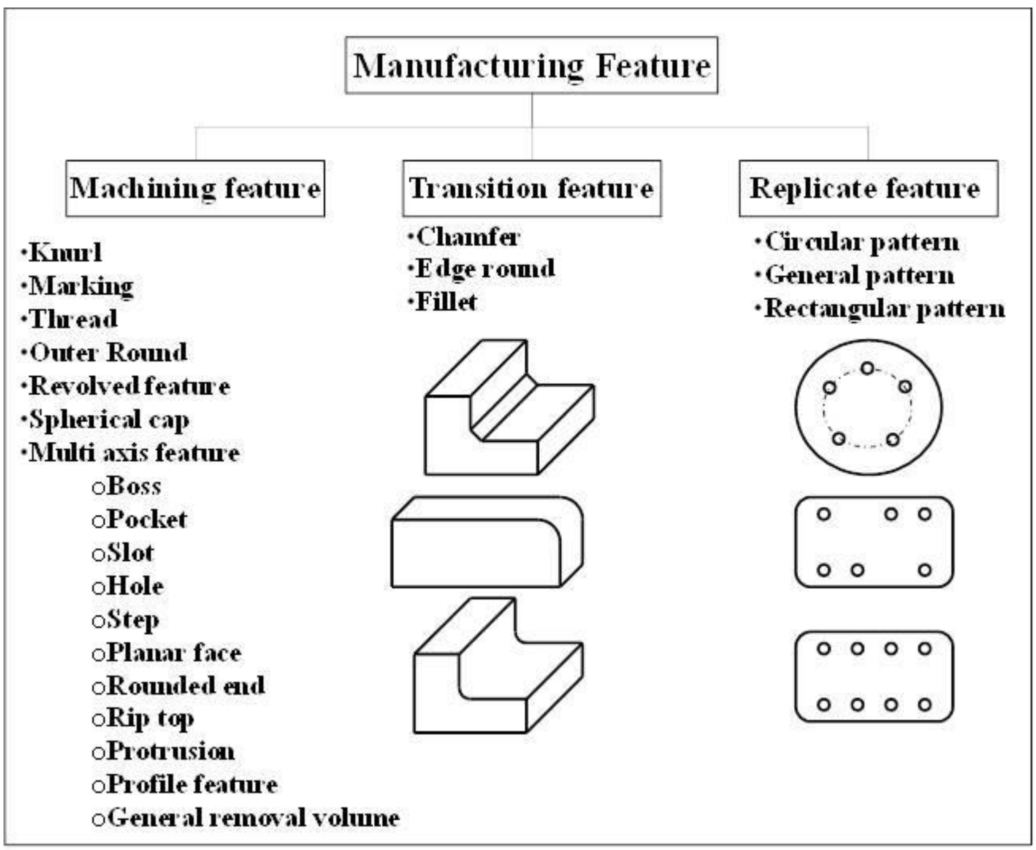


Figure 2.2 Manufacturing features according to STEP AP224 standard [40]

- Machining features: Unlike form features, machining features are specified only as negative since machining features are concerned with metal removal process as illustrated in Figure 2.3.

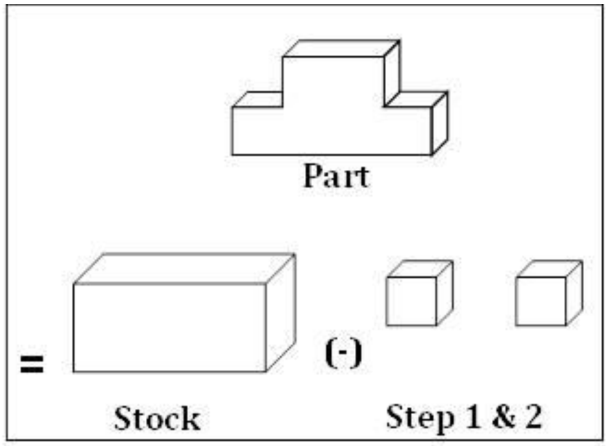


Figure 2.3 Illustration of machined features (adopted from [33])

- Abstract features: Since detailed features description is not available before the end of design process, this type of feature is used during the design process.
- Material features: Is a region within a part which is characterized by material composition variation. Such material variation is different in function from the neighbouring volume material. Material composition is accompanied by engineering significance such as thermal balance, bio-compatibility and corrosion protection [42]. Figure 2.4 illustrates the material feature and how is it different from the form feature.

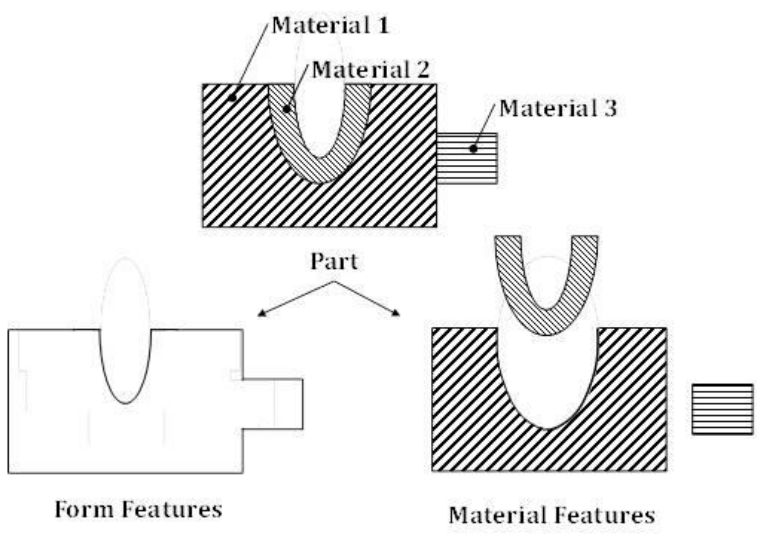


Figure 2.4 Illustration of material feature (adopted from [42])

- Precision feature: This type of feature is concerned with the geometry deviation from the nominal value. This feature is divided further into tolerance feature and surface finish [37]
- Assembly features: This type of features is concerned with the relationship between components (e.g. orientation of components, mating relationships…etc.) within a mechanical assembly [43].

2.3 Machine Capability

Machine capability refers to characteristics within machine tools which permits a machine tool to process certain features within parts and products. Technical data catalogues of machine tools manufacturers include several characteristics and capabilities which distinguish one machine from the other. These characteristics and capabilities include machine axes, working envelope dimensions, available power, machine accuracy, maximum number of tools a tool magazine can hold…etc.

2.3.1 Machining axes

The 5-axis machine in Figure 2.5 possesses 5 degrees of freedom. Three of them are transitional in the Cartesian directions X, Y and Z. The other two degrees of freedom are rotational about the x-axis with an angle A and about y-axis with angle B. The 3-axis machine in Figure 2.5 possesses 3 degrees of freedom which are only transitional in the Cartesian directions X, Y and Z. Two distinguishing machine configuration exist, namely; modular architecture and integrated architecture machines. Modular architecture machines are composed of modules which can be changed. For example, in modular machine architecture, machining axes can be added or removed by the changing the table in Figure 2.5. On the other hand, integrated architecture machines care integral types of machines in which machining axes cannot be added or removed.

2.3.2 Working envelop

Working envelope refers to the maximum available volume within a machine tool for machining a certain workpiece as seen in Figure 2.5. The dimensions of the workpiece attached to the machine tool table must not exceed the working envelope within a machine tool.

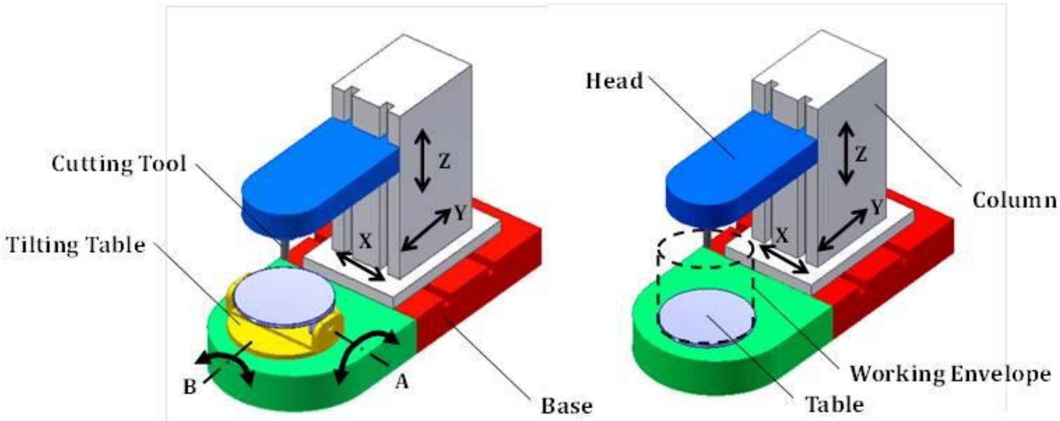


Figure 2.5 Machining capabilities for 5-axis CNC machine (left) and 3-axis CNC machine (right)

2.3.3 Machine Accuracy

Machine accuracy is defined as the deviation of a cutting tool position from a true or standard value. Machine accuracy can be in the form of linear accuracy (in mm) as a result of the transitional motion and rotational accuracy (in seconds) as result of the rotational motion.

2.3.4 Compliance

An important term in automated assembly is *Compliance*. Compliance permits flexibility within the end effector relative to the robot end-effector mounting plate to compensate for angular and positional errors as a result of misalignment between mating parts during assembly process. In addition, a compliance device is used when the tolerance of a part in assembly is less than the repeatability or accuracy of a robot [44]. Figure 2.6 illustrates the passive compliance device in which springs are used as a flexible element. When inserting a part to misaligned base part, linear and rotational allowance motions are permitted to allow for the correct assembly. *Accuracy* [45] refers to the deviation between the achieved point and command point. *Repeatability* [45] refers to the ability of end effector to reach a command point.

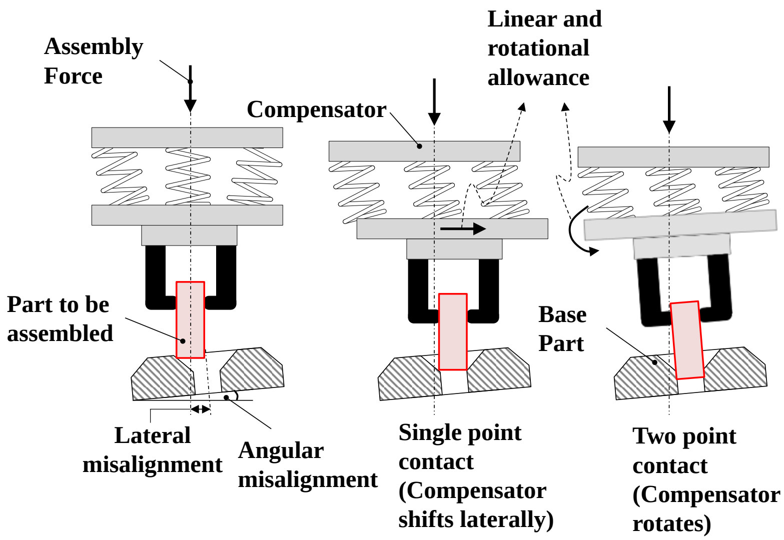


Figure 2.6 Example of a compliance resulting during an assembly process

2.4 Manufacturing System Configuration

The manufacturing system configuration is defined as the number of stages, types of machines in each stage and the number of machines in each stage [46]. Manufacturing system configuration is divided into two main types which are symmetric and asymmetric. The symmetric manufacturing system configuration is classified as cell configuration, RMS configuration and combination of cell and RMS as shown in Figure 2.7(a), Figure 2.7(b) and Figure 2.7(c), respectively. The cell configuration consists of a number of serial machines. However, crossover between the different stages is not permitted. The RMS configuration is similar to cell configuration where crossover between the different stages is permitted. In addition, machines within each stage must be identical.

The asymmetric manufacturing system configuration is classified into variable process configuration and single process configurations with non-identical machine in one stage at least as shown in Figure 2.7(d) and Figure 2.7(e), respectively. For variable process configuration, several different flow paths, according to the process plans, are implemented for a single part. For example, in Figure 2.7(d), the possible flow paths, according to the process plans, of a single part can be (A-B-C-D-E) or (A-B-C-F) or (G-C-D-E) or (G-C-F). The impracticality of this configuration is the exhaustive effort required to prepare several process plans for a single part which is reflected on the flow paths in addition to increasing part quality problems due to the different alternatives available for the production of a single part. For single process configurations in Figure 2.7(e), though the process plans are identical within each possible flow path, non-identical machines can exist in a single stage such as machine (B) in stage 2 as shown in Figure 2.7(e). The mix in machines within one stage impose difficulty in line balancing due to the difference in processing time from one machine to the other.

In this research, only symmetric manufacturing system configuration is considered since it is suitable for manufacturing systems [47].

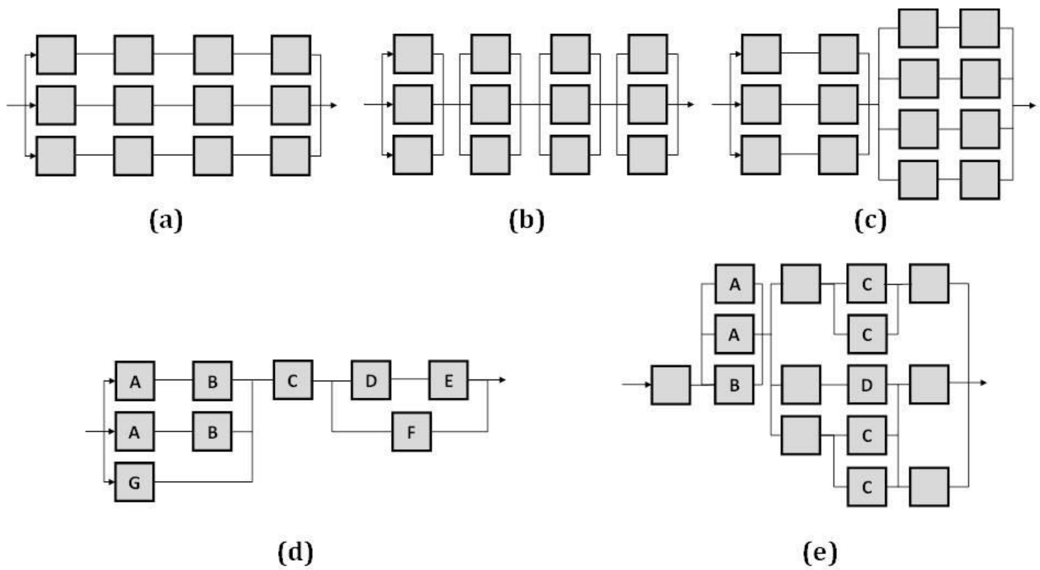


Figure 2.7 Different types of symmetric manufacturing system configuration (a) cell configuration (b) RMS configuration (c) combination of both (cell and RMS) and asymmetric manufacturing system configuration (d) variable process configuration (e) single process configurations with non-identical machines in one stage at least [47]

2.5 Product platform

Core features/components or *product platform* are defined as a set of common and strongly connected features, components, subassemblies or modules shared by all product variants within a product family [48] as seen in Figure 2.8. In literature, there exist three types of product platform, namely scale based platform [49, 50], module based platform [51] and adaptive based platform [52].

In scale based platform, the different components are described in terms of scalable characters and variables such as length, radius, thickness, number of turns…etc. These variables are used as decision variables in optimization models with objective to minimize or maximize performance measures such as power, mass, efficiency…etc. and maximizing the common variables among product variants within a product family in order to determine which variables are common among all product variants (platform variables) and which variables are not common (non-platform variables). A famous example for this type of product platform is a jet plane in which decision variables such wing span, fuselage dimensions are used to describe different product families. In addition, sensitivity and clustering analysis are methods used [53] to design scaled based product family. First, sensitivity analysis is carried on the different decision variables based on the performance criteria (power, mass, efficiency…etc.). relatively low sensitivity (lower than a threshold value) values for certain decision variables indicates that low performance is acquired if these decision variables are taken as common within the different variants in the product family. Hence, low sensitivity values for decision variables indicate that such variable are considered platform. Afterwards, clustering analysis is carried out to group product variants into product families.

In module based platform, the problem is concerned with choosing a combination of module instances for each module slot in each product family which in turn leads to a certain performance of each product variant. A famous example of this type of product platform is the personal computers in which several module instances exist for one module type. For example, a webcam module includes several module instances with different resolution. Several techniques in literature exist in order to design the product family and product platform for a module based type product platform. These techniques include but not limited to network science in which the whole product family are described in the form of network and product platform are identified based on topological properties such as degree of node, betweeness…etc [54]. Mathematical models, formulation, heuristics and optimization had been also used to design the module based type product platform in which module instances of each module are selected in accordance with product structure constraints (in the form of rules) in order to maximize certain performance measures such as quality and performance or minimize cost [55, 56]. Other strategies of product platforms exist in literature as shown in Figure 2.9, namely; single platform strategy based on majority of common components within variants [57] and multiple platform strategy (sub-platform) [58]. For example, in Figure 2.9a, in single platform strategy based on the majority of common components within variants, each variant can be composed of 4 components described by the binary string in each rectangle (1 if component is present and 0 otherwise). The product platform is selected based on the majority of common components within the product family. As component 1 is available in variants 2 and 3 but not in variant 1. Therefore, component 1 is considered a product platform since it is available in 2 variants out of the three variants. In multiplatform strategy (sub-platform) in Figure 2.9b, the product platform is viewed in hierarchical manner. The product platform circle in the uppermost level is shared by all variants

1,2,3 and 4. Sub-platform 1 in the second level contains components only shared by variants 1 and 2. Sub-platform 2 in the second level contains components only shared by variants 3 and 4.

In adaptive based platform, the scale and module based product platform are used simultaneously to design the product family. The techniques that exist for the adaptive base platform include but not limited to heuristics and mathematical models [52] and bi-level optimization [59].

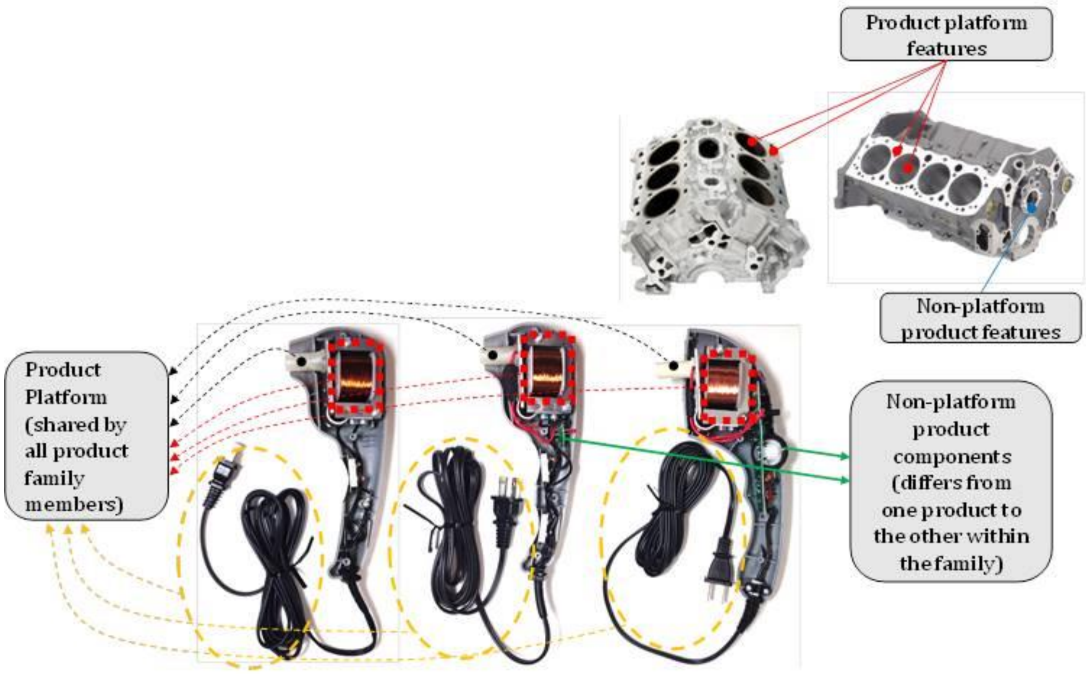


Figure 2.8 Product platform illustration

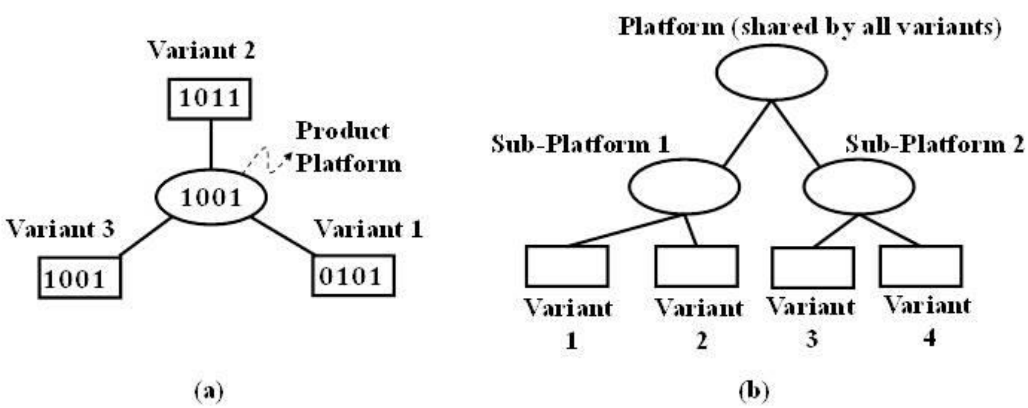


Figure 2.9 Product platform design strategies (a) Single platform with majority of component among product variants (b) Multiple platform (sub-platform)

2.6 Platform machines

Platform machines or manufacturing system platform refer to a set of machines and manufacturing system components required to process at least all product platform features and components (platform machines can process non-platform product features if they possess the machining capabilities to process non-platform product features). On the other hand, the non-platform machine is used to refer to machines that can only process the non-platform product features and components.

Several characteristics of manufacturing system platform and machines are: (1) Platform machines must possess sufficient machining capabilities to process all product platform features/components. (2) Platform machines remain unchanged from one production period to another. (3) Non-platform product features/components within product family can be realized in each product production period either by adding, removing or modifying the non-platform machines or by platform machines (if the platform machines possess sufficient capability to process the non-platform product features/components). Characteristic number 3 can be aligned with the concept of static and evolving product families introduced by [5] in which new product features and components (i) within a predefined boundary can be processed with existing manufacturing system components (use of existing machines, reprogramming, add axes) or (ii) outside the predefined boundary can be processed by system change (add machines).

2.7 Co-platforming

An important term which is introduced for the first is *Co-platforming*. Co-platforming is defined as the synthesis of manufacturing systems through mapping between product platform features and components and platform machine to have highly responsive manufacturing system for different periods of product families. At the same time, non-platform product features and components are mapped to non-platform machines to account for customization and evolution of the product family and the corresponding manufacturing system in the different periods. The co-platforming concept is also illustrated in Figure 2.10.

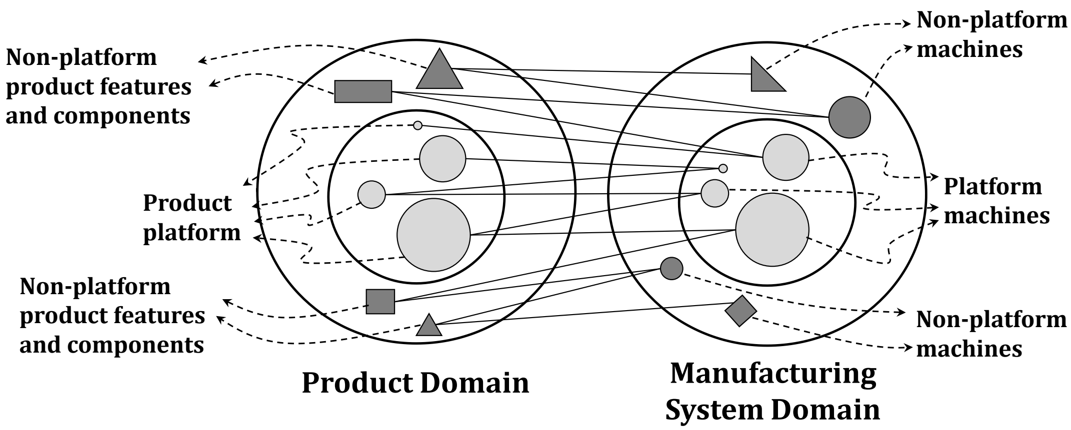


Figure 2.10 Co-platforming illustration

CHAPTER 3. LITERATURE REVIEW

3.1 Overview

This chapter provides detailed literature survey on the most relevant topic within this dissertation. The first section is concerned with the literature survey in the topic of product family and platforms, the second section is concerned with the literature of in the topic of manufacturing system synthesis and the third section is concerned with the literature in the joint development of products and systems. The fourth section provides the literature review for the topic matrix domain mapping. The last section identifies the research gaps in the literature and provides discussion on how to fill these gaps.

3.2 Product families and platforms

The topic of product families and platforms design has been a rich topic in literature as well as in papers discussing the state of art of the topic of product families and platforms through the years such as Simpson [50], Jose and Tollenaere [51] and Zhang [60]. Hanafy and ElMaraghy [61] proposed a mathematical model for product family design which takes into account the assembly and disassembly of components. The formulated model is effective in determining the optimum platform for large number of components as well as dealing with zero demand periods for some variants. Fan et al. [54] proposed a methodology for modular product platform planning using network science. The methodology is built based on two types of networks; one relating the products to its components and parts and the other relating products to the generic modules included within it. Module types (basic, scaled or may selected modules) as well as the evolution of each module types according to customer demand are identified based on the node properties such as centrality, node degree…etc. Though the methodology can handle large size problems, yet, the module type identification is based on judgement since no thresholds is provided to distinguish between module types. In addition, optimality in their methodology is not guaranteed. AlGeddawy and ElMaraghy [62] introduced a new model for reactive platform design of product variants. That model used physical commonality instead of the commonality index in order to generate product variants. The model was also able to find the right balance between integration and modularization of the different product components by balancing the two conflicting strategies namely, Design for Manufacturing and Assembly (DFMA), which aims to decrease the number of parts/components and promotes their integration, and product modularity. The model was applied to a variant of household kettles and solved twice; with a single and two platforms and provided a reduction in the number of components as well as the balance between modularity and integration. Fujita and Yoshida [63] proposed an optimization method to design module combination as well as module attributes across multiple products by hybridizing genetic algorithm, branch and bound technique and a successive quadratic programming method. The process started by optimizing the combinatorial pattern of module commonality and similarity among the different products, then optimizing the directions of similarity-based variety and finally, optimizing the continuous product design space in order to obtain the attributes of the modules. They applied their algorithm to multiple airplanes in which the results of optimization method ascertained the validity and effectiveness of the method. ElMaraghy and AlGeddawy [64] introduced the concept of co-development between market segments and product design where common components/modules were used to satisfy common needs by using a novel Product Variant Design Model (PVDM). ElMaraghy [7] introduced the term evolving product families. Evolving product families can either be new product features within a constant and rigid pre-defined boundary (which can be processed by existing machines, adding new capabilities or different programming) or new product features outside the pre-defined boundary which is no longer constant or rigid (which can be processed by adding new capabilities or system reconfiguration).Zhang et al. [65] presented a new functional modeling approach in order to identify shared and individual behavioural modules across product family of a module based product family design. Yan Ling et al. [66] applied the concept of hierarchical component platform (HCP), in which the platform design variables are identified in different levels of commonalities, in order to design a hybrid modular architecture product family. In order to identify the possible uncoupled interface, interference analysis matrix and demand calculation matrix was used.

Olivares-Benitez and Gonzalez-Velarde [55] introduced a meta heuristic approach for platform selection based on two stages. The first stage is based on finding optimum performance values such as torque, power, mass…etc. The second stage is based on minimizing the manufacturing cost and the deviation of the performance of each product from the optimum performance value obtained in the stage 1. A family of motors had been used as a case study. It was found that the results provided from the metaheuristics approach coincides with the optimum results of the same problem. Jiao et al. [67] proposed a generic genetic algorithm and implemented it in product family design. The customer perceived benefit per unit cost was used as the objective function and implemented for a family of motors. A configuration space was generated containing the feasible design alternatives, modules, design parameters...etc. Chowdhury et al. [68] presented the

Comprehensive Product Platform Planning (CP3) as a new approach to design optimal product platforms. The CP3 method provides flexibility in designing sub-families (a portion of product variants within a product family which share common components) as well as simultaneously addressing the modular and scalar attributes in the product family. In addition, a cost function was developed in order to represent the cost of the product family as a function of the number products manufactured and commonality between the products. They implemented their methodology on a family of universal electric motors.

Qu et al. [69] Developed a two stage method for product platform identification. The first stage is concerned with identification of initial product platform based on maximum clique in graph theory which is solved through genetic algorithm. The second stage is concerned with selection of the final product platform based on performance loss which is carried out through sensitivity analysis. D'Souza and Simpson [3] used a non-dominated sorting genetic algorithm for multi-objective optimization in order to find acceptable balance between commonality among product family and the desired performance of the individual products in the family. Kumar et al. [70] addressed integrating of market considerations with the product family concerns and expanded the scope of the product family design in order to assign the different product variants within a family to their appropriate market segment. Khajavirad et al. [71] developed a decomposed multi-objective genetic algorithm in order to find the platform selection, design and variants of a product family. This methodology permits sharing of components within subset of variants. The methodology has been implemented on a universal electric motor as a case study. Alizon et al. [72] proposed four processes based on concurrent engineering principles for product family design using two platform approaches (top down and bottom up) and two development drivers (product driven and platform driven). In addition, they introduced some examples of existing companies and the type of processes implemented within the organization including Top down product driven, top down platform driven, bottom up product driven and bottom up platform driven. Farrell and Simpson [73] proposed a method in order to improve commonality in a customized volume product line which focused mainly on redesigning a set of components that are characterized by high potential for cost saving rather than redesigning the whole product line. Simpson et al. [74] introduced an approach that integrates several methods and tools that are commonly used in the product family design such as market segmentation grid, generational variety index, design structure matrix, commonality indices in order to define what components should be common and unique and best parameter settings for each component and subsystem within the family. Thevenot and Simpson [75] proposed a method of product family benchmarking which focuses on dissection and utilized the comprehensive metric for product development in order to access the level of commonality and variety in each product family design alternatives. By comparing the existing product family design alternative and potential savings with the commonality and variant improvement after redesign, it was concluded that the method proposed can assist designers in selecting product family design alternative in benchmarking with other competitors as well as for internal benchmarking. Alizon et al. [76] introduced a methodology to improve the design, commonality and diversity within an existing family as well as defining new components and their interfaces by using design structure matrix flow, value analysis and commonality versus diversity analysis.

Moon et al. [77] proposed an agent based recommender system in order to support product family design based on customer preferences in a dynamic electronic market environment by using a learning mechanism. They proposed two scenarios for their simulated experiment. The first scenario investigates whether the aforementioned learning mechanism selects products in the same customers' preferences. The second scenario utilizes the learning mechanism to select proper products for different customers' preferences. They concluded from the two experiments that the proposed Multi-agent system could be used to determine proper products based on selections based on preference values.

In flexible and adaptive product platforms, Suh et al. [78] introduced a multidisciplinary process for designing flexible product platform components under future uncertainties. They demonstrated their methodology via a case study in which 4 different flexible design alternatives for an automotive floor pan were created. Accordingly, 4 demand scenarios were created and optimized in order to minimize the cost of the equipment. Their results showed how the flexibility embedded in components influenced the product platform economically during its lifetime. Also, they concluded that as the degree of future uncertainty in requirements increased, the component embedded flexibility also increased in return. Suh and de Weck [79] proposed a platform design process that is responsive to future market uncertainty. The proposed process consists of seven iterative steps: (i) identifying market, variants and uncertainties, (ii) determining uncertainty functional attributes and design variables, (iii) optimizing product family and platform bandwidth, (iv) determining the critical elements for flexibility, (v) creating flexible design alternatives, (vi) determining cost of design alternatives and (vii) performing uncertainty analysis. They applied their method to two Body in White (BIW) platforms under different uncertainty scenarios. They found that when uncertainty wasn't considered, it would be better to use inflexible BIW design. On the other hand, when degree of uncertainty increased, the flexible BIW platform design showed higher Net Present Value (NPV). They concluded that it is better to use flexible BIW platform design if the appearance of vehicle changed every 3 years or less. Li and Huang [52] proposed a meta-heuristic using NSGA-II for adaptive product family design. In their dissertation, adaptive product family design refers to product family that is composed of common modules, scalable variables and unique instances. The objective is to minimize the loss in performance criteria (which is the weight in this case) as well as increasing commonality. They implemented their method on a product family of gantry cranes. They found from the Pareto solutions the solution that had better balance between commonality and performance. Ma et al. [80] developed a design process based on flexible product platform and parametric design. They applied their process to design belt conveyor. Their design process steps were: (i) dividing the market grid, (ii) analyzing uncertainty, (iii) optimizing uncertain factors and determining their ranges, (iv) analyzing the structure of the belt conveyor and finally, (v) establishing the parameterized flexible product platform of the belt conveyor.

In technology platform, Alblas et al. [81] presented function-technology platform representation using Unified Modeling Language (UML). Generic function structure and generic technology structure were manually constructed. In addition, association rules governing the two domains were defined a priori. Derivation of the technology variant is based on specifying the functional requirement. A main drawback in this approach is the difficulty in automating the mapping procedure between the functional and technology elements in both domains. Levandowski et al. [82] proposed an approach for integrating technology and product platforms. The technology platform development is achieved by a wiki support system (which is a database including types, information and working principles of technologies) while the product platform and variants development is achieved by Product Lifecycle Management (PLM) architecture. Alblas and Wortmann [83] investigated the design issues of the intangible platform elements for firms that deliver complex products and systems labeled as function-technology platform. Their research has been implemented at a supplier of lithography machinery. The main outcome from their research illustrates the benefits of the reuse of these intangible elements in product development process in addition to the reuse of the tangible platform elements (product platform).

In process platform, Zhang et al. [84] proposed a knowledge based system method to generate production processes for product variants. The proposed model utilized integrated product and process structure as well as petri nets in order to generate the different production processes based on the parameters specified according to the customer requirements such as car body colour, engine horse power, type of gear transmission…etc. Zhang and Jiao [85] proposed adopting the graph rewriting systems for generate production processes for the different variants within product family. They defined the system by using PROGRES that includes three levels of abstraction which are (i) meta model at meta level, (ii) generic model at family level and (iii) instance model at variant level. They demonstrated their methodology through a study case on spindle family. Zhang and Rodrigues [86] studied the logic of configuring production process by using dynamic modeling and visualization approach through the development of a new form of nested coloured times Petri nets. They identified three types of nets: process nets, assembly nets and manufacturing nets all combined with a net system. They implemented their methodology on a family of vibration motors as a case study. As a result, they were able to obtain more than one production process, each consisting of different machine combinations that are feasible in order to fulfil each of the vibration motor requirements.

From the product family and platforms literature review, it is evident that various techniques and methods were implemented (mathematical programming, heuristics, graph theory…etc.) in order to design product families based on common features and components among the different product variants. Subfamilies (partial commonality among product variants) and simultaneous assembly and disassembly of components were also introduced within the literature review in order to maximize the number of shared components and delay the point differentiation within a manufacturing system. However, there is a lack of integrating the common and non-common components and features within a product family with the associated manufacturing system.

3.3 Manufacturing system synthesis

ElMaraghy and Kashkoush [17] proposed a mixed integer linear programming model to synthesis assembly systems through association rules and knowledge discovery. The main input to the model includes existing or historical data within a manufacturing firm about products and their features on one side and the systems capabilities that realise that product. The model output is in form of a relationship matrix that relates each product feature with the corresponding capabilities which can assist in determining the capabilities required to assemble a new product. Ko and Hu [87] presented a model for manufacturing systems design taking into consideration the stochastic evolution of product families through different production periods. A mixed integer programming model was developed to reduces the cost of the manufacturing system configuration due to product change and, increase the recurrences of manufacturing operation on the same machine along the product evolution. A case study of a toaster was used to verify their model. Youssef and ElMaraghy [46] proposed a model that optimizes the capital cost of Reconfigurable

Manufacturing Systems (RMS) configurations with multiple-aspect (includes arrangement of machines, equipment selection and operations assignment) with the aid of Genetic Algorithm by including the arrangement of machines, equipment selection and operations.-machines assignment The model was implemented for two test parts (ANC-90 and ANC-101) which are widely used in literature For validation The proposed method provided more than one configuration with the same optimal capital cost where the system developer can make a final choice based on other criteria in addition to cost.

Hanafy and ElMaraghy [57] proposed a model to develop the assembly system layout for delayed product differentiation based on phylogenetic networks. The model implemented the concept of customizing a pre-optimized product family platform which is made to stock to produced different product variant as orders are received using both assembly and disassembly of components. In addition, a postponement metric was developed which determines the effectiveness of a designed platform in delaying the point of product variants differentiation. AlGeddawy and ElMaraghy [88] introduced a novel changeability design structure matrix for synthesizing manufacturing systems based on the best granularity level of the system. The granularity level of the system determines the optimum balance between modularity and integration of the manufacturing system components. Eguia et al. [89] proposed a new paradigm for a Reconfigurable Disassembly System (RDS) which is used when there is rapid changes in quantities and mix of products in disassembly operations. The methodology is composed of grouping products into families by taking into consideration the similarity between the products to disassemble, sequencing the families in the RDS and computing the machines and configurations required for each family by using a mixed integer linear programming model. AlGeddawy and ElMaraghy [90] presented a new optimization model based on cladistics to construct the optimum layout of a delayed differentiation single line assembly system for a mix of product variants by optimizing the locations of the products delayed differentiation points. The different variants are identified according to the required operations and the assembly system is synthesized using a cladistics-based classification technique adopted from biology. AlGeddawy and ElMaraghy [91] proposed a cladistics technique which synthesize manufacturing capabilities for new products based on existing data of product features and their corresponding manufacturing capabilities. The proposed model was based on association rules and knowledge discovery which is achieved by tree classification and tree reconciliation algorithms. Ko and Hu [92] developed a mathematical programming model for line balancing of asymmetric assembly lines configuration designed for delayed product differentiation. The developed model assists in determining the assembly system configuration in terms of idle time, number of machine types, demand satisfaction and operational tasks for the product family. The developed model is beneficial in selecting different configurations as a response to product change. Li et al. [93] proposed a nested combinatorial optimization algorithm to generate the asymmetric assembly system configuration for repetitive tasks within the product hierarchy and equipment selection. The algorithm is applied on automotive battery assembly which is characterized by stacking of repetitive modules. Ko and Hu [94] proposed a mixed integer programming model for manufacturing systems design and configuration taking into consideration the recurrences of tasks within the different product generations.

Shabaka and ElMaraghy [95] developed a methodology to synthesis a reconfigurable CNC machine tool which defines the optimum machine configuration with minimum capabilities (e,g, number of motion axes) required to machine given product features, which can be efficiently altered when process plan change. The research focused on machine tools kinematic structure configuration and required tools. Chen et al. [96] developed a methodology for the synthesis of optimal yet sufficient reconfigurable machine tool for parts family. The mapping between functional requirements (machining features) and design parameters (machine tools) was implemented through Analytical Hierarchical Process. Their methodology was only limited to the machine level. Mesa et al. [97] proposed a systematical approach for reconfiguration within the machine level by removing, adding and widening of modules within product family. In addition, Analytical Hierarchal process has been applied to select the best solution based on reconfiguring specific sub-functions within the system. However, the proposed methodology focused on functions of system without exploiting machine capabilities.

In the context of manufacturing system synthesis, system configuration, which is defined as the arrangement of machines, number of stages and number of machines within each stage, and the machine synthesis are the main output. There is a lack of inter-relating the manufacturing system configuration with the common and non-common components and features among product variants within a product family for the purposes of synthesizing adaptable manufacturing systems.

3.4 Products-manufacturing systems joint development

Various papers address the joint products-manufacturing systems development strategy. Hanafy and ElMaraghy [98] proposed a design methodology using Bayesian networks which extracts relationships between product features and manufacturing capabilities from existing and historical data available in a manufacturing firms. These relationships are utilized to synthesize manufacturing capabilities associated with newly introduced products with different features. Bryan et al. [11] formulated a mathematical model for concurrent design of product family and reconfigurable assembly systems without considering the relationship between the platform of the product and the assembly system. In addition, they compared the results from their concurrent mathematical model with a sequential mathematical model. According to the presented case study, it was concluded that implementing the concurrent approach results in less cost than the sequential approach. Bryan et al. [18] introduced an Assembly System Reconfiguration Planning (ASRP) method that takes into account the product family design evolution over generations and its related assembly system concurrently by minimizing the investment cost in manufacturing system. However, their solution mainly involved operational tasks without considering the platform in either products or assembly system. AlGeddawy and ElMaraghy [13] proposed a model of co-evolution based on cladistics to track the co-evolution of features of individual products and their manufacturing systems capabilities and predict the future development of new products and manufacturing systems in which association product features and machines capability is achieved using trees reconciliation. Demoly et al. [19] proposed a framework for integration of product design and assembly sequence planning. They proposed association rules for establishing the link between the product domain and assembly process domain. The machine or system level mapping was not considered. Gedell et al. [10] proposed a framework for the co-development of products and their associated production systems which were considered as co-equal objects with interactions, interfaces and subsystems. Wang et al. [99] proposed a multi objective optimization model which considered the complexity of co-development between products and assembly systems. The main purpose of the model was increase product variety offering according to the market requirement while reducing the induced complexity within the assembly system. Xu and Liang [22] proposed a mathematical model which concurrently solves the problem of module type selection and assembly line design. The types of module instances within products are selected based on four performance criteria (product reliability, product function, cost of system reconfiguration and line smoothness) and assembly line is designed based on balancing and resources issues such as choosing alternative assembly system either assembly machine, robots or human resources. However, the interrelationship between core module instances and platform equipment/machines was not considered. Michalek et al. [20] developed a mathematical model which takes into consideration manufacturing, product and market domain. The mathematical model solves the conflict between revenue and cost without taking into consideration the relationship between the product platform and the manufacturing system platform. De Lit et al. [21] used the concept of functional entities, which suits the design of product families, and its effect on product family design as well as synthesizing the corresponding assembly system design for the product family. Functional entities were used to represent the different components or modules within product family. For example, four variants of car body are referred to as one functional entity. Similarly, three chassis variants are referred to as another functional entity and so forth. Roemer and Ahmadi [100] provided a framework to address product design and manufacturing process concurrently. They used two approaches that synchronize production flow through manufacturing system. The first approach was the exact Design Selection Algorithm which addresses all product designs simultaneously through the same linear flow. The second approach separated the product set into subsets by preserving the linear portion of the flow line for common operations and dividing the line to accommodate different operations within the product designs. They compared the results obtained from the previous two approaches with benchmarking cases by considering the minimum processing time and minimum number of operations. They concluded that the two proposed approaches outperform the benchmarking cases in terms of distance traveled by product, lead time and Work-In-Process. However, the benchmarking case had better cycle times.

Though the previous work addressed the integration and co-development of products and manufacturing system, yet the different product features and components are described in terms of tasks and operations which overshadow the product structure with its common and non-common components and features. The common and non-common components and features among product variants within a product family were not clearly differentiated and mapped to manufacturing system components in an attempt to synthesize more efficient manufacturing systems.

3.5 Domains Mapping Matrices

In the topic of mapping between different domains through matrices, the most recognized and well established work is that introduced by Suh [101] which quantitatively maps between functional domain, design domain and process domain through design matrix, Each two considered domains are defined a priori. The design matrix is formulated and analyzed for the purpose of determining coupled, decoupled and uncoupled designs. Therefore, the work done by Suh [101] is considered a design analysis methodology unlike the work done in this dissertation which deals with design synthesis. Sameh and ElMaraghy [102] developed a methodology to map product complexity and assembly equipment complexity using a complexity dependency matrix which represents the relationship between assembly functions and product attributes. The methodology was applied to several case studies and found, through regression analysis, that assembly system complexity increases with the increase in part complexity. In addition, various research works can be found on mapping using matrices which mainly focus on the product development process. For example, Fung et al. [103] used fuzzy sets in addition to a rule-based system to map customer requirements to design targets. Gu and Huang [104] analyzed the mapping relationships between the physical domain and functional domain in the conceptual, detail and enhancement design phases. They established the mapping between physical and functional domains by integrating subjective and objective information through fuzzy set theory. Krishnapillai and Zeid [105] proposed a methodology for mapping customer requirements to design specifications in order to extract feasible design specifications from customer requirements taking into consideration mass customization. They used matrix formulation to map design parameters to scalable platform design parameters. They applied their methodology on spring design. Danilovic and Browning [106] proposed domain mapping matrix (DMM) that can be used to compare between two design structure matrices (DSMs) within different project domains. Yassine et al. [107] introduced a system analysis technique called connectivity map which is matrix based. It is used to extract the connection between two parameters. The connectivity map was mainly used to analyze relations between design parameters, information flows, development tasks and organizational relationships.

The different domain mapping through matrix formulation in literature mainly focused on design analysis in which the different domains are specified and analysis is carried out. In addition, various domains mapping through matrix formulation has been used to map between the different product development process phases as well as mapping of complexity of product and assembly system. However, there is a lack of work in synthesizing a system based on matrix mapping.

3.6 Discussions

Most of the literature considers the manufacturing system synthesis and joint product-system development from investment and operation costs point of view. Previous research focused on relating individual product features and machines capabilities and did not consider the notion of mapping platforms of both products and manufacturing systems. In addition, the different operations within product features and product components are mostly referred to as operational tasks without addressing the common and non-common components and features within a product family and the corresponding mapping of these components and features to manufacturing systems. Furthermore, though a great amount of work has been implemented on product families and platforms with different methods, algorithms and frameworks, it is evident that there is a lack of research on forming manufacturing systems platforms and relating them to the product family platform and non-platform product features and components. Furthermore, matrix -based mapping has been used to map different phases within product development and analysis purposes as well as mapping the complexity of the product to the associated assembly system.

Therefore, it is proposed to investigate synthesizing a manufacturing system considering both the product platform and manufacturing system platform. This strategy is defined as co-platforming. It is proposed to solve this problem using matrix based mapping and mathematical programming optimization models.

The synthesis methodology will consider both the functional and physical domains. In functional synthesis, the type of machines selected as platform or non-platform machines are determined as well as the number of each machine type. This level is further decomposed:

- First, a group of candidate machines are selected as platform or non-platform machines among a pool of available machines (either existing or can be purchased) using a matrix-based model formulation. This is presented in chapter 4.
- Second, after determining the group of candidate platform and non-platform machines, it is required to find the optimum types of platform and non-platform machines and the number of each machine among the candidates determined earlier. This will be presented in chapters 5.
- Third, cost of change in machine (in terms of addition or removal of axes) and system level (in terms of addition or removal of machines) is considered to find the types and numbers of platform and non-platform machines, as well as the axes added or removed from these machines. This will be presented in chapter 6.

At the physical level, after determining the selected machine types and numbers, it is required to determine the manufacturing system configuration by finding the number of machine stages, the type and number of machines in each stage. This is presented in chapter 7.

CHAPTER 4. FUNCTIONAL SYNTHESIS OF GENERIC MACHINE CANDIDATES

4.1 Overview

This section is concerned with the construction of the co-platforming methodology using matrix-based mapping. Figure 4.1 illustrates the co-platforming methodology using matrix based mapping. The methodology consists of three main parts; the first part is the mapping matrix which consists of several input matrices, the second part is the input vector which is a binary vector describing the product platform and finally, the third part is the output vector which describes the platform machines.

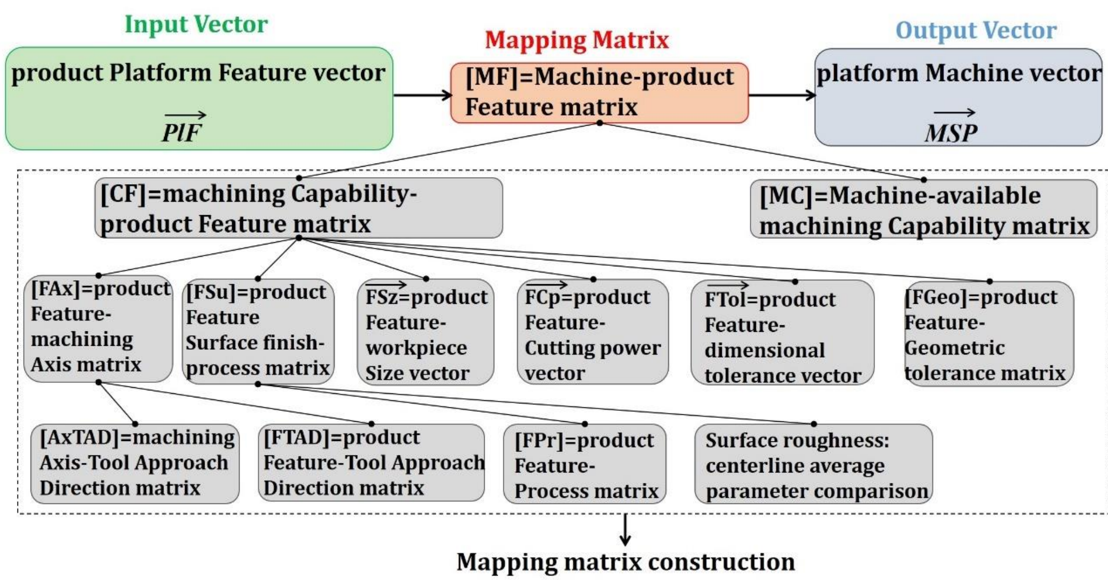


Figure 4.1 Co-platforming mapping methodology

4.2 Matrix Mapping Model Development

This section is divided into twelve subsections. Each subsection is concerned with developing or defining each matrix shown in Figure 4.1.

4.2.1 Product feature-machining axis matrix

The product feature-machining axis matrix [*FAx*] relates each product feature with the required machining axis according to the orientation of the product feature within a part or product. This matrix is derived from two matrices as seen in Figure 4.1, namely; the product feature-tool approach direction matrix [*FTAD*] and the machining axis-tool approach direction matrix [*AxTAD*].

The product feature-tool approach direction matrix [*FTAD*] relates each product feature to the Tool Approach Direction (TAD) in terms of its orientation within the product variant. Tool Approach Direction can be illustrated using the standard machined part ANC-101 as shown in Figure 4.2 and Table 4.1. Part ANC-101 is used in various literatures discussing the topic of setup planning. The TAD data related to the ANC-101 are taken from [108] with a few samples of machining product features with different orientation (e.g. horizontal, inclined and vertical). For example, product feature 1 is a hole inclined by an angle of 45 degrees with respect to the x-axis. The cutting tool (e.g. drill bit) approaches product feature 1 in a direction indicated by the encircled number 1 in Figure 4.2. This direction is resolved in positive x-axis and negative z-axis. Hence, the *TAD* is (cos45,0,-sin45) as shown in Table 4.1.

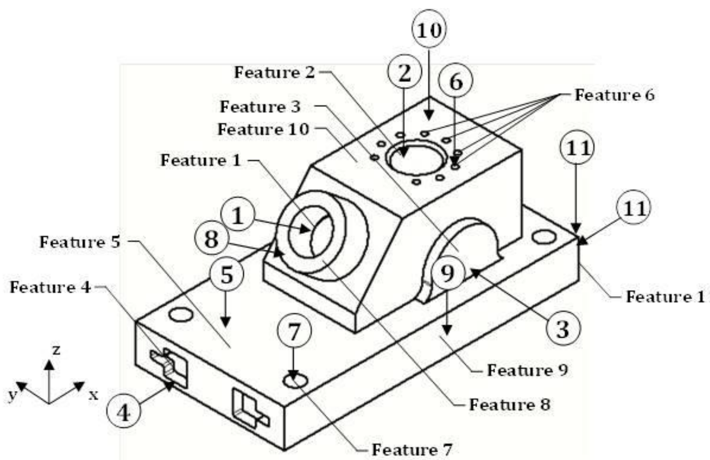


Figure 4.2 ANC-101 Test part

Table 4.1: TAD for the different product features in ANC-101 and the corresponding product feature-tool direction approach matrix formulation

Feature	Machining features	TAD	x+	x-	y+	y-	z+	z-
1	Hole	(cos45,0,-sin45)	1	0	0	0	0	1
2	Hole	(0,0,-1)	0	0	0	0	0	1
3	Protrusion	(0,1,0)	0	0	1	0	0	0
4	Pocket	(1,0,0)	1	0	0	0	0	0
5	Planar face	(0,0,-1)	0	0	0	0	0	1
6	Replicated feature (Circular pattern)	(0,0,-1)	0	0	0	0	0	1
7	Hole	(0,0,-1)	0	0	0	0	0	1
8	Boss	(cos45,0,-sin45)	1	0	0	0	0	1
9	Planar face	(0,0,-1)	0	0	0	0	0	1
10	Planar face	(0,0,-1)	0	0	0	0	0	1

The elements of the product feature-tool approach direction matrix [*FTAD*] are defined as:

$$ftad_{f,k} = \begin{cases} 1, if\ product\ feature\ f\ has\ a\ spatial\ component\ in\ the\ k\ direction \\ 0, otherwise \end{cases}, \forall f,k \tag{4.1}$$

Where $k=\{1, 2, 3, 4, 5, 6\}$ corresponds to Cartesian directions *x+*, *x-*, *y+*, *y-*, *z+* and *z-*, respectively and $f=\{1,2,\ldots F\}$ is the set of product feature and *F* is the total number of considered product features. Second, a machining axis-tool direction approach (TAD) matrix [*AxTAD*] is defined which relates machining axes type (such as 3, 4 or 5-axis) to the product feature in terms of its orientation on machine fixture. The different elements of the machining axis-tool direction approach matrix [*AxTAD*] are defined as:

$$axtad_{p,k} = \begin{cases} 1, machining\ axis\ type\ p\ can\ machine\ in\ k\ direction \\ 0, otherwise \end{cases}, \forall p,k \tag{4.2}$$

Where $p=\{1,2,\ldots P\}$ is the set of machining axis type and *P* is the total number of machining axes considered. It is evident that the product feature-machining axis matrix [*FAx*] can be calculated through matrix multiplication of product feature-tool approach direction matrix in equation (4.1) and machining axis-tool direction approach matrix in equation (4.2). However, the matrix product can result in an unfeasible solution. For example, consider the situation in which the f^{th} row of the product feature-tool direction approach matrix $ftad_{f,k(=1,2,3,4,5,6)}$=[000101], which describes a product feature *f* having an orientation within the negative *y* and negative *z* directions, is multiplied by the p^{th} column in the Machining axis-tool approach direction (TAD) matrix $axtad_{k(=1,2,3,4,5,6),p}$=[000001], which describes a machining axis within negative *z* direction only, giving a result of 1 which indicates that machining axis type *p* can process product feature "*f*" which is not true. In order to avoid such an outcome, an intermediate product feature-machining axis matrix [*IFAx*] is proposed the elements of which can be calculated as:

$$ifax_{f,p} = \frac{1}{\sum_{k=1}^{K} ftad_{f,k}} \sum_{k=1}^{K} (ftad_{f,k} \times axtad_{p,k}), \forall f,p \tag{4.3}$$

Therefore, the final form of the product feature-machining axis matrix can be calculated as:

$$fax_{f,p} = \begin{cases} 1, if\ ifax_{f,p} = 1 \\ 0, otherwise \end{cases}, \forall f,p \tag{4.4}$$

4.2.2 Product feature surface finish-process matrix

The aim of the product feature surface finish-process matrix [FSu] is to insure that the surface quality of each product feature is correctly mapped to the appropriate machining process (and finally to the appropriate machine tool) which is capable of producing the specified surface finish. The product feature surface finish-process matrix is developed according to:

- First, the product feature must be mapped to an appropriate machining process that can produce the required product feature regardless of the required surface quality. For example, consider the example in Figure 4.2, product feature 5 is planar feature which requires milling processes. In this case the other process (drilling, boring, reaming and honing) do not apply. Hence, in Table 4.2, a value of 1 is evident for milling process corresponding to product feature 1 and 0 is written for processes drilling, boring, reaming and honing. An input matrix called product feature-process matrix [FPr] is required in order to map the product features to the process in which the elements are given by:

$$fpr_{f,r} = \begin{cases} 1, if\ product\ feature\ f\ require\ process\ r \\ 0, otherwise \end{cases}, \forall f, r \tag{4.5}$$

  Where $r=\{1,2,\dots R\}$ is the process type index such as milling, drilling, honing…etc. and R is the total number of processes considered.

Table 4.2: product feature-process matrix for ANC-101

Product Feature	Machining features	Processes				
		Milling	Drilling	Boring	Reaming	Honing
1	Hole	0	1	1	1	0
5	Planar face	1	0	0	0	0

- Second, the different product features must be mapped to the specific process which produces the desired surface finish. For the hole feature 1 in Table 4.2, though various process can be applied on hole feature 1 (drilling, boring and reaming), the final decision depends on the surface finish required. For example, reaming and drilling are applied on hole features however, depending on the surface finish required, the model must choose the process which produces the required surface finish. Table 4.3 provides a sample of the minimum and maximum centerline average parameter value (Ra) for each machining process. In order to calculate the product feature surface finish-process matrix, it is essential to determine the centerline average parameter value (Ra) required for each product feature. Then each centerline average parameter (Ra) required for a product feature is compared with the centerline average parameter for each process in Table 4.3. Therefore, the product feature surface finish-process matrix [*FSu*] can be calculated as:

Table 4.3: Centerline average parameter value for various machining processes [109]

	Processes				
	Milling	Drilling	Boring	Reaming	Honing
Min Ra (μin)	32	63	16	32	4
Max Ra(μin)	250	125	250	125	32

$$fsu_{f,r} = \begin{cases} 1, if\ fpr_{f,r} = 1\ and\ Ra_{r,min} \leq Ra_f \leq Ra_{r,max} (for\ finishing\ features) \\ 1, if\ fpr_{f,r} = 1\ (for\ roughing\ features) \\ 0, otherwise \end{cases} , \forall f, r \quad (4.6)$$

4.2.3 Product feature-workpiece size vector

The product feature-workpiece size vector *FSz* ensures that the workpiece in which product feature *f* lies is within working envelope of the machine processing it. The elements within the product feature-workpiece size vector *FSz* are continuous type and calculated as:

$$fsz_f = L_0 \times W_0 \times H_0, \forall f \quad (4.7)$$

Where L_0 , W_0 and H_0 are the maximum length, width and height, respectively of the workpiece which contains product feature *f*. However, since manufactured products are not perfectly rectangular, the workpiece size is taken as the block that confines the workpiece boundary. Figure 4.3 shows the workpiece size for ANC-101.

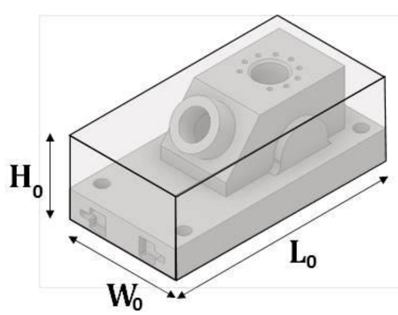


Figure 4.3 Workpiece size volume determination

4.2.4 Product feature-cutting power vector

The product feature-cutting power vector *FCp* ensures that the cutting power required to process a certain product feature does not exceed the available machine tool power. The elements of the product feature-cutting power vector *FCp* are continuous type and take the value of (http://www.mitsubishicarbide.net/):

$$fcp_f = \frac{ap_f \times ae_f \times vf_f \times kc_f}{60 \times 10^6 \times \eta}, \forall f \tag{4.8}$$

Where ap_f is the depth of cut (*mm*), ae_f is the cutting width (*mm*), vf_f is the table feed (*m/min*), kc_f is the specific cutting force (*MPa*) and η is the machine efficiency.

4.2.5 Product feature-dimensional tolerance vector

The product feature-dimensional tolerance vector *FTol* relates each feature to its dimensional tolerance. Dimensional tolerance is defined as the difference between the maximum size limit and minimum size limit [29]. For example, if a mechanical shaft has a maximum dimensional size limit of 30.05mm and a minimum of dimensional size limit of 30.00mm, the dimensional tolerance in this case is equal to 0.05mm. The elements of the product feature- dimensional tolerance vector *FTol* are continuous and defined by equation (4.9):

$$ftol_f = tol_f, \forall f \tag{4.9}$$

Where tol_f is the dimensional tolerance that a certain product feature "*f*" shall lie within according to the product specifications.

4.2.6 Product feature-geometrical tolerance matrix

The product feature-geometrical tolerance matrix [*FGeo*] relates each feature with its geometric tolerance. When deriving the machine-product feature mapping matrix [*MF*], the geometric tolerance value of the geometric control type (cylindrical, flatness, perpendicularity...etc.) will be compared with machine's linear (*ds*) and rotational accuracy capability (*dϴ*) as shown in Figure 4.4. A product feature-geometrical tolerance matrix element for a product feature corresponding to an irrelevant geometric control type will be given a value of 1. Such large values of 1 are used for geometric tolerance than are not applicable to certain product features. For example, the cylindricity geometric tolerance only applied to cylinders and does not apply to planar surfaces. Therefore, the hypothetical value of 1 is used for the planar face feature corresponding to cylindricity. The different elements of the product feature-geometrical tolerance are expressed as:

$$fgeo_{f,g} = \begin{cases} 1, if\ geometric\ control\ type\ g\ is\ not\ relevant\ to\ product\ feature\ f \\ geometric\ tolerance\ value, otherwise \end{cases}, \forall f, g \qquad (4.10)$$

Where *g={1, 2,..G}* is the set of the geometric tolerance type considered and *G* is the total number of geometric types considered. The value of the geometric tolerance value for different types of geometric tolerances is shown in Figure 4.4 in the right hand side of the inequality sign within the equations in the grey box.

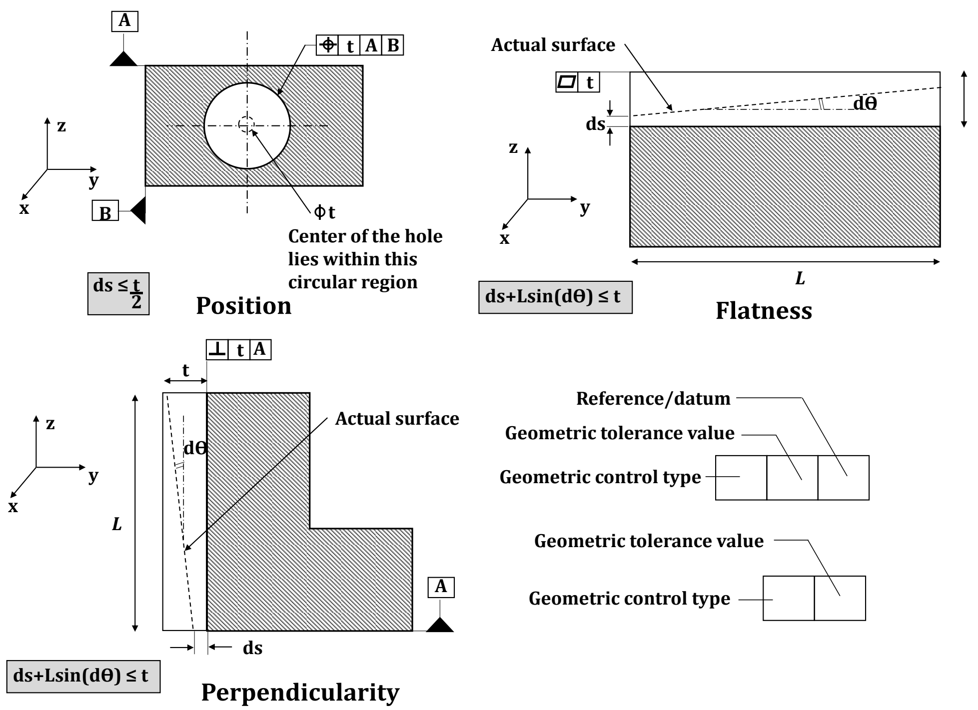


Figure 4.4 Effect of linear and rotational axes error on the geometric tolerance of the workpiece adapted from [110]

4.2.7 Machining capability-product feature matrix and machine-available machining capability matrix

The machining capability-product feature matrix [*CF*] is obtained by combining the matrices and vectors obtained in the previous subsections in a single matrix as seen in Figure 4.5a. The machine-available machining capability matrix [*MC*], shown in Figure 4.5b, is an input matrix which relates the machine types with the machining capability accompanying each machine such as available machining axis type (3, 4 or 5-axis), working envelope, machining accuracy…etc.

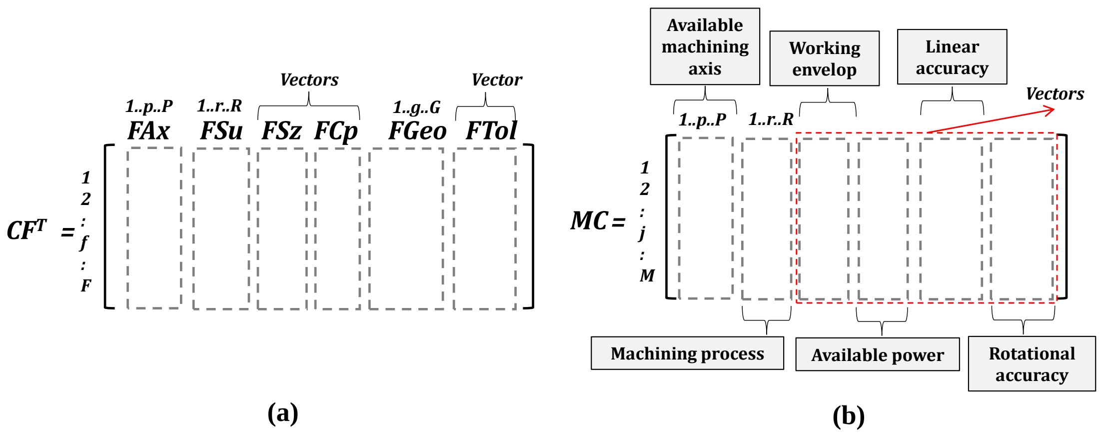


Figure 4.5 (a) Machining capability-product feature matrix and (b) machine-available machining capability matrix

4.2.8 Machine-product feature matrix

After obtaining the machining capability-product feature matrix [*CF*] and the machine-available machining capability matrix [*MC*], the different elements of the machine-product feature matrix [*MF*] are calculated as:

$$
\begin{aligned}
mf_{j,f} = \\
& max_{p=1..P} \min\left(mc_{j,p}, fax_{f,p}\right) \\
& \wedge max_{r=1..R} \min\left(mc_{j,r}, fsu_{f,r}\right) \\
& \wedge \mathbb{1}\left(mc_{j,P+R+1} > fsz_{f,P+R+1}\right) \\
& \wedge \mathbb{1}\left(mc_{j,P+R+2} > fcp_{f,P+R+2}\right) \\
& \wedge \mathbb{1}\left(mc_{j,P+R+3} < ftol_{j,P+R+3}\right) \\
& \wedge \mathbb{1}\left(mc_{j,P+R+3} + L_f \sin\left(mc_{j,P+R+4}\right) < fgeo_{f,g=1}\right) \\
& \wedge \mathbb{1}\left(mc_{j,P+R+3} + L_f \sin\left(mc_{j,P+R+4}\right) < fgeo_{f,g=2}\right) \\
& \wedge \ldots \\
& \wedge \mathbb{1}\left(mc_{j,P+R+3} < fgeo_{f,g=G}\right) \\
& \wedge \mathbb{1}\left(mc_{j,P+R+3} + L_f \sin\left(mc_{j,P+R+4}\right) < ftol_{j,P+R+3}\right), \forall f, j
\end{aligned}
\tag{4.11}
$$

Where L_f is the length of product feature "*f*" as shown in Figure 4.4, $j=\{1, 2,\ldots J\}$ is the set of machine type and *J* is the total number of available machines. The first term of equation (4.11) is equal to 1 if a certain product feature *f* orientation (in the product feature-required machining axis matrix [*FAx*]) requires the machining axis type available in machine type "*j*" (in the machine-available machining axis matrix) and 0 otherwise.

The second term in equation (4.11) is equal to 1 if product feature f is assigned to machine type "*j*" which can perform process "*r*" to produce the desired surface finish, and is 0 otherwise.

A different operator which accompanies the rest of the terms in equation (4.11) is the indicator function. If the logic statement between the parentheses is satisfied, the output from the indicator function is 1 or 0 otherwise. The third and fourth terms in equation (4.11) take a value of 1 if the machine work envelop and available power are greater than the workpiece volume and required cutting power, respectively and, and is 0 otherwise.

The fifth term in equation (4.11) is equal to 1 if the accuracy of machine type "*j*" is within the dimensional tolerance of the product feature "*f*", and is 0 otherwise. The rest of the terms in equation (4.11) (except the last term) take a value of 1 if the combined effect of the linear and rotational accuracy of machine type "*j*" produce feature "*f*" within the acceptable geometrical tolerance value and are 0 otherwise as shown in Figure 4.4. In equation (4.11), the value of $fgeo_{f,g}=G$ is the value of the positional geometric tolerance, hence, the positional geometric tolerance is divided by 2 as shown in Figure 4.4. For example, consider the positional geometric tolerance in Figure 4.4, if the geometric tolerance value is 0.01 for product feature "*f*", then "*fgeo*" is equal to 0.005. The last term in equation (4.11) takes a value of 1 if the combined effect of the linear and rotational accuracy of machine type "*j*" produce feature "*f*" within dimensional tolerance and is 0 otherwise as shown in Figure 4.6.

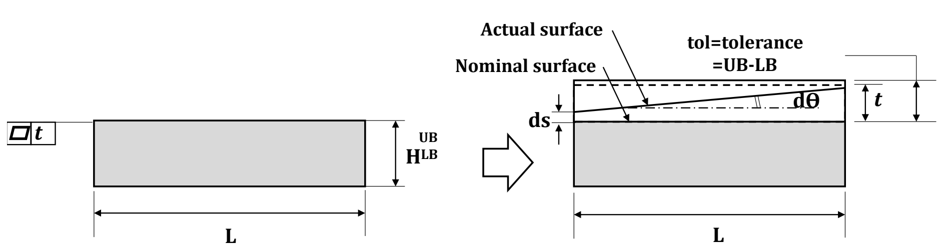


Figure 4.6 Effect of linear and rotational axes accuracy on the dimensional and geometric tolerance adapted from [111]

4.2.9 Product platform feature vector

In order to calculate the product platform feature vector *PlF*, it is essential to represent each product according to its product features. A product variant-product feature matrix [*PtF*] is proposed in which its elements are defined such that:

$$ptf_{i,f} = \begin{cases} 1, if\ product\ variant\ i\ contains\ product\ feature\ f \\ 0, otherwise \end{cases}, \forall i, f \tag{4.12}$$

Where $i=\{1,2,\ldots I\}$ is the variant index and I is total number of product variants considered. The product platform feature vector takes the form:

$$\overrightarrow{PlF} = \left[plf_1\ plf_2\ \ldots\ plf_f\ \ldots\ plf_F\right] \tag{4.13}$$

The different elements of the product platform feature vector *PlF* equation (4.13) can be calculated according to two methods; product features common in all product variants and product features available within the majority of product variants which is analogous to the majority of common components within variants [57] and sub-platform strategy [58]. The different elements of the product platform feature vector based on common features in all product variants are calculated as:

$$plf_f = \begin{cases} 1, if\ ptf_{1,f} = ptf_{2,f} = \cdots = ptf_{I,f} = 1 \\ 0, otherwise \end{cases}, \forall f \tag{4.14}$$

In addition, the different elements in the product platform feature vector *PlF* based on the majority of features within the product variants are calculated as:

$$plf_f = \begin{cases} 1, if\ \sum_{i=1}^{I} ptf_{i,f} \geq \frac{I+1}{2} \\ 0, otherwise \end{cases}, \forall f \tag{4.15}$$

4.2.10 Platform machine vector

The final step is to calculate the output vector (platform machine vector *MSP*). The platform machine vector *MSP* is obtained by:

$$msp_j = min(1, \sum_{f=1}^{F} mf_{j,f} \times plf_f), \forall j \tag{4.16}$$

The formulation of equation (4.16) insures that "msp_j" takes a value of 1 if the value "$\Sigma_f\, mf_{j,f} plf_f$" is greater than 0. Values of "$\Sigma_f\, mf_{j,f} plf_f$" greater than 0 mean that machine type "j" is a platform machine since it can process product platform features. Therefore, the value of "msp_j" is equal to 1 if machine type "j" is a platform machine and 0 otherwise.

4.2.11 Platform machines candidate ranking

After the platform machine vector has been calculated, it is required to develop a ranking procedure in order to facilitate the selection of machines from the group of candidate platform machines proposed in the previous subsection according to their machining capabilities. The objective is to rank each platform machine according to the number of product platform features a machine can fabricate compared to the total number of product platform features. Hence a ranking formula called Candidate Ranking coefficient "*CR*" is proposed which is the ratio between the number of product platform features a machine can fabricate and the total number of product platform features. Therefore, the proposed formula candidate ranking coefficient "*CR*" can be written as:

$$CR_j = \frac{\sum_{f=1}^{F} mf_{j,f} \times plf_f}{\sum_{f=1}^{F} plf_f} \text{ , } \forall\, j = 1,2..J \tag{4.17}$$

The candidate ranking coefficient output value from equation (4.17) falls within the interval 0 to 1 such that the maximum value of 1 indicates that the machine can fabricate all product platform features and the minimum value 0 indicates that the machine cannot fabricate any product platform features. Values between 0 and 1 indicate an intermediate state between the maximum and minimum states. The candidate ranking coefficient provides a quantitative decision making measure for manufacturing firms to select the required machines. For example, as the candidate ranking coefficient for a machine approaches 1, it indicates that the machine is equipped with high machining capabilities since it can fabricate a large portion of the product platform features. On the other hand, as the candidate ranking coefficient for a machine approaches 0, it indicates that the machine is dedicated for a limited product platform feature.

4.3 Case Study: Machining of cylinder blocks taken from Mitsubishi Heavy Industries

An automobile engine cylinder block manufacturing case study adopted from Mitsubishi heavy industries [112] is considered. Initially, the company was producing I-4 cylinder block using the production line which consists of 4 or 5-axis CNC machines for rough cutting operations and special purpose machines for finishing operations. The company wanted to replace the I-4 cylinder block with V-6 and V-8 cylinder blocks on the same line. The various product features of the I-4 and V8 cylinder blocks are shown in Figure 4.7.

The description of each product feature is given in Table 4.4 and Figure 4.7. For illustration purposes, several cylinder block variants listed by ElMaraghy et al. [113] will be taken for each model of I-4, V-6 and V-8 and will be used to form the product variant-product feature matrix [*PtF*] as shown in Table 4.4.

Table 4.4: I-4, V-6 and V-8 Cylinder blocks product features description

Product Feature	Machining feature	Tool Direction Approach (TAD)	Product Variants									
			G13B 1298cc	4A-GEU 1587cc	711 M 1691cc	QR20DE 1998cc	Mopar 2360cc	Cosworth 2935cc	Buick215 2900cc	Cyclone 3496cc	LN3 3800cc	LS2 5967cc
1	Planar face	(-cos φ, 0, -sin φ)	0	0	0	0	0	1	1	1	1	1
2	Planar face	(cos φ, 0, -sin φ)	0	0	0	0	0	1	1	1	1	1
3	Planar face	(0,0,-1)	1	1	1	1	1	0	0	0	0	0
4	Planar face	(-cos φ, 0, -sin φ)	0	0	0	0	0	1	1	1	1	1
5	Planar face	(cos φ, 0, -sin φ)	0	0	0	0	0	1	1	1	1	1
6	Planar face	(0,0,-1)	1	1	1	1	1	0	0	0	0	0
7	Planar face	(0, 1, 0)	1	1	1	0	1	0	0	1	1	1
8	Planar face	(0, 1, 0)	1	1	1	1	1	1	1	1	1	1
9	Planar face	(0, -1, 0)	1	1	1	1	1	1	1	1	1	1
10	Planar face	(0, 1, 0)	1	0	0	1	1	1	1	1	1	1
11	Hole	(-cos φ, 0, -sin φ)	0	0	0	0	0	1	1	1	1	1
12	Hole	(cos φ, 0, -sin φ)	0	0	0	0	0	1	1	1	1	1
13	Hole	(0, 0, -1)	1	1	1	1	1	0	0	0	0	0
14	Hole	(-cos φ, 0, -sin φ)	0	0	0	0	0	1	1	1	1	1
15	Hole	(cos φ, 0, -sin φ)	0	0	0	0	0	1	1	1	1	1
16	Hole	(0, 0, -1)	1	1	1	1	1	0	0	0	0	0
17	Hole	(0, 1, 0)	0	0	1	0	0	0	1	0	1	1
18	Hole	(0, 1, 0)	0	0	1	0	0	0	1	0	1	1
19	Hole	(0, 1, 0)	1	1	0	0	0	1	1	1	1	1
20	Hole	(0, 1, 0)	1	1	0	0	0	1	1	1	1	1

The introduction of the V-6 and V-8 cylinder blocks requires replacing the special purpose machines for finishing operations, initially used to process the finishing operations of I-4 cylinder blocks, with 5-axis CNC machines to accommodate the inclined surfaces in the V-6 and V-8. The 5-axis CNC machines will be kept since they can perform rough cutting operations for the features of V-6 and V-8 cylinder blocks.

At this point, it is required to build the machining capability-product feature matrix [*CF*]. In order to relate each product feature to its required machining axis, it is essential to establish the product feature-tool approach direction matrix and [*FTAD*] the machining axis-tool approach direction matrix [*AxTAD*]. With the aid of Table 4.4 and equation (4.1), the product feature-tool approach direction matrix [FTAD] is formulated as shown in Table 4.5.

Table 4.5: Product features-tool direction approach matrix [FTAD]

	Product features																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
x+	0	1	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
x-	1	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
y+	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	1	1	1	1
y-	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
z+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
z-	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	0	0	0	0

The machining axis-tool approach direction matrix [*AxTAD*] is shown in Table 4.6. The machining axes chosen are 3, 4 and 5 axes which normally found in CNC machines as well single axes in *x*, *y* and *z* directions which are available in special purpose machines.

Table 4.6: machining axis-tool approach direction matrix [AxTAD]

	x+	x-	y+	y-	z+	z-
3-axis	0	0	0	0	0	1
4-axis	1	1	0	0	0	1
5-axis	1	1	1	1	0	1
x-axis	1	1	0	0	0	0
y-axis	0	0	1	1	0	0
z-axis	0	0	0	0	0	1

The product feature-required machining axis matrix [*FAx*] can be calculated as shown in Table 4.8. The second matrix to be developed is the product feature-surface finish matrix [*FSu*]. First, the product feature-process matrix [*FPr*] is expressed as shown in the upper part of Table 4.7. Then the centerline average parameter (Ra) for each product feature requiring finish cutting is listed as shown in the mid part of Table 4.7 and compared with the minimum and maximum centerline average parameter value (Ra). Minimum and maximum centerline average parameter (Ra) for milling, drilling, boring, reaming and honing are (32µin,250µin), (63µin,125µin), (16µin,250µin), (32µin,125µin) and (4µin, 32µin), respectively [109]. It is worth noting that the centerline average parameter (Ra) is only provided for the product features requiring finishing operations and accordingly, product features with roughing operations only will have "x" as shown in the lower part of Table 4.7. From equation (4.6), the product feature surface finish-process matrix [*FSu*] is calculated as shown in Table 4.8.

The rest of the terms in the machining capabilities-product feature matrix are listed in Table 4.8. However, it is worth pointing out that in the geometric tolerance, some values are equal to 1mm which is a relatively high value for dimensional and geometric tolerance.

Table 4.7: Product feature-process matrix [FPr]

Process	Product features																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Milling	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Drilling	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
Boring	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
Reaming	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	1
Honing	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	1
Ra(μin) [114]	x	x	x	60	60	60	60	x	x	60	x	x	x	15	15	15	x	15	x	15
Milling	x	x	x	1	1	1	1	x	x	1	x	x	x	0	0	0	x	0	x	0
Drilling	x	x	x	0	0	0	0	x	x	1	x	x	x	0	0	0	x	0	x	0
Boring	x	x	x	1	1	1	1	x	x	1	x	x	x	0	0	0	x	0	x	0
Reaming	x	x	x	1	1	1	1	x	x	1	x	x	x	0	0	0	x	0	x	0
Honing	x	x	x	0	0	0	0	x	x	0	x	x	x	1	1	1	x	1	x	1

Physically, the value of 1mm in the geometrical tolerance portion of Table 4.8 indicates that the type of the geometric tolerance does not apply to a certain product feature. For example, consider product feature 1 which is planar face has a flatness geometrical tolerance value 0.12mm since flatness geometrical tolerance applies on planar surfaces and faces. However, for hole features (11 to 20), the flatness tolerance value is 1mm since flatness geometric tolerance is not applicable for hole features. Mathematically, the value of 1mm is chosen for geometric tolerance types that do not apply to a certain product feature and can be illustrated with the aid of equation (4.11). For equation (4.11) to be equal to 1 (i.e. machine type "*j*" can process product feature "*f*"), all the terms need to be equal to 1. Therefore, it is essential to ensure that a high tolerance value (e.g. 1mm) is chosen for non-applicable geometrical tolerances on certain product features in order to produce a value of 1 within the appropriate terms in equation (4.11) when compared with machine's accuracy. This facilitates the mathematical manipulation of the matrices.

The machine-available machining capabilities matrix is listed in Table 4.9. The values of the machine-available machining capabilities are taken from machine tool manufacturers catalogues (http://www.Huron.fr & http://www.maxprecimachines.com).

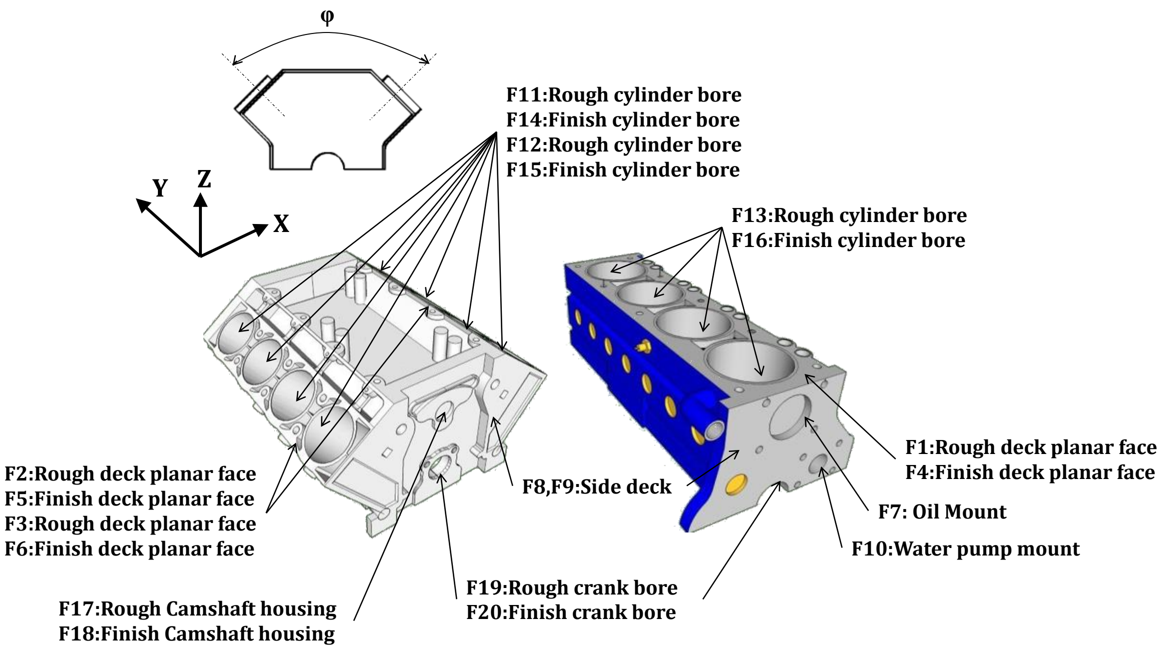


Figure 4.7 Engine cylinder blocks features

Table 4.8 Required machining capability-product feature matrix

Product feature	Length of feature L_f (mm)	Axis						Processes					Workpiece envelop (mm^3)	Cutting power (KW)	Geometric tolerance mm			Feature dimensional tolerance (mm) [89]
		3	4	5	x	y	z	Milling	Drilling	Boring	Reaming	Honing			Flatness	Perpendicular	Position	
1	500	0	1	1	0	0	0	1	0	0	0	0	3.80E+08	5	0.12	1	1	0.05
2	500	1	1	1	0	0	1	1	0	0	0	0	3.80E+08	5	0.12	1	1	0.05
3	500	0	1	1	0	0	0	1	0	0	0	0	3.80E+08	1	0.12	1	1	0.05
4	500	0	1	1	0	0	0	1	0	0	0	0	3.80E+08	1	0.12	1	1	0.05
5	500	1	1	1	0	0	1	1	0	0	0	0	3.80E+08	1	0.12	1	1	0.05
6	500	0	0	1	0	1	0	1	0	0	0	0	3.80E+08	1	0.12	1	1	0.05
7	150	0	0	1	0	1	0	1	0	0	0	0	3.80E+08	1	0.12	1	1	0.05
8	300	0	0	1	0	1	0	1	0	0	0	0	3.80E+08	1	1	0.12	1	0.05
9	300	0	0	1	0	1	0	1	0	0	0	0	3.80E+08	1	1	0.12	1	0.05
10	150	0	1	1	0	0	0	1	0	0	0	0	3.80E+08	5	0.12	1	1	0.05
11	92	0	1	1	0	0	0	0	1	1	0	0	3.80E+08	5	1	1	0.008	0.05
12	92	1	1	1	0	0	1	0	1	1	0	0	3.80E+08	5	1	1	0.008	0.05
13	92	0	1	1	0	0	0	0	1	1	0	0	3.80E+08	1	1	1	0.008	0.05
14	92	0	1	1	0	0	0	0	0	0	0	1	3.80E+08	1	1	1	0.008	0.025
15	92	1	1	1	0	0	1	0	0	0	0	1	3.80E+08	1	1	1	0.008	0.025
16	92	0	0	1	0	1	0	0	0	0	0	1	3.80E+08	1	1	1	0.008	0.025
17	500	0	0	1	0	1	0	0	1	1	0	0	3.80E+08	1	1	1	0.008	0.05
18	500	0	0	1	0	1	0	0	0	0	0	1	3.80E+08	1	1	1	0.008	0.05
19	500	0	0	1	0	1	0	0	1	1	0	0	3.80E+08	1	1	1	0.008	0.05
20	500	0	0	1	0	1	0	0	0	0	0	1	3.80E+08	1	1	1	0.008	0.025

Table 4.9: machine-available machining capability matrix (http://www.Huron.fr & http://www.maxprecimachines.com)

Machine Name	Machine Description	Axis						Processes					Envelop			Power KW	Accuracy	
		3	4	5	x	y	z	Milling	Drilling	Boring	Reaming	Honing	Length mm	Width mm	Height mm		Linear mm	Rotating sec
KX50M	5-axis CNC	0	0	1	0	0	0	1	1	1	1	0	2200	1250	955	75	0.007	10
KX50L	5-axis CNC	0	0	1	0	0	0	1	1	1	1	0	3300	1250	955	75	0.007	10
KX100	5-axis CNC	0	0	1	0	0	0	1	1	1	1	0	2500	1250	900	30	0.007	10
KX200	5-axis CNC	0	0	1	0	0	0	1	1	1	1	0	3500	1250	900	30	0.007	10
KXG45-14	5-axis CNC	0	0	1	0	0	0	1	1	1	1	0	4700	1390	985	75	0.025	10
KXG 45-23	5-axis CNC	0	0	1	0	0	0	1	1	1	1	0	4700	2480	985	75	0.025	10
KX 10i	3-axis CNC	1	0	0	0	0	0	1	1	1	1	0	1250	700	450	26.4	0.015	x
K2X10	3-axis CNC	1	0	0	0	0	0	1	1	1	1	0	1150	800	500	35	0.004	x
K2X 20	3-axis CNC	1	0	0	0	0	0	1	1	1	1	0	1400	1000	650	35	0.005	x
KX 10	3-axis CNC	1	0	0	0	0	0	1	1	1	1	0	1250	700	600	35	0.007	x
KX 30	3-axis CNC	1	0	0	0	0	0	1	1	1	1	0	2000	1000	680	35	0.009	x
LBM 1500	Horizontal honing	0	0	0	0	1	0	0	0	0	0	1	1500	750	750	2	0.005	x
VCB 1500V	Vertical honing	0	1	0	0	0	0	0	0	0	0	1	1500	450	900	2	0.005	x

4.4 Results and discussion

The case study is solved using Matlab (www.mathworks.com) on processor Intel® Xeon® CPU 2.67 GHz and RAM12GB.The machine-product feature mapping matrix [MF] was calculated as shown in Table 4.10 using the machining capability-product feature matrix [CF] in Table 4.8 and the machine-available machining capability [MC] in Table 4.9 together with equation (4.11).

Two scenarios in this case study will be solved with three different input product platform feature vectors:

1. Case no. 1: Common features within I-4, V-6 and V-8 cylinder blocks (Co-platforming-I).
2. Case no. 2: Majority of features within I-4, V-6 and V-8 cylinder blocks (Co-platforming-II).

4.4.1 Case Study no. 1: Co-platforming-I

From the product variant-product feature matrix [*PtF*] in Table 4.4, the product platform feature vector *PlF* is determined according to equation (4.14). For example, product features 8 and 9 (planar face side wall) are available in all product variants (I-4, V-6 and V-8) as indicated in the product variant-product feature matrix [*PtF*] in Table 4.4, and for this reason, product features 8 and 9 (planar face side wall) have a value of 1 in the product platform feature vector *PlF*. Product feature 10 (planar face water pump mount) is not available in all variants as seen in product variant-product feature matrix. Therefore, product feature 10 (planar face water pump mount) has a value of 0 in the product platform feature vector. Accordingly, the product platform feature vector can be written as:

$$\overrightarrow{PlF} = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0] \qquad (4.18)$$

The platform machine vector is calculated from equation (4.16) using the machine-product feature matrix in Table 4.10 and product platform feature vector in equation (4.14) as:

$$\overrightarrow{MSP} = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0] \qquad (4.19)$$

The synthesized manufacturing system in this case study scenario is shown in Figure 4.8a. According to vector (4.19) and Figure 4.8a, the platform machines are the 5-axis CNC machines

KX50M, KX50L, KX100, KX200, KXG45-14, KXG45-23 or KXG60-23. These machines are used to process the product platform features 8 and 9 (planar face side wall).

Such machining capabilities include a 5 machining axis which permits the 5-axis CNC machines KX50M, KX50L, KX100, KX200, KXG45-14, KXG45-23 or KXG60-23 to process product features 8 and 9 (planar face side wall) located on a vertical plane. In addition, the machining accuracy (0.007mm linear and 10 seconds rotational) of these machines permits them to process product features 8 and 9 (planar face side wall) according to their required dimensional and geometrical tolerances listed in Table 4.8.

In Table 4.10, it is evident that there are platform machine candidates that process non-platform product feature. The platform machines candidates 5-axis CNC machines KX50M, KX50L, KX100, KX200, KXG45-14 or KXG45-23 can process non-platform product features 1 (rough deck planar face), 2 (rough deck planar face), 3 (rough deck planar face), 4 (finish deck planar face), 5 (rough deck planar face) and 6 (rough deck planar face). The platform machines candidates 5-axis CNC machines KX50M, KX50L, KX100, KX200, KXG45-14, KXG45-23 or KXG60-23 can process non-platform product features 7 (planar face oil pump mount) and 10 (planar face water pump mount). The platform machines candidates 5-axis CNC machines KX50M, KX50L, KX100 or KX200 can process product features 11 (rough cylinder bore), 12 (rough cylinder bore), 13 (rough cylinder bore), 17 (rough camshaft housing) and 19 (rough crank bore).

Non-platform machines, according to Figure 4.8a and vector (4.19), is the vertical honing machine VCB1500V which processes hole features 14 (finish cylinder bore), 15 (finish cylinder bore), 16 (finish cylinder bore) and horizontal honing machine LBM1500 which processes the hole features 18 (finish camshaft bore) and 20 (finish crank bore).These machines are capable of producing high quality surface finish which is required by these product features.

According to the machine-product feature matrix [*MF*] in Table 4.10, non-platform product features 14 (finish cylinder bore), 15 (finish cylinder bore), 16 (finish cylinder bore) and 18 (finish camshaft bore) can also be processed by platform machines KX50L or KX200 (instead of non-platform machine LBM1500 and VCB1500V) and the non-platform machine in this case is the horizontal honing machine LBM1500 which process the hole features 20 (finish crank bore). The alternate synthesized manufacturing system in this case is shown in Figure 4.8b.

The candidate ranking coefficient for the platform machines candidates are equal to 1 (CR=2/2=1) which indicates that the platform machines KX50M, KX50L, KX100, KX200, KXG45-14, KXG45-23 and KXG60-23 can process all the available product platform features.

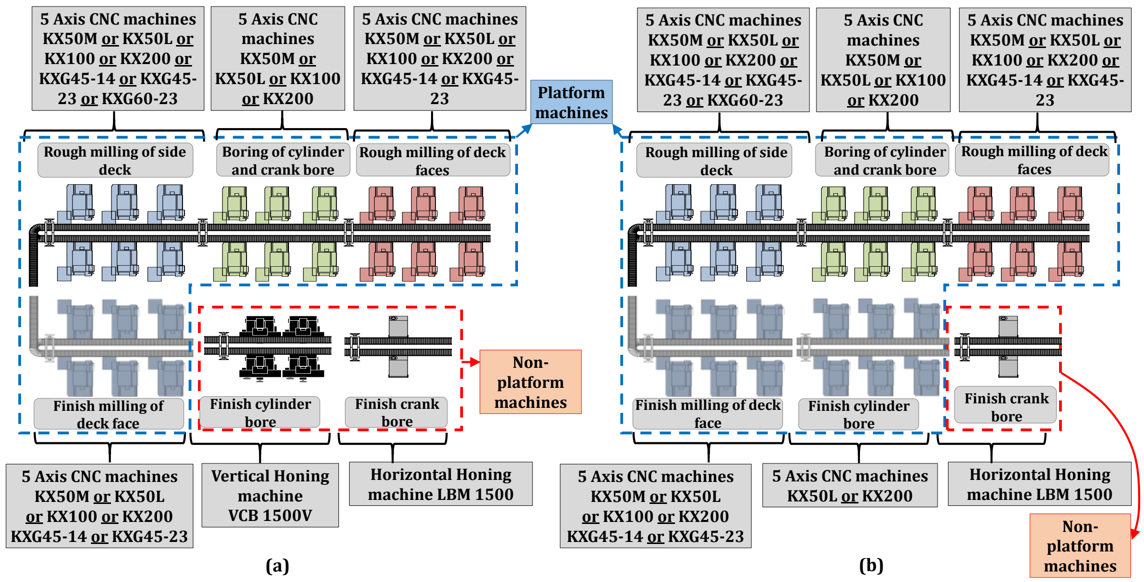


Figure 4.8 Synthesized manufacturing system according to case 1 (a) configuration 1 (b) configuration 2

Table 4.10: Machine-product feature matrix

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20
KX50M	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	1	0
KX50L	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
KX100	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	1	0
KX200	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
KXG45-14	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
KXG 45-23	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
KXG 60-23	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
KX 10i	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K2X10	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
K2X 20	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
KX 10	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
KX 30	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LBM 1500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
VCB 1500V	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0

4.4.2 Case Study no. 2: Co-platforming-II

From the product variant-product feature matrix [*PtF*], the product platform feature vector *PlF* is determined according to equation (4.15). For example, product feature 19 (rough crank bore) is available in *7* product variants out of the total 10 product variants available and hence, product feature 19 (rough crank bore) is taken as product platform feature. Similarly, the rest of the product platform feature vector *PlF* elements are calculated as:

$$\overrightarrow{PlF} = [0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 1] \quad (4.20)$$

The platform machine vector is calculated using the machine-product feature matrix in Table 4.10 and product platform feature vector *PlF* in equation (4.20) by using equation (4.16) as:

$$\overrightarrow{MSP} = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 1\ 0] \quad (4.21)$$

The synthesized manufacturing system for this case study is shown in Figure 4.9a. From vector (4.21) and the machine-product feature matrix [*MF*] in Table 4.10, the platform machines candidates are 5-axis CNC machines are KX50M, KX50L, KX100, KX200, KXG45-14, KXG45-23, KXG60-23 and horizontal honing machine LBM1500. These 5-axis CNC machines are used to process the product platform features 7 (planar face oil pump mount), 8 (planar face sidewall), 9 (planar face side wall) and 10 (planar face water pump mount). The platform machines candidates either KX50M, KX50L, KX100 or KX200 are used to process platform product feature 19 (rough crank bore). The reason for choosing the 5-axis CNC machines KX50M, KX50L, KX100, KX200, KXG45-14, KXG45-23 or KXG60-23 are due to their 5 machining axis available within each machine which makes these machines which are capable of processing features 7 (planar face oil pump mount), 8 (planar face sidewall), 9 (planar face side wall), 10 (planar face water pump mount) and 19 (rough crank bore) (excluding machines KXG45-14, KXG45-23 or KXG60-23 from processing product feature 19) which are located on inclined planes. In addition, the 5-axis CNC machines KX50M, KX50L, KX100,KX200, KXG45-14, KXG45-23 or KXG60-23 possess machining accuracies (0.007mm linear and 10 seconds rotational) which makes these machines capable of producing product features 7 (planar face oil pump mount), 8 (planar face sidewall), 9 (planar face sidewall), 10 (planar face water pump mount) and 19 (rough crank bore) (excluding machines KXG45-14, KXG45-23 or KXG60-23 from processing product feature 19) within the acceptable dimensional and geometric tolerance as listed in Table 4.8. Finally, available power and work envelop of the 5-axis CNC machines KX50M, KX50L, KX100, KX200 , KXG45-14, KXG45-23 or KXG60-23 exceed the required cutting power and volume of the three cylinder blocks where platform product features 7 (planar face oil pump mount), 8 (planar face sidewall), 9 (planar face side wall), 10 (planar face water pump mount) and 19 (rough crank bore) (excluding machines KXG45-14, KXG45-23 or KXG60-23 from processing product feature 19) are located as listed in Table 4.8 and Table 4.9. Product platform feature 20 (finish crank bore) is processed by the platform machine LBM1500. An important specification of feature 20 (finish crank bore) is the high surface finish (centerline average parameter (Ra) of 15μin as shown in Table 4.7, which can be achieved by a honing process which is accomplished by horizontal honing machine LBM1500. The honing process can produce a minimum centerline average parameter value (Ra) of 4μin and maximum centerline average parameter value (Ra) of 32μin.

In Table 4.10, it is evident that the 5-axis CNC platform machines can process several non-platform product features. The 5-axis CNC machines either KX50M, KX50L, KX100, KX200, KXG45-14 or KXG45-23 (platform machines candidates) can process non-platform product features 1 (rough deck planar face), 2 (rough deck planar face), 3 (rough deck planar face), 4 (finish deck planar face), 5 (finish deck planar face), 6 (finish deck planar face). The 5-axis CNC machines either KX50M, KX50L, KX100 or KX200 (platform machines candidates) can process non-platform product features 11 (rough cylinder bore), 12 (rough cylinder bore), 13 (rough cylinder bore) and 17 (rough camshaft bore) as shown in Table 4.10. Non-platform product feature 18 (finish camshaft bore) can be processed by platform machine LBM1500.

The non-platform machine, according to Figure 4.9a and vector (4.21), is the vertical honing machine VCB1500V which is used to process non-platform product features 14 (finish cylinder bore), 15 (finish cylinder bore) and 16 (finish cylinder bore) which are finish cylinder bore hole for the different types of the cylinder blocks I-4, V-6 and V-8. The reason the co-platforming model chose the vertical honing machine VCB1500V as a non-platform machine is because it can process features 14 (finish cylinder bore), 15 (finish cylinder bore) and 16 (finish cylinder bore) which are non-platform product features.

According to the machine-product feature matrix [*MF*] in Table 4.10, non-platform product features 14 (finish cylinder bore), 15 (finish cylinder bore) and 16 (finish cylinder bore) can also be processed by platform machines KX50L or KX200 (instead of non-platform machine VCB1500V). Non-platform product feature 18 (finish camshaft bore) can be processed with platform machines KX50L or KX200 instead of platform machine LBM1500. The alternate synthesized manufacturing system in this case is shown in Figure 4.9b where there are no non-platform machines. Candidate machines are those that can produce a certain feature. For example, if a feature requires several operations to be completed, a 5-axis CNC machine can process all of them, but when using CNC machine tools with less axes of motion, several operations may require using more than one type of machine (i.e. 3-axis machine, special purpose machine, etc.).

The candidate ranking coefficient for each platform machine is calculated according to equation (4.17) as 0.833, 0.833, 0.833, 0.833, 0.67, 0.67, 0.67 and 0.17 for platform machines KX50M, KX50L, KX100, KX200, KXG45-14, KXG45-23, KXG60-23 and LBM1500, respectively. The 5-axis machines KX50M, KX50L, KX100, KX200 have the same value of candidate ranking coefficient of 0.833 since these machines can process 5 product platform features out of the total 6 product platform features as shown in Table 4.10. Relatively high values of candidate ranking coefficients for the 5-axis machines KX50M, KX50L, KX100, KX200 are because they are highly capable (can process 5 product platform features out of the total 6 product platform features). The candidate ranking coefficient of the horizontal honing machine LBM1500 is 0.17 since it can process only one product platform feature out of the total 6 product platform features due to its limited machining capabilities (single reciprocating axis in y-direction and one honing tool).

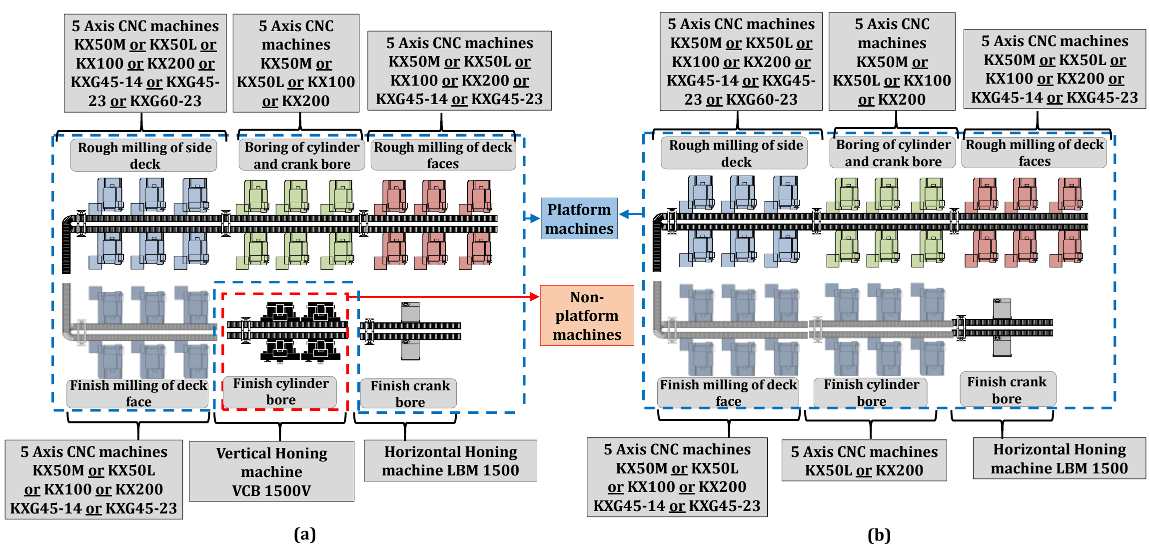


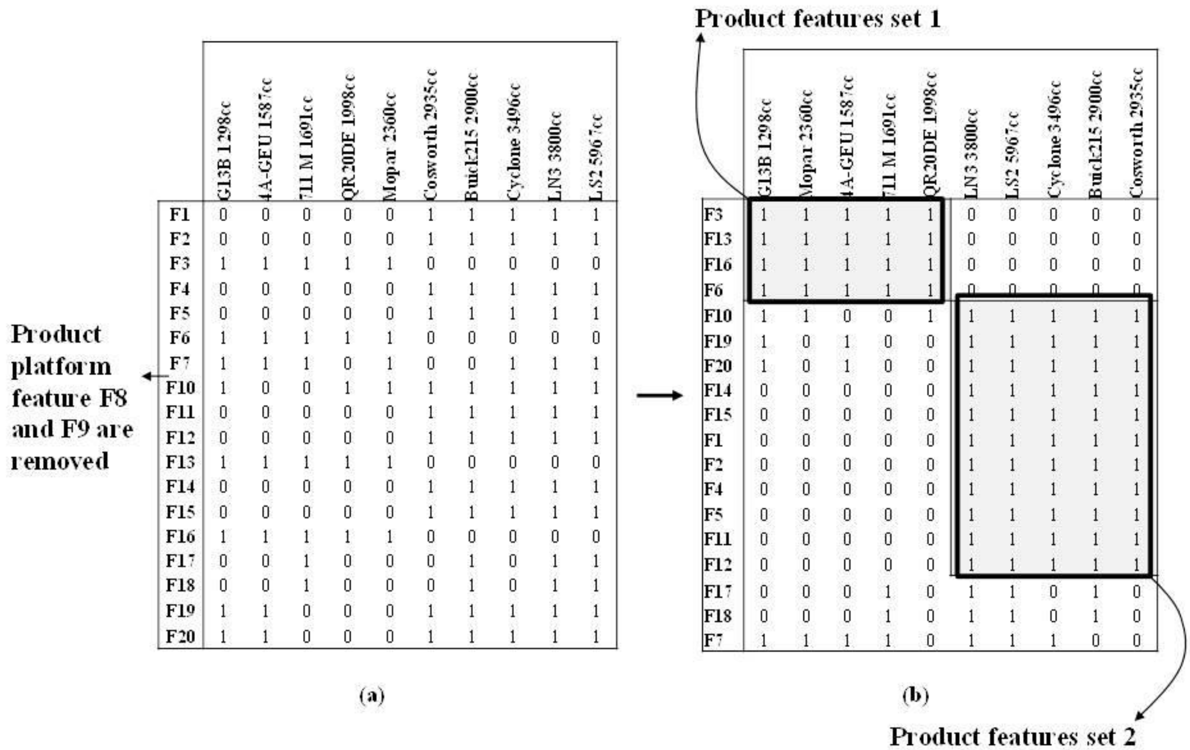
Figure 4.9 Synthesized manufacturing system according to case 2 (a) configuration 1 (b) configuration 2

4.5 Sub-platform

The co-platforming method illustrated in this chapter can handle the problem of sub-platform machines. Sub-platform product family design is defined as a set of design variables, components, modules, product features that are shared only among product variants within a product family [53]. Similar to the definition of sub-platform for product family design, the definition of sub-platform machines can be defined as a set of machines that process a group of product features that are shared only among some (not all) product variants within a product family. The procedure to determine the sub-platform machines is stated as follows:

- *Step 1: Start the procedure by finding the product platform features and platform machines and omit the columns and rows corresponding to the product platform features and platform machines from the machine-product features matrix*
- *Step 2: Omit the rows corresponding to the product platform features from the product variant-product feature matrix.*
- *Step 3: Apply Rank Order Clustering to the matrix in step 2*
- *Step 4: From the clustered matrix in step 3, find the sets of product features that are shared across a set of product variants*
- *Step 5: Find the sets of machines corresponding to each set of product features (specified in step 4) using the matrix in step 1*

Step 1 is already implemented in subsection 4.4.1 and therefore, it will not be discussed again. Steps 2, 3 and 4 involve identifying the sub-platform product features. This is achieved by the product variant-product feature matrix [*PtF*] after removing the product platform feature and then applying the rank order clustering. Steps 2, 3 and 4 are applied on the case study from section 4.3 as shown in Figure 4.10.



(a)

	G13B 1298cc	4A-GEU 1587cc	711 M 1691cc	QR20DE 1998cc	Mopar 2360cc	Cosworth 2935cc	Buick215 2900cc	Cyclone 3496cc	LN3 3800cc	LS2 5967cc
F1	0	0	0	0	0	1	1	1	1	1
F2	0	0	0	0	0	1	1	1	1	1
F3	1	1	1	1	1	0	0	0	0	0
F4	0	0	0	0	0	1	1	1	1	1
F5	0	0	0	0	0	1	1	1	1	1
F6	1	1	1	1	1	0	0	0	0	0
F7	1	1	1	0	1	0	0	1	1	1
F10	1	0	0	1	1	1	1	1	1	1
F11	0	0	0	0	0	1	1	1	1	1
F12	0	0	0	0	0	1	1	1	1	1
F13	1	1	1	1	1	0	0	0	0	0
F14	0	0	0	0	0	1	1	1	1	1
F15	0	0	0	0	0	1	1	1	1	1
F16	1	1	1	1	1	0	0	0	0	0
F17	0	0	1	0	0	0	1	0	1	1
F18	0	0	1	0	0	0	1	0	1	1
F19	1	1	0	0	0	1	1	1	1	1
F20	1	1	0	0	0	1	1	1	1	1

(b)

	G13B 1298cc	Mopar 2360cc	4A-GEU 1587cc	711 M 1691cc	QR20DE 1998cc	LN3 3800cc	LS2 5967cc	Cyclone 3496cc	Buick215 2900cc	Cosworth 2935cc
F3	1	1	1	1	1	0	0	0	0	0
F13	1	1	1	1	1	0	0	0	0	0
F16	1	1	1	1	1	0	0	0	0	0
F6	1	1	1	1	1	0	0	0	0	0
F10	1	1	0	0	1	1	1	1	1	1
F19	1	0	1	0	0	1	1	1	1	1
F20	1	0	1	0	0	1	1	1	1	1
F14	0	0	0	0	0	1	1	1	1	1
F15	0	0	0	0	0	1	1	1	1	1
F1	0	0	0	0	0	1	1	1	1	1
F2	0	0	0	0	0	1	1	1	1	1
F4	0	0	0	0	0	1	1	1	1	1
F5	0	0	0	0	0	1	1	1	1	1
F11	0	0	0	0	0	1	1	1	1	1
F12	0	0	0	0	0	1	1	1	1	1
F17	0	0	0	1	0	1	1	0	1	0
F18	0	0	0	1	0	1	1	0	1	0
F7	1	1	1	1	0	1	1	1	0	0

Figure 4.10 Illustration of (a) step 1, (b) steps 2, 3 and 4 in the sub-platform procedure

According to the machine-product feature matrix [MF] in Table 4.10, the first set of product features 3 (rough deck planar face), 6 (finish deck planar face), 13(rough cylinder bore) and 16 (finish cylinder bore) can be processed by the candidate machines KX10i, K2X10, K2X20, KX10, KX30 and VCB1500V as shown in Figure 4.11a. These machines are called the sub-platform machine candidates set 1 as shown in Figure 4.12. The second set of product features (according to Figure 4.10b) 1 (rough deck planar face), 2 (rough deck planar face), 14 (finish cylinder bore), 15 (finish cylinder bore) and 20 (finish crank bore) can be processed by the candidate machines LBM1500 and VCB1500V as shown in Figure 4.11b. It is worth noting that there exist several product features in Figure 4.11b that do not correspond to any machines such as product features 4 (finish deck planar face), 5 (finish deck planar face), 10 (planar face water pump mount), 11(rough cylinder bore), 12 (rough cylinder bore) and 19 (rough crank bore). These product features are processed only by the platform machines as shown in the machine-product feature matrix in Table 4.10. The final results for the multi-platform machine problem is shown in Figure 4.12.

Product features set 1

Sub-platform machine candidates 1

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20
KX 10i	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K2X10	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
K2X 20	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
KX 10	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
KX 30	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LBM 1500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
VCB 1500V	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0

(a)

Product features set 2

Sub-platform machine candidates 2

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20
KX 10i	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K2X10	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
K2X 20	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
KX 10	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
KX 30	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LBM 1500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
VCB 1500V	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0

(b)

Figure 4.11 Determination of (a) sub-platform machine candidate 1 and (b) sub-platform machine candidate 2

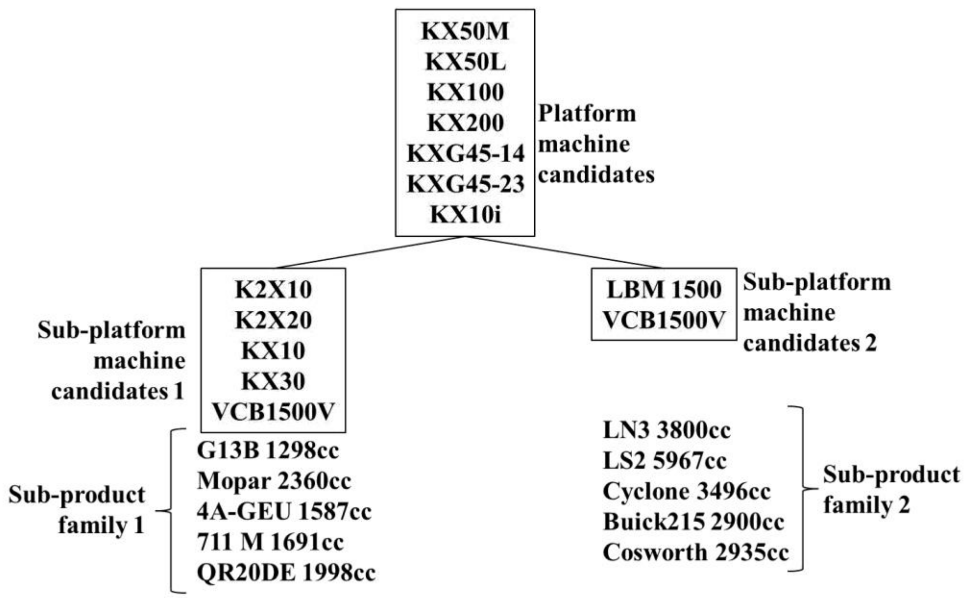


Figure 4.12 Platform and sub-platform machines candidate for the case study

4.6 Conclusion

This chapter proposes a matrix based formulation for the functional synthesis of generic machine candidates based on the co-platforming concept. The method considers product features characteristics such as the required cutting power, workpiece size, dimensional and geometrical tolerances and the surface finish as well as manufacturing systems capabilities including available power, size of work envelop and machining accuracy.

The proposed method uses input vector, mapping matrix and output vector. The input vector describes the product platform. Product features which are mapped to different machine tools if: 1) the machine tool possess the motion axis type required to process a product feature and orientation, 2) the machine tool's accuracy is smaller than the specified product features dimensional and geometric tolerances , 3) workpiece volume within which the product feature lies is within the limits of the machine tool work envelop, and 4) the required cutting power for product features is less than the available power of a machine tool. The output vector describes the platform and non-platform machines.

The proposed matrix based formulation is applied on two scenarios of a case study adopted from an automotive engine cylinder block manufacturer. The proposed method synthesized two manufacturing systems based on: i) the platform made of the common product features among all product variants, and ii) the platform made of product features existing in the majority of product variants.

The developed manufacturing system synthesis method using co-platforming is easy to use. The two case instances are solved using Matlab on process Intel® Xeon® CPU 2.67GHz and RAM 12.0 GB. The elapsed CPU time for case instances 1 and 2 is approximately 0.034 seconds. On the same computer configuration, the elapsed CPU time for 500 types of features, 500 machines, 500 different axis and 500 variants is 317.8 seconds. The elapsed CPU time for 1000 types of features, 1000 machines, 1000 different axis and 1000 variants is 2493.4 seconds.

A procedure has been proposed on the co-platforming method to accommodate sub-platform machines. Accordingly, machines on different levels of commonality are calculated. In the upper level, platform machines that are used to process product platform features are calculated. In addition, on the lower level, sub-platform machines are calculated in which a group of machines required to process sub-platform product features

The proposed method is beneficial in synthesizing manufacturing system with low investment costs which is achieved by maintaining a group of platform machines that do not change with the change in product variants. Therefore, a stable manufacturing system is synthesized which requires less re-tooling, upgrades and purchases of manufacturing system components which supports economic sustainability of the manufacturing system. In addition, the synthesized manufacturing system supports product customization, evolution and changes cost effectively. Frequent changes in product design (in the non-platform product components and features) can be accomplished by easily adding or removing non- platform system components with minor layout changes while the platform system components remain intact.

CHAPTER 5. FUNCTIONAL SYNTHESIS OF MACHINE TYPES AND NUMBER OF EACH MACHINE TYPE

5.1 Overview

After obtaining the candidate platform and non-platform machines candidates in chapter 4, the aim of this chapter is to select the specific types of platform and non-platform machines as well as the number of each machine type that will be used in the production operation, from the candidates identified earlier. A mathematical programming model is proposed to synthesize the functional level of the manufacturing system (types of machines and number of each machine type). Figure 5.1 shows the IDEF0 for the mathematical model proposed in this chapter. The main expected output from the model is the selected types of platform and non-platform machines from the machine candidates obtained earlier as shown in Figure 1.3 as well as the number of each selected machine. Additional auxiliary outputs from this model are the product platform and non-platform features and components. However, these outputs are already obtained in the model in chapter 4 and hence, they will not appear in the IDEF0 model below.

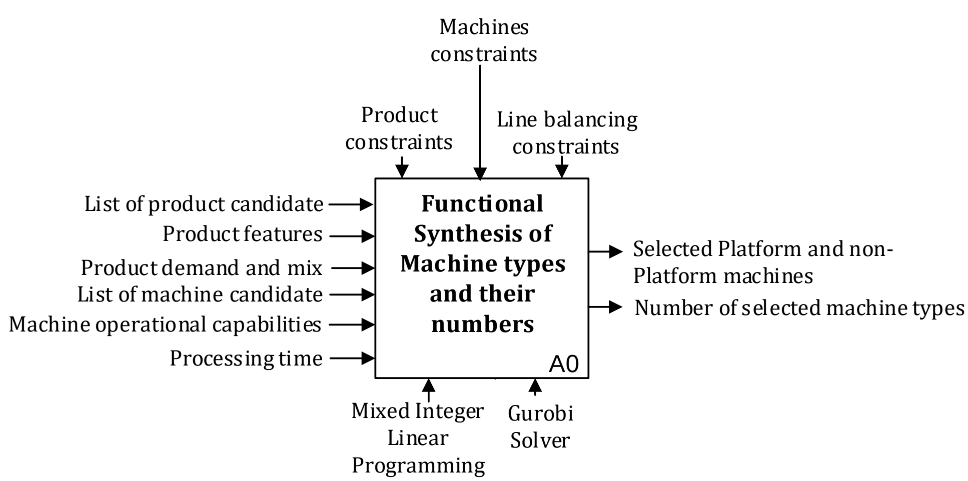


Figure 5.1 IDEF0 of the mathematical model for functional synthesis of machine types

This chapter is organized as follows: the second section is concerned with the mixed integer linear programming mathematical model development. The third section introduces some techniques to obtain the equivalent linear formulation of the mathematical model. The fourth section is concerned with applying the mathematical model on practical case study from automotive cylinder blocks machining. The fifth section provides the results and the discussion of the obtained results. The sixth section discusses the limitation of the mathematical programming model and finally, the seventh section provides the conclusion.

5.2 Mixed Integer Linear Model Development

Mathematical programming such linear programming and mixed integer linear programming are characterized by their ability to obtain global optimum solutions unlike meta-heuristics method that produce sub-optimal solution (meta-heuristics does not guarantee optimal solution in reasonable time). The main drawback of the mathematical programming models is their high computational time if the size of the problem increases. In this dissertation, the problem is solved using mixed integer linear programming as optimum solution is found at reasonable time. The various subsections below define the detailed model formulation, various input parameters, decision variables, constants and indices, objective function and finally the constraints. It will be evident that the mathematical model is initially formulated as a mixed integer nonlinear programming model. However, linearization techniques will be carried out in order to obtain the equivalent linear form of the mathematical model. For this reason, the model is referred to as a linear mathematical programming model.

5.2.1 Input parameters

The list of input parameters is given as:

$$z_{i,t} = \begin{cases} 1, if\ product\ variant\ i\ is\ available\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.1}$$

$$\rho_{i,f} = \begin{cases} 1, if\ product\ feature\ f\ is\ available\ in\ product\ variant\ i \\ 0, otherwise \end{cases} \tag{5.2}$$

$$\gamma_{f,o} = \begin{cases} 1, if\ operation\ o\ is\ required\ by\ product\ feature\ f \\ 0, otherwise \end{cases} \tag{5.3}$$

$$McOp_{j,o} = \begin{cases} 1, if\ machine\ j\ processes\ operation\ o \\ 0, otherwise \end{cases} \tag{5.4}$$

$$purcost_j: Purchase\ cost\ of\ machine\ type\ j \tag{5.5}$$

$$sellcost_j: Salvage\ cost\ of\ machine\ type\ j \tag{5.6}$$

$$ptime_{o,j}: processing\ time\ of\ operation\ o\ on\ machine\ j \tag{5.7}$$

$$demand_{i,t}: demand\ of\ product\ variant\ i\ in\ production\ period\ t \tag{5.8}$$

5.2.2 Decision Variables

The list of decision variables is given as:

$$x_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ a\ platform\ machine\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.9}$$

$$y_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ non-platform\ machine\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.10}$$

$$a_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ added\ as\ non-platform\ machine \\ \quad in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.11}$$

$$r_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ removed\ from\ non-platform\ \ machines \\ \quad in\ prodction\ period\ t \\ 0, otherwise \end{cases} \tag{5.12}$$

$$x_{f,t}^{p} = \begin{cases} 1, if\ product\ feature\ f\ is\ product\ platform\ feature \\ \quad in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.13}$$

$$y_{f.t}^{p} = \begin{cases} 1, if\ product\ feature\ f\ is\ non-platform\ product\ feature \\ \quad in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.14}$$

$$\varphi_{i,j,o,f,t} = \begin{cases} 1, if\ operation\ o\ required\ for\ product\ feature\ f\ in\ product \\ \quad variant\ i\ in\ production\ period\ t\ is\ assigned\ to\ machine\ j \\ 0, otherwise \end{cases} \tag{5.15}$$

$$\psi_{o,f,t} = \begin{cases} 1, if\ product\ feature\ f\ is\ available\ within\ all\ products \\ \quad and\ requires\ \ operation\ o\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.16}$$

$$\varepsilon_{f,t} = \begin{cases} 1, if\ product\ feature\ f\ is\ available\ in\ all\ product\ produced \\ \quad in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.17}$$

$$\delta_{f,t} = \begin{cases} 1, if\ product\ feature\ f\ is\ available\ in\ at\ least\ one\ product \\ \quad in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{5.18}$$

$$\sigma_{o,f} = \begin{cases} 1, if\ operation\ o\ for\ product\ feature\ f\ is\ available\ in \\ \quad all\ production\ periods \\ 0, otherwise \end{cases} \tag{5.19}$$

$Nst_{j,t}$: $Number\ of\ machine\ type\ j\ in\ production\ period\ t$ (5.20)

It is worth noting that the decision variables "$a_{j,t}^{m}$" and "$r_{j,t}^{m}$" are only applied on non-platform machines. The reason for that is attributed to characteristic number 2 for platform machines discussed in section 2.6 in which platform machines should be available in all production periods. However, the number of platform machines can vary depending on the demand for each product variant in each production period.

5.2.3 Constants and indices

The model contains a number of sets and constants:

F[1,..,s,..],[1,..,ŝ,..],[1,..,q,..],[1,..,f,..]=set of product features

J[1,..,a,..],[1,..,b,..],[1,..,b̂,..],[1,..,j,..]=set of machines

O[1,..,o,..]=set of operations

T[1,..,t,..]=set of production periods

I[1,..,i,..]=set of product variants

M is constant large value ($M=10000$) and ϵ is constant small value larger than 0 and less than 1 ($\epsilon=0.1$). These constants are used to relate a binary variable to a continuous variable or expression. The constant "T_0" is the initial production period ($T_0=1$).

5.2.4 Objective function

The objective function is formulated as:

Minimize:

$$\begin{aligned}
&\sum_{j=1}^{J} purcost_j Nst_{j,t=T_0} x_{j,t=T_0}^{m} + \sum_{j=1}^{J} purcost_j Nst_{j,t=T_0} y_{j,t=T_0}^{m} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J} \max(0, Nst_{j,t+1} - Nst_{j,t}) purcost_j x_{j,t+1}^{m} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J} min(0, Nst_{j,t+1} - Nst_{j,t}) sellcost_j x_{j,t}^{m} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J} \max(0, Nst_{j,t+1} - Nst_{j,t}) purcost_j y_{j,t+1}^{m} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J} min(0, Nst_{j,t+1} - Nst_{j,t}) sellcost_j y_{j,t}^{m} \\
&+\sum_{t=1}^{T} \frac{A_{0,t}^{m} B^{m}}{I_0^{m} \alpha_t^{m}} \begin{pmatrix} \sum_{b=1}^{J}\sum_{\hat{b}=1}^{J} d^{f_{b,\hat{b}}-1}\, y_{\hat{b},t}^{m} r_{b,t}^{m} + \sum_{b=1}^{J}\sum_{\hat{b}=1}^{J} d^{f_{b,\hat{b}}-1}\, y_{\hat{b},t}^{m} a_{b,t}^{m} \\ + \sum_{a=1}^{J}\sum_{b=1}^{J} d^{f_{a,b}-1}\, x_{b,t}^{m} r_{a,t}^{m} + \sum_{a=1}^{J}\sum_{b=1}^{J} d^{f_{a,b}-1}\, x_{b,t}^{m} a_{a,t}^{m} \end{pmatrix} \\
&+100 \sum_{j=1}^{J}\sum_{t=1}^{T} Nst_{j,t}
\end{aligned} \tag{5.21}$$

Where:

$$\alpha_t^m = \frac{\sum_{j=1}^{J} x_{j,t}^m}{\sum_{j=1}^{J} x_{j,t}^m + \sum_{j=1}^{J} y_{j,t}^m}, \forall t \tag{5.22}$$

$$I_0^m = \sum_{j=1}^{J} purcost_j Nst_{j,t} x_{j,t}^m \quad, t = T_0 = 1 \tag{5.23}$$

The objective function equation (5.21) is related to the investment cost in manufacturing system which includes the machines addition and removal as well as integration and testing cost. The first and second terms are concerned with the addition of platform and non-platform machines, respectively in production period "$t=T_0=1$". The term "$Nst_{j,t}$" refers to the number of machine "j" added in production period "t". The third and fifth terms are concerned with the addition of platform and non-platform machines, respectively in the subsequent production periods "$t>1$". The term $max(0,Nst_{j,t+1}-Nst_{j,t})$ is concerned with adding machine "j" in production period "$t+1$" compared to production period "t". This term takes the value "$Nst_{j,t+1}-Nst_{j,t}$" if the number of machines in production period "$t+1$" is more than the number of machines in production period "t" and 0 otherwise.

The fourth and sixth terms are concerned with the removal of platform and non-platform machines, respectively in the subsequent production periods "$t>1$". The term $min(0,Nst_{j,t+1}-Nst_{j,t})$ is concerned with removing machine "j" in production period "$t+1$" compared to production period "t". This term takes the value "$Nst_{j,t+1}-Nst_{j,t}$" if the number of machines in production period "$t+1$" is less than the number of machines in production period "t" and 0 otherwise. The seventh term is the integration and testing cost of adding non-platform machines to the existing manufacturing system. This term is adopted from [115] in which the integration and testing cost for system elements depends on the amount of commonality "α_t^m" within the manufacturing system (commonality "α_t^m" is the ratio between the platform machines types to the total manufacturing system type including the platform and non-platform machine types) and initial investment within the platform portion of the system "I_0^m". As commonality "α_t^m" increases, the number of platform machines within the system increase compared to non-platform machines. For example, when investing in highly flexible machines in the initial production period which is characterized by high investment cost, a small portion of non-platform machines are likely to be added in the subsequent periods and hence, integration and testing cost is reduced. In addition, when the initial investment within the platform portion of the system "I_0^m" increases, the manufacturing system can easily accommodate non-platform machines whenever required since high amount of investment cost has been acquired to facilitate integration of the non-platform machines to the existing platform machines. The term "B_m" is the total available budget and "$A_{0,t}^m$" is the base cost of testing and integration in production period "t".

The term "$\sum_a \sum_b d^{f_{a,b}-1} x_{b,t}^m r_{a,t}^m$" is considered in order to illustrate the various terms in equation (5.21). An integration and testing cost will be acquired if non-platform machine "a" is removed from the manufacturing system in production period "t" (i.e. $r_{a,t}^m$=1) and at the same time, platform machine "b" is available within the manufacturing system in production period "t" (i.e. $x_{b,t}^m$=1). Therefore, integration and testing cost is acquired. The term "$f_{a,b}$" is the number of interfaces (material flow) between machine type "a" and "b". For a flow line type manufacturing system, machine "a" has only one interface with machine "b" and accordingly, the term "$d^{f_{a,b}-1}$" is equal to 1. Since at this chapter, the manufacturing system configuration is not of a concern, the value of "$d^{f_{a,b}-1}$" is equal to 1. However, in chapter 7, this statement will be enhanced since the manufacturing system configuration will be determined.

The eighth term is a penalty term which puts restrictions on the number of machines in each period. When determining the investment cost within the manufacturing system in terms of addition and removal of machines, the eighth term should be subtracted from the optimum value of the objective function equation (5.21) in order to find the optimum investment cost within the manufacturing system in terms of addition or removal of machines.

5.2.5 Constraints

The mathematical model constraints are given in this subsection. Equation (5.24) is concerned with the addition of non-platform machine "j" in production period "$t+1$". If a machine "j" can process a certain operation "o" required by product feature "f" within product variant "i" in production period "$t+1$" (i.e. $\varphi_{i,j,o,f,t+1}=1$) and machine "j" is not available as non-platform machine in production period "t" (i.e. $y_{j,t}^m=0$) and machine "j" is not available within the platform machine portion of the system (i.e. $x_{j,t}^m=0$), therefore, machine "j" is added as non-platform machine in production period "$t+1$" (i.e. $a_{j,t+1}^m=1$).

$$a_{j,t+1}^m \leq \sum_{i=1}^{P} \sum_{o=1}^{O} \sum_{f=1}^{F} \varphi_{i,j,o,f,t+1}(1-y_{j,t}^m)(1-x_{j,t}^m) \leq M a_{j,t+1}^m, \forall j,t \tag{5.24}$$

Equation (5.25) is concerned with the removal of non-platform machine "j" in production period "$t+1$". If machine "j" is available in production period "t" as a non-platform machine (i.e. $y_{j,t}^m=1$) and machine "j" cannot process operation "o" for product feature "f" in product variant "i" in period "$t+1$" (i.e. $\varphi_{i,j,o,f,t+1}=0$), therefore non-platform machine "j" is removed from production period "$t+1$" (i.e. $r_{j,t+1}^{m}=1$). The reason for the decision to remove machine "j" within production period "$t+1$" from the non-platform portion of the system is due to its non-necessity since it does not possess the operational capability to perform any operation on any production feature in production period "$t+1$".

$$r_{j,t+1}^{m} \leq \sum_{i=1}^{I} \sum_{o=1}^{O} \sum_{f=1}^{F} y_{j,t}^{m} (1-\varphi_{i,j,o,f,t+1}) \leq M r_{j,t+1}^{m} \ \forall j,t \qquad (5.25)$$

Equations (5.26) and (5.27) concerned with mapping product platform features to platform machines.

$$M\sigma_{o,f} - M + 1 \leq \ 1 - T + \sum_{t=1}^{T} \psi_{o,f,t} \leq \ (1-\epsilon)\left(1-\sigma_{o,f}\right) + \sigma_{o,f}, \forall o,f \qquad (5.26)$$

$$x_{j,t}^{m} \ \leq \sum_{i=1}^{I} \sum_{o=1}^{O} \sum_{f=1}^{F} \varphi_{i,j,o,f,t} \sigma_{o,f} \ \leq \ M x_{j,t}^{m}, \forall j,t \qquad (5.27)$$

Equation (5.28) insures that a non-platform machine is either added or removed in a certain production period.

$$a_{j,t}^{m} + r_{j,t}^{m} \leq 1, \forall j,t \qquad (5.28)$$

Equation (5.29) insures that platform machines are available in all production periods.

$$x_{j,t}^{m} = x_{j,t+1}^{m}, \forall j,t \qquad (5.29)$$

Equation (5.30) relates the type of non-platform machine in a certain production period "$t+1$" with respect to the preceding period "t".

$$y_{j,t+1}^{m} = y_{j,t}^{m} + a_{j,t+1}^{m} - r_{j,t+1}^{m}, \forall j,t \qquad (5.30)$$

Equation (5.31) is used to determine the type of operation "o" required for a product feature "f" which is available in all product variants in production period "t".

$$M\psi_{o,f,t} - M + 1 \leq 1 + \left(\sum_{i=1}^{I} z_{i,t} \gamma_{f,o} \rho_{i,f} - \sum_{i=1}^{I} z_{i,t}\right) \leq (1-\epsilon)\left(1-\psi_{o,f,t}\right) + \psi_{o,f,t}, \forall t,f,o \qquad (5.31)$$

Equation (5.32) and (5.33) is used to determine the type of product features "f" which are available in all product variants in all production periods (i.e. product platform).

$$M\varepsilon_{f,t} - M + 1 \leq \ 1 + \left(\sum_{i=1}^{I} z_{i,t} \rho_{i,f} - \sum_{i=1}^{I} z_{i,t}\right) \leq \ (1-\epsilon)\left(1-\varepsilon_{f,t}\right) + \varepsilon_{f,t}, \forall f,t \qquad (5.32)$$

$$M x_{f,t=T_0}^{p} - M + 1 \leq \ 1 + \left(\sum_{t=1}^{T} \varepsilon_{f,t} - T\right) \leq \ (1-\epsilon)\left(1 - x_{f,t=T_0}^{p}\right) + x_{f,t=T_0}^{p}, \forall f,t \qquad (5.33)$$

Equation (5.34) is used to determine the type of product feature "f" that are available in at least one product variant in production period "t".

$$\delta_{f,t} \leq \sum_{i=1}^{I} z_{i,t}\rho_{i,f} \leq M\delta_{f,t}, \forall f,t \tag{5.34}$$

Equation (5.35) insures that a product feature "f" available in certain production period "t" is either a product platform or non-platform product feature.

$$x_{f,t}^{p} + y_{f,t}^{p} = \delta_{f,t}, \forall f,t \tag{5.35}$$

Equation (5.36) insures that a product platform feature is available in all production periods.

$$x_{f,t}^{p} = x_{f,t+1}^{p}, \forall f,t \tag{5.36}$$

Equations (5.37), (5.38) and (5.39) insures that operation "o" required for product feature "f" within product variant "i" in production period "t" is mapped to only one machine "j".

$$\sum_{j=1}^{J} \varphi_{i,j,o,f,t} = z_{i,t}\rho_{i,f}\gamma_{f,o}, \forall i,o,f,t \tag{5.37}$$

$$\varphi_{i,j,o,f,t} = z_{i,t}\rho_{i,f}\gamma_{f,o}McOp_{j,o}\mu_{i,j,o,f,t}(x_{j,t}^{m} + y_{j,t}^{m}), \forall i,j,o,f,t \tag{5.38}$$

$$\sum_{j=1}^{J} \mu_{i,j,o,f,t} = 1, \forall i,o,f,t \tag{5.39}$$

Equation (5.40) is related to line balancing which restrains the number of each machine type according to the product demand. "NHD" is the number of hours available per day.

$$\sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{f=1}^{F} demand_{i,t} \times ptime_{o,j} \times \varphi_{i,j,o,p,t} \leq 3600 \times NHD \times \left(x_{j,t}^{m} + y_{j,t}^{m}\right)Nst_{j,t}, \forall j,t \tag{5.40}$$

5.3 Decision variables equivalent linear formulation

Due to the presence of non-linear terms (e.g. multiplication of decision variables, absolute value of decision variables, maximum and minimum values of a set of decision variables) within the mathematical model described above, it is required to obtain the equivalent linear formulation. In the following subsections, some techniques [116] will be used for the purpose of the obtaining the equivalent linear formulation to guarantee a global optimum solution for the mathematical model provided the model can be solved in reasonable time.

5.3.1 Multiplication of two binary variables

The expression "u_1u_2", where u_1, $u_2 \epsilon \{0,1\}$, can be replaced with "v" in addition to the following set of constraints:

$$
\begin{aligned}
&v \leq u_1 \\
&v \leq u_2 \\
&v \geq u_1 + u_2 - 1 \\
&v \in \{0,1\}
\end{aligned}
\tag{5.41}
$$

5.3.2 Multiplication of binary and continuous variables

The expression "u_1u_2", where $u_1 \epsilon \{0,1\}$ and $u_2 \epsilon [0,UL_2]$, can be replaced with "v" in addition to the following set of constraints:

$$
\begin{aligned}
&v \leq UL_2 u_1 \\
&v \leq u_2 \\
&v \geq u_2 - UL_2(1 - u_{1)} \\
&v \geq 0
\end{aligned}
\tag{5.42}
$$

5.3.3 Maximum and minimum values of a set of decision variables

The equivalent linear formulation of maximum value of a set of decision variables is:

$$
\begin{aligned}
&v = \max(u_1, u_2, \dots, u_n) \\
&L_i \leq u_i \leq U_i \\
&v \geq u_i \\
&v \leq u_i + (U_{max} - L_i)(1 - d_i) \\
&\textstyle\sum_i d_i = 1
\end{aligned}
\tag{5.43}
$$

The equivalent linear formulation of minimum value of a set of decision variables is:

$$
\begin{aligned}
&v = \min(u_1, u_2, \dots, u_n) \\
&L_i \leq u_i \leq U_i \\
&v \leq u_i \\
&v \geq u_i + (U_i - L_{min})(1 - d_i) \\
&\textstyle\sum_i d_i = 1
\end{aligned}
\tag{5.44}
$$

5.3.4 Absolute values

Consider the decision variable "v" such that;

$v = |u_1 - u_2|, u_1$ & $u_2 \in \{0,1\}$

The equivalent linear formulation of absolute values is:

$$
\begin{aligned}
&0 \le u_i \le U\\
&0 \le v - (u_1 - u_2) \le 2Ud_1\\
&0 \le v + (u_2 - u_1) \le 2Ud_2\\
&d_1 + d_2 = 1
\end{aligned} \tag{5.45}
$$

5.3.5 Multiplication of two continuous variables

Consider the two continuous variables "u_1" and "u_2" and they are multiplied by one another such that "u_1" has a lower and upper limit of "LL_1" and "UL_1" and "u_2" has a lower and upper limit of "LL_2" and "UL_2". The product of the two variables is replaced by the separable function such that:

$$v_1^2 - v_2^2 = u_1 u_2 \tag{5.46}$$

Where:

$$
\begin{aligned}
&v_1 = \frac{1}{2}(u_1 + u_2), && \frac{1}{2}(LL_1 + LL_2) \le v_1 \le \frac{1}{2}(UL_1 + UL_2)\\
&v_2 = \frac{1}{2}(u_1 - u_2), && \frac{1}{2}(LL_1 - UL_2) \le v_2 \le \frac{1}{2}(UL_1 - LL_2)
\end{aligned} \tag{5.47}
$$

Consider the example in Figure 5.2 in which it is required to find the approximated form of the non-linear function "$v_1 = u_1^2$". The solid line is the non-linear function "$v_1 = u_1^2$" while the dashed line is the piecewise approximation. Let $\lambda_1, \lambda_2, \lambda_3$ and λ_4 be non-negative weights which sums to 1. Therefore, the piecewise approximation is written as:

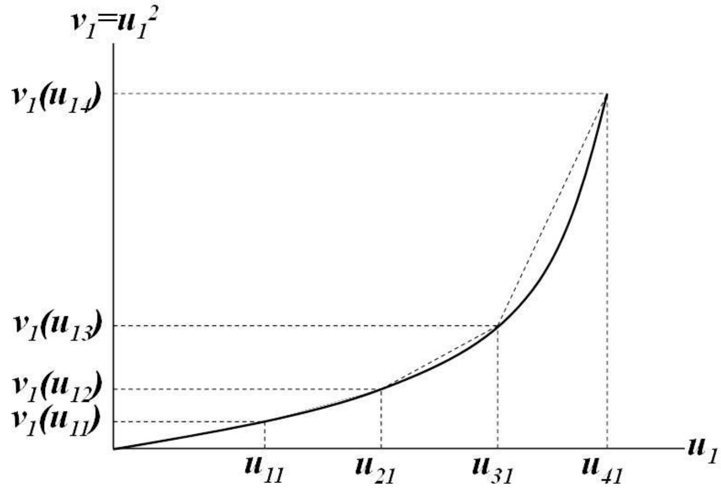


Figure 5.2 Piecewise linear approximation the v=u²

$$\lambda_1 v_1(u_{11}) + \lambda_2 v_1(u_{12}) + \lambda_3 v_1(u_{13}) + \lambda_4 v_1(u_{14}) = v_1$$
$$\lambda_1 u_{11} + \lambda_2 u_{12} + \lambda_3 u_{13} + \lambda_4 u_{14} = u_1 \quad (5.48)$$

Where:

$$\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 1 \quad (5.49)$$

$$\lambda_1 + \lambda_3 \leq 1 \quad (5.50)$$

$$\lambda_1 + \lambda_4 \leq 1 \quad (5.51)$$

$$\lambda_2 + \lambda_4 \leq 1 \quad (5.52)$$

In addition, a maximum of two adjacent values of λ must be greater than 0. This condition is satisfied within equations (5.50), (5.51) and (5.52).

5.4 Case Study: Machining of cylinder blocks taken from Mitsubishi Heavy Industries

The case study considered is concerned with a cylinder block manufacturing firm adopted from Mitsubishi [112]. The manufacturing company was producing inline 4 (I-4) cylinder blocks. Due to new design requirements, the company is willing to introduce V-6 cylinder blocks and V-8 cylinder blocks to its production line.

The main objective of the case study is, first, functional synthesis of the manufacturing system (types and number of machines) in production period 1 (where the I-4 cylinder block is produced) and production period 2 (where the V-6 and V-8 is produced) according to the co-platforming. Second, it is required to demonstrate the cost reduction achieved when applying co-platforming. The product features for the I-4 and V-6 cylinder blocks are shown in Figure 5.3. Product variants for each model are taken from [113] for illustration purposes. The input parameters are given in Table 5.1, Table 5.2 and Table 5.3. Salvage cost of machines is taken as 1% of the purchase cost [18]. Base cost of integration and testing is calculated as $400 [18]. Available budget is $50,000,000 which is considered as a one time budget.

The CNC machines specifications and technical data are taken from http://huron.fr since this manufacturer provides detailed data. However, the purchase cost was not available. For this reason, the purchase cost was acquired from http://haasCNC.com. Purchase cost of CNC machines in Table 5.3 has been calculated using linear regression.

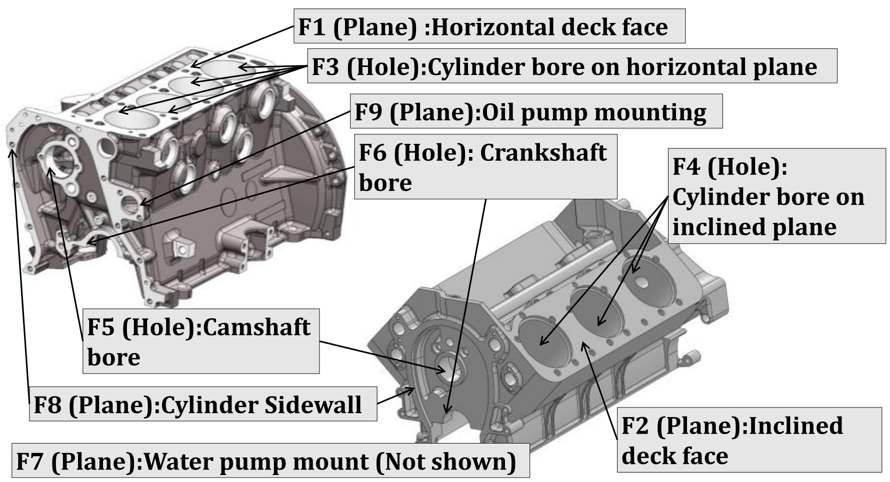


Figure 5.3 Product features for the I-4 and V-6 cylinder blocks

Table 5.1: Product variant-product features matrix and demand of each product in each production period (units/day).

Product variants	Product features									Production period	
	1	2	3	4	5	6	7	8	9	1	2
4A-GEU 1587cc	1	0	1	0	0	1	0	1	1	0	0
711 M 1691 cc	1	0	1	0	1	0	0	1	1	500	0
QR20DE 1998	1	0	1	0	0	0	1	1	0	800	0
Mopar 2360 cc	1	0	1	0	0	1	1	1	1	0	0
Cosworth 2935	0	1	0	1	0	1	1	1	0	0	800
Buick215 2900	0	1	0	1	1	1	1	1	0	0	0
Cyclone 3496 cc	0	1	0	1	0	1	0	1	1	0	900
LN3 3800 cc	0	1	0	1	1	1	1	1	1	0	400

Table 5.2: Machining operations-product feature matrix.

OP	Operations description	Product features								
		1	2	3	4	5	6	7	8	9
01	Rough milling horizontal surface	1	0	0	0	0	0	0	0	0
02	Finish milling horizontal surface	1	0	0	0	0	0	0	0	0
03	Rough milling inclined surface	0	1	0	0	0	0	0	0	0
04	Finish milling inclined surface	0	1	0	0	0	0	0	0	0
05	Rough boring horizontal surface	0	0	1	0	0	0	0	0	0
06	Finish boring horizontal surface	0	0	1	0	0	0	0	0	0
07	Rough boring inclined surface	0	0	0	1	0	0	0	0	0
08	Finish boring inclined surface	0	0	0	1	0	0	0	0	0
09	Rough camshaft boring	0	0	0	0	1	0	0	0	0
10	Finish camshaft boring	0	0	0	0	1	0	0	0	0
11	Rough crankshaft boring	0	0	0	0	0	1	0	0	0
12	Finish crankshaft boring	0	0	0	0	0	1	0	0	0
13	Rough Water pump milling	0	0	0	0	0	0	1	0	0
14	Finish Water pump milling	0	0	0	0	0	0	1	0	0
15	Side wall rough milling	0	0	0	0	0	0	0	1	0
16	Side wall finish milling	0	0	0	0	0	0	0	1	0
17	Oil pump rough milling	0	0	0	0	0	0	0	0	1
18	Oil pump finish milling	0	0	0	0	0	0	0	0	1

Table 5.3: Operations-machine matrix and processing time of each operation on each machine (in seconds)

Operations	Machines									
	KX50M (CNC-M1)	KX10i (CNC-M2)	KXG45-14 (CNC-M3)	K2X10 (CNC-M4)	KX50L (CNC-M5)	Vertical boring machine (M6)	Horizontal milling machine (M7)	LBM2500 (Horizontal Honing-M8)	VCB1500V (Vertical Honing-M9)	LBM1500 (Horizontal Honing-M10)
01	222	156	234	156	240	0	150	0	0	0
02	138	0	0	210	132	0	0	0	0	0
03	132	0	288	0	144	0	0	0	0	0
04	216	0	0	0	210	0	0	0	0	0
05	162	0	0	162	294	216	0	0	0	0
06	132	0	0	0	258	0	0	0	282	0
07	294	0	0	0	216	0	0	0	0	0
08	0	0	0	0	240	0	0	0	240	0
09	222	0	0	0	282	0	0	0	0	0
10	0	0	0	0	294	0	0	282	0	0
11	270	0	0	0	264	0	0	0	0	0
12	0	0	0	0	0	0	0	144	0	186
13	246	0	0	0	150	0	0	0	0	0
14	216	0	0	0	138	0	0	0	0	0
15	198	0	0	0	222	0	0	0	0	0
16	288	0	0	0	150	0	0	0	0	0
17	180	0	0	0	120	0	0	0	0	0
18	210	0	0	0	186	0	0	0	0	0
Cost ($\$x10^3$)	270	157	461	162	336	80	10	100	50	80
Working envelop ($\times 10^6$ mm^3)	2626	393	6435	460	3939	-	-	-	-	-

The purchase cost of CNC machines has been modeled through simple linear regression since it involves one independent variable. The dependent variable in this case is the CNC machine purchase cost and the independent variable is the machine's working envelop. Further enhancements can be achieved in calculating the purchase cost of CNC machine by using multiple linear regression in which further independent variables can be taken into consideration such as axes type, precision of machine...etc. The best fit line equation and the correlation value is shown in Figure 5.4.

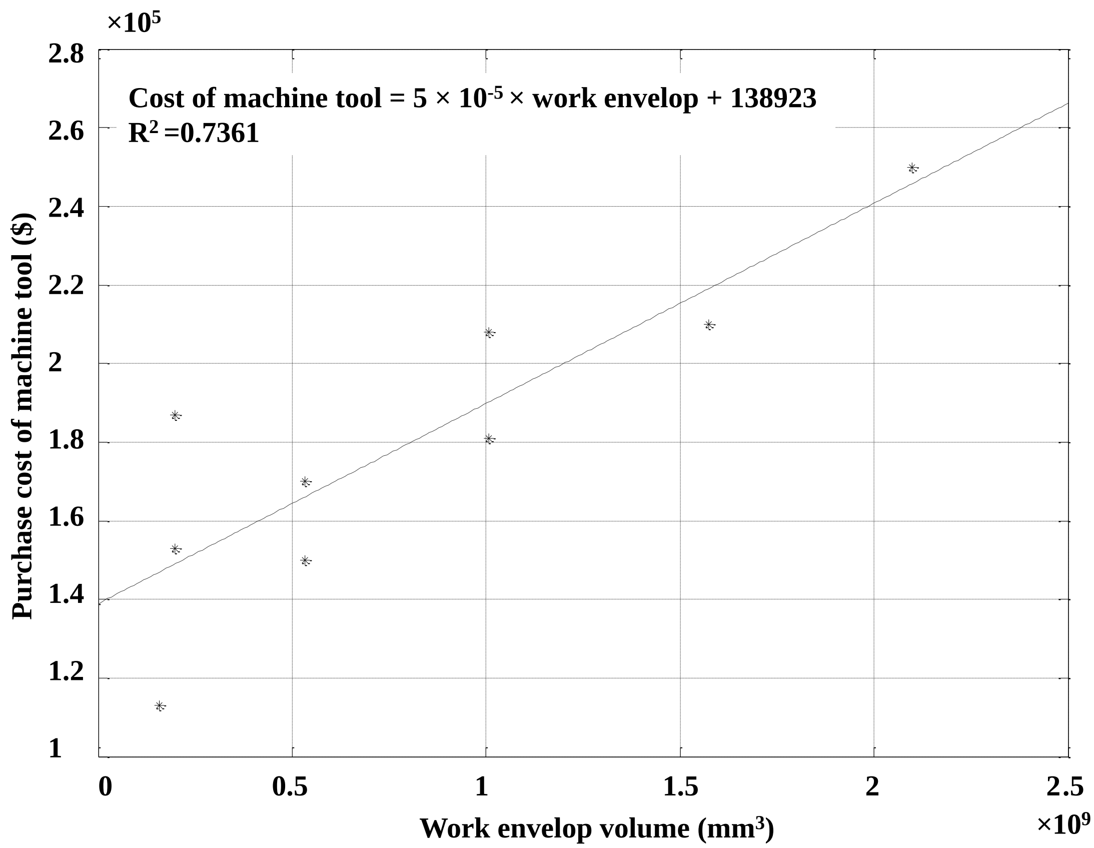


Figure 5.4 Linear regression results

5.5 Results and Discussions

The mathematical model is written using AMPL (http://ampl.com/) and solved by Gurobi MILP in NEOS [117, 118, 119] in 144.12 seconds. Optimal solution of the objective function within equation (5.21) of $12,438,830 is found (excluding the eighth term since it is a penalty term that is not included as a cost). The main results from the model are shown in Figure 5.5. The configuration of the NEOS server machines used through the whole dissertation is: CPU - 2x

Intel Xeon E5-2698 @ 2.3GHz (32 cores total) and Memory - 192GB RAM (http://neos-guide.org/content/FAQ).

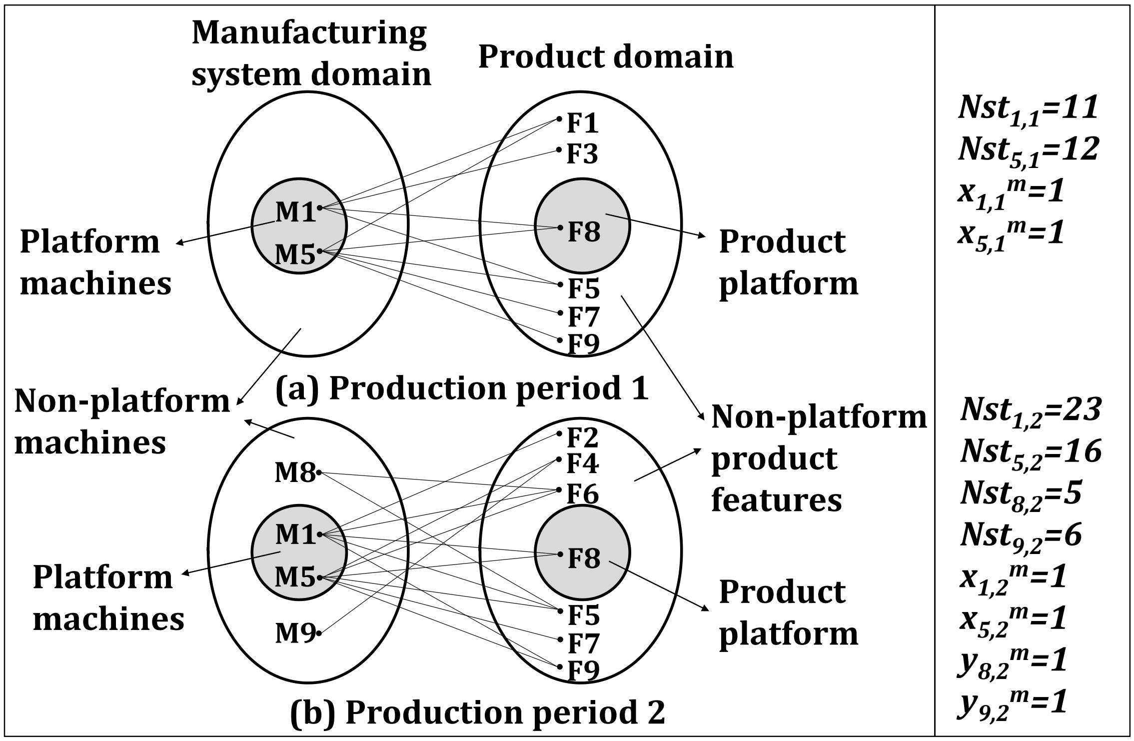


Figure 5.5 Results from the mathematical model

The product platform features in this case study is product feature 8 (cylinder side wall planar face) since it is available in all products within the two production periods. The rest of the non-platform product features in production periods 1 and 2 are either available within all products in only a single production period or available in both production periods but not within all product variants.

In production period 1, platform machines type 1 and 5 possess the machining capabilities (5 axes with tool magazine) to process the roughing and finishing machining operations for product platform feature 8. However, the mathematical model also assigns platform machine type 1 to process the machining operations required for some operations for non-platform product features such as product feature 1 (horizontal deck planar face), 3 (cylinder bore on horizontal surface) and 5 (camshaft bore). The reason for this is, first, machine type 1 possesses the machining capabilities to process machining operations required for non-platform product features 1 (horizontal deck planar face), 3 (cylinder bore on horizontal surface), and 5 (camshaft bore) and second, due to the nature of the mathematical model which minimize a cost function which requires providing the least number and types of machines. Platform machine type 5 is assigned to non-platform product features 1 (horizontal deck planar face), 5 (camshaft bore), 7 (water pump mount planar face) and 9 (oil pump mount planar face) since platform machine type 5 possess the machining capabilities required to process required operations for the non-platform product features 1 (horizontal deck planar face), 5 (camshaft bore), 7 (water pump mount planar face) and 9 (oil pump mount planar face).

In production period 2, platform machines type 1 and 5 possess the machining capabilities to process the rough and finish machining operations for product platform feature 8 (cylinder side wall planar face) as in production period 1. In addition, the mathematical model assigns platform machine type 1 to process required operations for non-platform product features 2 (inclined deck planar face), 5 (camshaft bore) and 9 (oil pump mount planar face) and the rough operation for non-platform product feature 6 (crankshaft bore) since platform machine type 1 possesses the capability required to process these non-platform product features for the reasons mentioned in the previous paragraph. The platform machine type 5 is assigned to non-platform product features 4 (cylinder bore inclined surface), 5 (camshaft bore), 7 (water pump mount planar face) and 9 (oil pump mount planar face) and the rough operation for non-platform product feature 6 (crankshaft bore). Finishing operation of the non-platform product features 5 (camshaft bore) and 6 (crankshaft bore) are assigned to non-platform machine type 8 (horizontal honing machine LBM2500). Finish operation of the non-platform product feature 4 (cylinder bore inclined surface) is assigned to non-platform machine type 9 (vertical honing machine VCB1500V).

It is worth noting that real implementation of the case study from Mitsubishi [112] involves performing the rough cutting operations and finish cutting operations for the V-6 and V-8 on 5-axis CNC machines only which is different from the solution proposed in this dissertation as non-platform product feature 6 (crankshaft bore) is assigned to a special purpose machine type 8 for honing operation (LBM2500). This difference is due to the special design of the 5-axis CNC machines implemented by Mitsubishi [112] which is equipped with a special tool required for honing operations. The machine tools chosen in this dissertation are taken from standard catalogues.

In production period 1, machine type 1 processes operations for the four product features 1, 3, 5 and 8 with a total number of units of 1300 units per day. In production period 2, machine type 1 processes operations for the five product features 2, 5, 6, 8 and 9 with a total number of units of 2100 units per day. Due to the increase in number of product features that require processing by machine type 1 (from four product features in production period 1 to five product features in production period 2) as well as the increase in demand from production period 1 to 2, therefore, the number of platform machine type 1 increased from 11 in period 1 to 23 in period 2.

In production period 1, platform machine type 5 processes operations for the five product features 1, 5, 7, 8 and 9 within total number of 1300 units per day. In production period 2, machine type 5 processes operations for the six product features (4, 5, 6, 7, 8 and 9) on total number of 2100 units per day. Hence the number of machine type 5 increases from 12 in production period 1 to 16 in period 2.

Table 5.4 provides the processing time for each operation being processed on machine type 1. The bold number between the parenthesis is the total processing time for a single product variant on platform machine type 1. This number must be multiplied by the total demand units for each product. Therefore, with the aid of equation (5.40), the total number of platform machine type 1 in production periods 1 and 2 is calculated as follows:

$$Nst_{1,1}^{m} = \frac{500\times738 + 800\times714}{3600\times24} \approx 11$$
$$Nst_{1,2}^{m} = \frac{800\times816 + 900\times1026 + 400\times978}{3600\times24} \approx 23 \qquad (5.53)$$

Finally, it is required to determine the effect of maintaining a common core of platform machines within the different production periods on the cost objective function. This effect can be visualized graphically in Figure 5.6. The results in Figure 5.6 are obtained using the mathematical programming model illustrated earlier while varying the value of "α_t^m" from 0 to 1 and capturing the corresponding optimum cost objective function. The cost value for different values of "α_{av}" are obtained from separate runs (i.e. discrete points) and the general trend of the plotted and a spline is fitted. The *x*-axis is the average value of "α_t^m" in production periods 1 and 2 while the *y*-axis is cost objective function (the eighth term in equation (5.21) is not included since it is not part of the cost since it is only a penalty term).

At "α_{av}" lies between 0 and 1, a group of common core or platform machines are maintained. In this bandwidth, the minimum cost of $12,438,830 is achieved at a value of "α_{av}" equal to 0.75. Based on this case study and from Figure 5.6, co-platforming can lead to cost savings compared to the other two extremes shown in Figure 5.6 at "$\alpha_{av}=0$" (dedicated system with no platform machines) and "$\alpha_{av} =1$" (flexible system with no non-platform machines) in terms of a manufacturing system investment.

Table 5.4: Total processing time on machine 1

Product 2 (demand=500units/day)						Product 3 (demand=800units/day)		
Feature	Operation	Process time (sec)				Feature	Operation	Process time (sec)
1	1	222				1	1	222
3	5	162				3	5	162
3	6	132				3	6	132
5	9	222				8	15	198
Total processing time		*(738)*				Total processing time		*(714)*
Product 5 (demand=800units/day)			Product 7 (demand=900units/day)			Product 8 (demand=400units/day)		
Feature	Operation	Process time (sec)	Feature	Operation	Process time (sec)	Feature	Operation	Process time (sec)
2	3	132	2	3	132	2	3	132
2	4	216	2	4	216	2	4	216
6	11	270	6	11	270	5	9	222
8	15	198	8	15	198	8	15	198
			9	18	210	9	18	210
Total processing time		*(816)*	Total processing time		*(1026)*	Total processing time		*(978)*

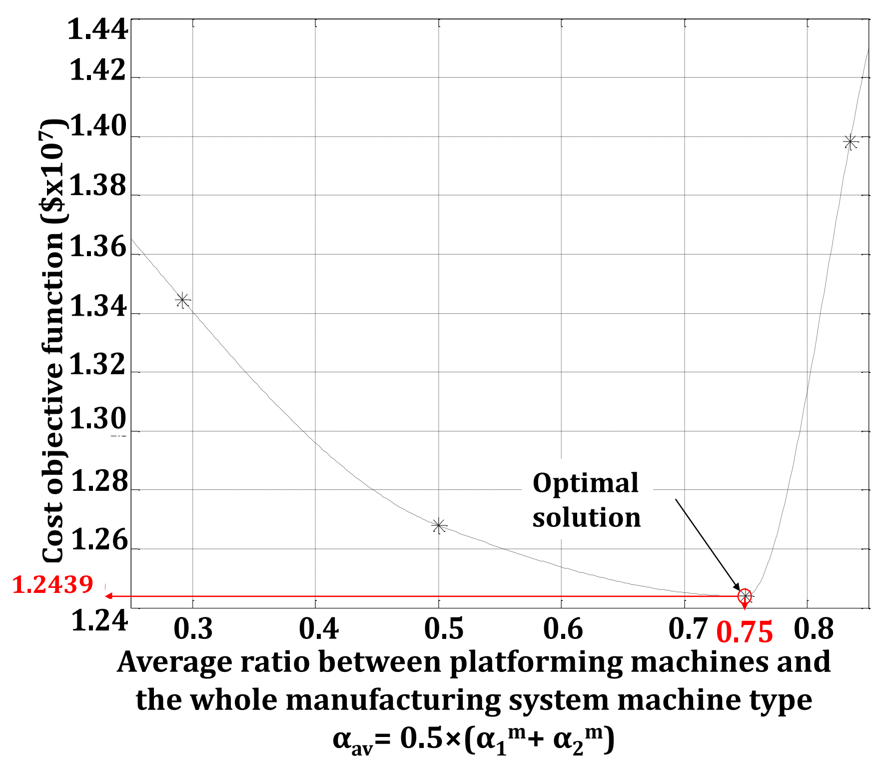


Figure 5.6 Effect of maintaining a common platform machines on the cost within the system level

5.6 Limitations

The mathematical programming model introduced in this chapter has limitations on the physical level as well as on the computational level. In the physical level, though the mathematical programming model in this chapter can be applied on fabrication and assembly system types, yet, the mathematical model in this form can be applied only on automated manufacturing systems. In order to extend the model to cope with manual manufacturing systems, the relationship between the machines and the operational capabilities must be reformulated to take into consideration human factors such as the types of capabilities (e.g. handheld tools and fixtures) that can be performed on the product by the worker which includes handheld tools, setups, learning curve…etc.

In addition, the model addressed in this chapter does not take into consideration manufacturing system components other than the machine tools. Furthermore, the number of each machine type and their arrangement are not taken calculated in this model.

On the computational level, various scenarios have been applied as indicated in Table 5.5. For the first scenario, the computational time for of periods=2, products=8, operations=54, features=20 and machines=8 is 105.7 seconds. At the second scenario, though the number of operations decreases to 18 and the number of features decreases to 9, yet the computational time increased to 144.12. This is attributed to the number of machines in scenario 2 which is 10 compared to 8 machines in scenario 1. This limitation can be enhanced by using meta-heuristics methods such as genetic algorithms. However, an optimal solution in this case will not be guaranteed. In the third scenario, the computational time for of periods=3, products=8, operations=54, features=20 and machines=8 is 177.93 seconds. This increase in computational time compared to scenario 1 is attributed to the increase in the number of periods which is 3 in the third scenario compared to 2 in the second scenario.

In the fourth scenario, the computational time for of periods=2, products=4, operations=54, features=20 and machines=14 is 201.26 seconds. The reason for the increase of computational time for the fourth scenario compared to the first scenario is attributed to the increase in number of machines in machines for the fourth scenario relative to the first scenario. In the last scenario, the computational time for of periods=2, products=8, operations=18, features=20 and machines=10 is 361.34 seconds.

Table 5.5: Computational time for different scenarios

Number of					MIPGap (%)	Computational time (sec)	Solution status
Period	Products	Operations	Features	Machines			
2	8	54	20	8	0	105.7	Optimal solution found
2	8	18	9	10	0	144.12	Optimal solution found
3	8	54	20	8	0	177.93	Optimal solution found
2	4	54	20	14	0	201.26	Optimal solution found
3	8	18	9	10	0	331.9	Optimal solution found
2	8	18	20	10	0	361.34	Optimal solution found

5.7 Conclusion

This chapter introduced a mathematical model in order to synthesize the product and manufacturing system through the co-platforming. This mathematical model takes into account initial investment cost of manufacturing system components (in terms of purchase and selling of equipment) and integration cost of machines within the manufacturing system in the different production periods according to the changes in the product variants in each product period. Various constraints were addressed for both product and manufacturing system domain. Several linearization techniques were used in order to obtain the equivalent linear formulation to insure a global optimum solution.

The mathematical model has been applied in a case study of a cylinder blocks manufacturing firm. The results from the mathematical model provided the optimum types of machines within each production period (whether platform or non-platform machines) and the number of each machine. The significance of the mathematical model is evident in providing a highly responsive manufacturing system, with minimum investment cost, that easily adapts and evolves as a result of the change within products to suit customers' requirement and needs. The effect of maintaining a common core or platform machines within the manufacturing system has also been studied based on the case study presented and the output indicates that co-platforming leads to cost savings compared to other manufacturing paradigms such as dedicated systems and flexible systems.

CHAPTER 6. COST OF CHANGE OF MANUFACTURING SYSTEM THROUGH CO-PLATFORMING TAKING INTO CONSIDERATION MACHINE AND SYSTEM LEVEL

6.1 Overview

Manufacturing firms are in continuous need to design manufacturing systems to cope with product variety and frequent changes in the product requirements. Switching from one product family in a certain production period to another product family in the subsequent production period requires reconfiguration of the manufacturing system. Such reconfiguration leads to extra cost which consititutes financial burden on manufacturing firms.

The objective of this chapter is to synthesize manufactuirng system based on co-platforming taking into consideration the machine level change (addition or removal of machining axes, changing setup) in addition to the system level change (addition or removal of machines).

A mixed integer linear programming is proposed which extends the model in chapter 5 in order to take the machine and system level change into consideration. The objective function is to minimize the cost of change in terms of manufacturing system investment when switching from one product family in a certain production period to another product family in the subsequent production period. The cost of change takes into consideration the machine level change (addition or removal of machining axes, changing setup) in addition to the system level change (addition or removal of machines).

The proposed model is applied on a mathematical example for verification purposed as well as on a case study taken from an automotive cylinder block manufacturer. Finally, the effect of maintaining a common core of machines within the manufacturing system on the total investment cost is investigated.

6.2 Model Development

6.2.1 Input Parameters

The input parameters in this model are same as the input parameters for the mathematical model in chapter 5. The input parameters are taken similar to equations (5.1) to (5.8). However, the only modified parameter to be considered is the "$McOp_{j,o}$" equation (5.4). The machine-machining operation matrix, whose elements are written as "$McOp_{j,o}$", is illustrated in Figure 6.1 and is divided into two parts; the initial machine configuration machining operation and the machine configuration machining operations after addition of machining axes.

For example, machine type 1 initial configuration has the index of "$j=1$". After addition of an extra machining axis, the new machine configuration takes the index of "$j=J\text{-}MDR+1$". The same issue applies with "$j=2$" as an initial configuration and "$j=J\text{-}MDR+2$" as the new machine configuration after adding the new machining axis. On the other hand, if machine configuration type "$j=J\text{-}MDR+1$" requires removal of machining axis, the new machine configuration takes the index of "$j=1$".

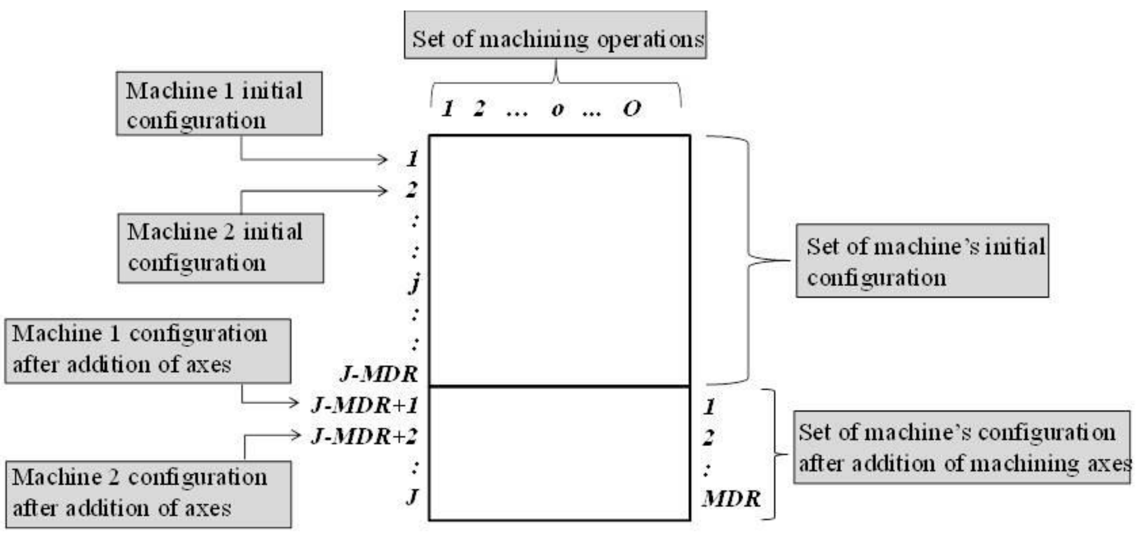


Figure 6.1 Illustration of machine operation matrix

6.2.2 Decision Variables

The decision variables in this model are same as the decision variables for the mathematical model in chapter 5. Therefore, the decision variables are taken as equations (5.9) to (5.20).

6.2.3 Constants and Indices

The constants and indices in this model are the same as the indices and constants for the mathematical model in chapter 5. However, another set and index is added for this model such that:

MDR [1,…,mdr,…] = set of modular structure machines

6.2.4 Objective Function

The objective function is given as:

$Minimize$:

$$\begin{aligned}
&\sum_{j=1}^{J-MDR} purcost_j Nst_{j,t=T_0} x^m_{j,t=T_0} + \sum_{j=1}^{J-MDR} purcost_j Nst_{j,t=T_0} y^m_{j,t=T_0} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J-MDR} purcost_j \Delta^{add} x_{j,t,t+1} + \sum_{t=1}^{T}\sum_{j=1}^{J-MDR} sellcost_j \Delta^{rem} x_{j,t,t+1} \\
&+\sum_{t=1}^{T}\sum_{j=MDR+1}^{J-MDR} purcost_j \Delta^{add} y_{j,t,t+1} + \sum_{t=1}^{T}\sum_{j=MDR+1}^{J-MDR} sellcost_j \Delta^{rem} y_{j,t,t+1} \\
&+\sum_{t=1}^{T}\sum_{\substack{j=1 \\ a=J+j-MDR}}^{MDR} purcost_a \Delta^{add}_x ax_{j,a,t,t+1} + \sum_{t=1}^{T}\sum_{\substack{j=1 \\ a=J+j-MDR}}^{MDR} purcost_a \Delta^{add}_y ax_{j,a,t,t+1} \\
&+\sum_{t=1}^{T}\sum_{\substack{j=1 \\ a=J+j-MDR}}^{MDR} (purcost_j + purcost_a)\Delta^{add} axmc_{j,a,t,t+1} \\
&+\sum_{t=1}^{T}\sum_{\substack{j=1 \\ a=J+j-MDR}}^{MDR} purcost_j (\Delta^{add} y_{j,t,t+1} - \Delta^{add} axmc_{j,a,t,t+1}) \\
&+\sum_{t=1}^{T}\sum_{\substack{j=1 \\ a=J+j-MDR}}^{MDR} (sellcost_j + sellcost_a)\Delta^{rem} axmc_{j,a,t,t+1} \\
&+\sum_{t=1}^{T}\sum_{\substack{j=1 \\ a=J+j-MDR}}^{MDR} sellcost_j (\Delta^{rem} y_{j,t,t+1} - \Delta^{rem} axmc_{j,a,t,t+1}) \\
&+\sum_{t=1}^{T}\sum_{\substack{j=1 \\ a=J+j-MDR}}^{MDR} sellcost_a \Delta^{rem}_y ax_{j,a,t,t+1} + \sum_{t=1}^{T}\sum_{\substack{j=1 \\ a=J+j-MDR}}^{MDR} sellcost_a \Delta^{rem}_x ax_{j,a,t,t+1} \\
&+\sum_{t=1}^{T} \frac{A^m_{0,t} B^m}{I^m_0 \alpha^m_t} \begin{pmatrix} \sum_{b=1}^{J}\sum_{\hat{b}=1}^{J} d^{f_{b,\hat{b}}-1}\, y^m_{\hat{b},t} r^m_{b,t} + \sum_{b=1}^{J}\sum_{\hat{b}=1}^{J} d^{f_{b,\hat{b}}-1}\, y^m_{\hat{b},t} a^m_{b,t} \\ + \sum_{a=1}^{J}\sum_{b=1}^{J} d^{f_{a,b}-1}\, x^m_{b,t} r^m_{a,t} + \sum_{a=1}^{J}\sum_{b=1}^{J} d^{f_{a,b}-1}\, x^m_{b,t} a^m_{a,t} \end{pmatrix}
\end{aligned} \tag{6.1}$$

Where:

$$\alpha^m_t = \frac{\sum_{j=1}^{J} x^m_{j,t}}{\sum_{j=1}^{J} x^m_{j,t} + \sum_{j=1}^{J} y^m_{j,t}}, \forall t \tag{6.2}$$

$$I_0^m = \sum_{j=1}^{J-MDR} purcost_j Nst_{j,t} x_{j,t}^m \ , t = T_0 \tag{6.3}$$

$$\Delta^{add} x_{j,t,t+1} = \begin{cases} \max\{(Nst_{j,t+1}+Nst_{a,t+1}) - (Nst_{j,t} + Nst_{a,t}),0\} x_{j,t+1}^m \\ \qquad \forall\, j = 1,2..,MDR, a = j + J - MDR \\ \max\{Nst_{j,t+1} - Nst_{j,t}, 0\}\, x_{j,t+1}^m \\ \qquad \forall\, j = MDR + 1,..,J - MDR \end{cases} \tag{6.4}$$

$$\Delta^{add} y_{j,t,t+1} = \begin{cases} \max\{(Nst_{j,t+1}+Nst_{a,t+1}) - (Nst_{j,t} + Nst_{a,t}),0\} y_{j,t+1}^m \\ \qquad \forall\, j = 1,2,..,MDR, a = j + J - MDR \\ \max\{Nst_{j,t+1} - Nst_{j,t}, 0\}\, y_{j,t+1}^m \\ \qquad \forall\, j = MDR + 1,..,J - MDR \end{cases} \tag{6.5}$$

$$\Delta^{rem} x_{j,t,t+1} = \begin{cases} \max\{(Nst_{j,t} + Nst_{a,t}) - (Nst_{j,t+1} + Nst_{a,t+1}),0\} x_{j,t+1}^m \\ \qquad \forall\, j = 1,2..,MDR, a = j + J - MDR \\ \max\{Nst_{j,t} - Nst_{j,t+1}, 0\}\, x_{j,t+1}^m \\ \qquad \forall\, j = MDR + 1,..,J - MDR \end{cases} \tag{6.6}$$

$$\Delta^{rem} y_{j,t,t+1} = \begin{cases} \max\{(Nst_{j,t} + Nst_{a,t}) - (Nst_{j,t+1} + Nst_{a,t+1}),0\} y_{j,t}^m \\ \qquad \forall\, j = 1,2..,MDR, a = j + J - MDR \\ \max\{Nst_{j,t} - Nst_{j,t+1}, 0\}\, y_{j,t}^m \\ \qquad \forall\, j = MDR + 1,..,J - MDR \end{cases} \tag{6.7}$$

$$\Delta_y^{add} ax_{j,a,t,t+1} = \max\{Nst_{a,t+1} - Nst_{a,t}, 0\}\, y_{a,t+1}^m y_{j,t}^m a_{a,t+1}^m \tag{6.8}$$

$$\forall\, j = 1,2..,MDR, a = j + J - MDR$$

$$\Delta_x^{add} ax_{j,a,t,t+1} = \max\{Nst_{a,t+1} - Nst_{a,t}, 0\}\, x_{a,t+1}^m x_{j,t}^m a_{a,t+1}^m \tag{6.9}$$

$$\forall\, j = 1,2..,MDR, a = j + J - MDR$$

$$\Delta^{add} axmc_{j,a,t,t+1} = \max\{Nst_{a,t+1} - Nst_{a,t}, 0\}\, y_{a,t+1}^m a_{a,t+1}^m (1 - y_{j,t}^m)(1 - x_{j,t}^m) \tag{6.10}$$

$$\forall\, j = 1,2..,MDR, a = j + J - MDR$$

$$\Delta^{rem}axmc_{j,a,t,t+1} = max\{Nst_{a,t} - Nst_{a,t+1}, 0\}\, y^m_{a,t} r^m_{a,t+1}(1 - y^m_{j,t+1}) \tag{6.11}$$

$$\forall\, j = 1,2..MDR, a = j + J - MDR$$

$$\Delta^{rem}_y ax_{j,a,t,t+1} = \max\{Nst_{a,t} - Nst_{a,t+1}, 0\}\, y^m_{a,t} y^m_{j,t+1} r^m_{a,t+1} \tag{6.12}$$

$$\forall\, j = 1,2..MDR, a = j + J - MDR$$

$$\Delta^{rem}_x ax_{j,a,t,t+1} = \max\{Nst_{a,t} - Nst_{a,t+1}, 0\}\, x^m_{a,t} r^m_{a,t+1} \;\; , j = 1,2..MDR, a \tag{6.13}$$

The first and second terms are the addition cost of platform and non-platform machine in the initial production period (i.e. $t=T_0$), respectively. The third and fourth terms are the addition and removal cost of platform machine type "*j*" in production periods "*t>1*", respectively. The fifth and sixth terms are the addition and removal cost of non-platform machine type "*j*" in production periods "*t>1*", respectively. The different terms within "$\Delta^{add}x_{j,t,t+1}$ ","$\Delta^{add}y_{j,t,t+1}$ ","$\Delta^{rem}x_{j,t,t+1}$ ",and "$\Delta^{rem}y_{j,t,t+1}$ " in equations (6.4), (6.5), (6.6) and (6.7), respectively can be illustrated as in subsection 5.1.4. The terms "$\Delta^{add}x_{j,t,t+1}$ ","$\Delta^{add}y_{j,t,t+1}$ ","$\Delta^{rem}x_{j,t,t+1}$ ",and "$\Delta^{rem}y_{j,t,t+1}$ " in equations (6.4), (6.5), (6.6) and (6.7) fall within two ranges; "*j=1,2,..MDR*" for modular architecture machines and "*j=MDR+1,..J-MDR*".

For the range "*j=1,2,..MDR*", in equations (6.4), (6.5), (6.6) and (6.7), the outcome is the number of modular architecture machine type "*j*" added or removed in production period "*t+1*" compared to "*t*". For the range "*j=MDR+1,...J-MDR*", in equations (6.4), (6.5), (6.6) and (6.7), the outcome is the number of integrated structure machine type "*j*" added or removed in production period "*t+1*" compared to "*t*".

The seventh and eighth terms is the cost of addition of machining axes in production period "*t+1*" to an existing platform and non-platform machine type "*j*" in production period "*t*", respectively. The terms "$\Delta_y^{add}ax_{j,t,t+1}$" and "$\Delta_x^{add}ax_{j,t,t+1}$" are the amounts of machining axis added to non-platform and platform machine type "*j*", respectively in production period "*t+1*" compared to production period "*t*". The term "$\Delta_y^{add}ax_{j,t,t+1}$ " can be illustrated with the aid of equations (6.8) and is only applied to modular architecture machines (i.e. *j=1,2…MDR*) since machining axes cannot be added to or removed from integrated structure machines. In equation (6.8), the first two terms on the right hand side refers to the amount of additional machining axes added to non-platform machine type "*j*" in production period "*t+1*" with respect to production period "*t*". The last two terms in equation (6.8) on the right hand side refers to whether an additional machining axis is added in production period "$t+1$" to an existing non-platform machine type "j". If non-platform machine type "j" is available in production period "t" (i.e. $y_{j,t}^{m}=1$) and machine type "a" is added in production period "$t+1$" (i.e. $a_{a,t+1}^{m}=1$), therefore, additional machining axis is added. In this case, machine type "j" is considered the initial configuration while machine type "a" refers to the new configuration of machine type "j" after addition of machining axis. The term "$\Delta_x^{add}ax_{j,t,t+1}$" in equation (6.9) can illustrated similar to the term "$\Delta_y^{add}ax_{j,t,t+1}$".

The ninth term refers to the cost of addition of a machine together with its machining axis in production period "$t+1$". The term "$\Delta^{add}axmc_{j,a,t,t+1}$" is defined as the number of non-platform machine type "j", together with its machining axis, added in production period "$t+1$" compared to production period "t". The term "$\Delta^{add}axmc_{j,a,t,t+1}$" is illustrated with the aid of equation (6.10) and is only applied to modular architecture machines (i.e. $j=1,2...MDR$) since machining axes cannot be added to integrated architecture machines. The first two terms on the right hand side refers to the number of machine type "a" added in period "$t+1$" with respect to production period "t". The last three terms in equation (6.10) on the right hand side refers to the whether a machine, together with its machining axis, are required in production period "$t+1$" or not. If machine type "a" is added in production period "$t+1$" (i.e. $a_{a,t+1}^{m}=1$) and machine type "j" is not available as platform machine in production period "t" (i.e. $x_{j,t}^{m}=0$) nor non-platform machine in production period "t" (i.e. $y_{j,t}^{m}=0$), therefore, machine type "j" is purchased in addition to machining axis in order to have machine type "a".

The major difference between the terms "$\Delta_y^{add}ax_{j,t,t+1}$" and "$\Delta^{add}axmc_{j,a,t,t+1}$" is the presence of non-platform machine type "j" in production period "t". For the term "$\Delta_y^{add}ax_{j,t,t+1}$" to apply in production period "$t+1$", machine type "j" should be available in production period "t" (i.e. the machining axis should be added to an already existing machine type "j"). For the term "$\Delta^{add}axmc_{j,a,t,t+1}$" to apply in production period "$t+1$", machine type "j" should not be available in production period "t" (i.e. if machine type "a" is required in period "$t+1$" but machine type "j", in which the machining axis is added to it, is not available in production period "t". Hence, the model will add machine type "j" together with machining axis in production period "$t+1$").

The tenth term refers to the cost of addition of machine type "j" with modular architecture in production period "$t+1$". The eleventh term refers to the removal cost of non-platform machine type "j" and its machining axis in production period "$t+1$" compared to production period "t". The eleventh term is only applied to modular architecture machine types (i.e. $j=1,2...MDR$) since machining axes cannot be removed from integrated architecture machine types. The term "$\Delta^{rem}axmc_{j,a,t,t+1}$" is the number of non-platform machine type "j" and its machining axis removed in production period "$t+1$" compared to production period "t". This term is illustrated with the aid of equation (6.11) and the ninth term illustrated previously.

The twelfth term is the cost of removal of machine type "j" with modular structure in production period "$t+1$". The thirteenth term refers to the cost of removal of machining axis from non-platform machine type "j" in production period "$t+1$" compared to production period "t". The thirteenth term is only applied to modular architecture machine types (i.e. $j=1,2...MDR$) since machining axes cannot be removed from integrated architecture machine types. The term "$\Delta^{rem}{}_{y}ax_{j,a,t,t+1}$" is the amount of machining axis removed from non-platform machine type "j" in production period "$t+1$" compared to production period "t". The term "$\Delta^{rem}{}_{y}ax_{j,a,t,t+1}$" is illustrated with the aid of equation (6.12). The first two terms on the right hand side refers to the number of machine type "a" removed in production period "$t+1$" with respect to production period "t". The last two terms on the right hand side in equation (6.12) refers to whether a machining axis is removed or not. If machine type "a" is removed from period "$t+1$" (i.e. $r_{a,t+1}{}^{m}=1$) and machine type "j" is required in period "$t+1$" (i.e. $y_{j,t+1}{}^{m}=1$), therefore machining axis is removed from machine type "a" in order to obtain machine type "j".

The fourteenth term refers to the cost of removal of machining axis in production period "$t+1$" compared to production period "t" from platform machine type "j". The term "$\Delta^{rem}{}_{x}ax_{j,a,t,t+1}$" is the amount of machining axis removed from platform machine type "j" in production period "$t+1$" compared to production period "t". The fourteenth term is only applied to modular architecture machine types (i.e. $j=1,2...MDR$) since machining axes cannot be removed from integrated architecture machine types. The term "$\Delta^{rem}{}_{x}ax_{j,a,t,t+1}$" is illustrated with the aid of equation (6.13). The first two terms on the right hand side refers to the number of machine type "a" removed in period "$t+1$" with respect to period "t". The last term in equation (6.13) refers to machining axis removal. If machine type "a" is available in production period "t" (i.e. $x_{a,t}{}^{m}=1$) and machine type "a" is removed from production period "$t+1$" (i.e. $r_{a,t+1}{}^{m}=1$), therefore, machining axis is removed from platform machine type "j". The fifteenth term is the cost of testing and integration and it is illustrated previously in chapter 5.

Further illustration of the different decision variables above is shown in Figure 6.2. The outer rectangle refers to the initial machine configuration without machining axis addition and the inscribed hatched rectangle refers to the machining axis added.

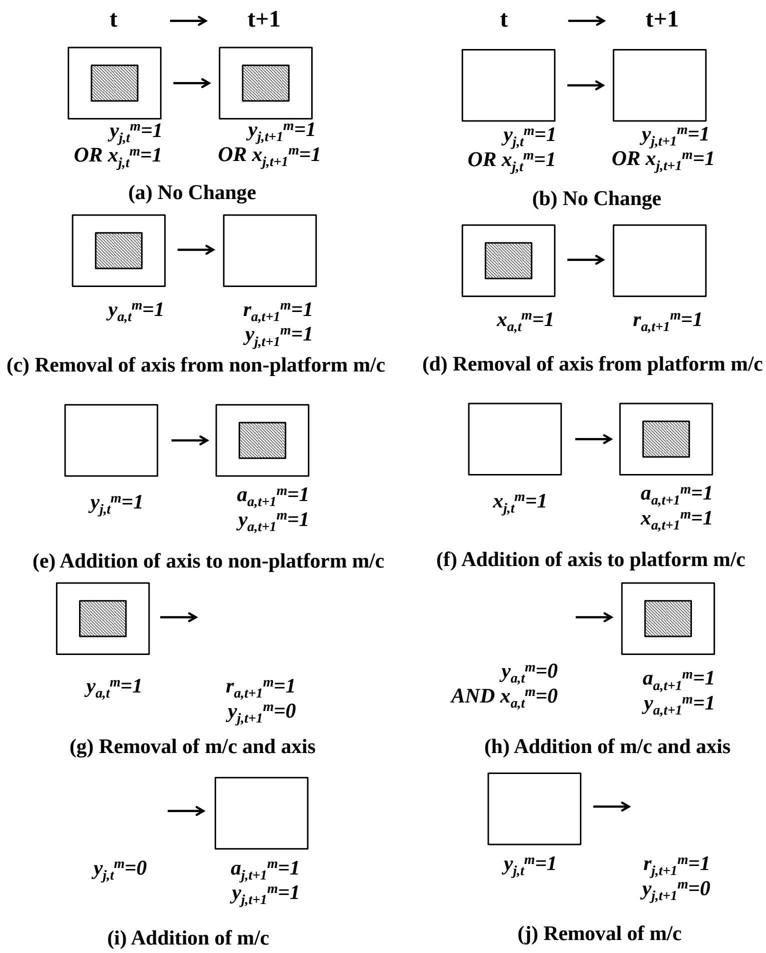


Figure 6.2 Illustration of the different decision variables in the mathematical model

6.2.5 Constraints

Constraints equations from (5.24) to (5.40) apply in this mathematical model. However, only constraint equations (5.29) and (5.30) are modified such that:

$$x_{j,t}^{m} = x_{j,t+1}^{m}, \forall t, j = 1,2,..J - MDR \quad (6.14)$$

$$y_{j,t+1}^{m} = y_{j,t}^{m} + a_{j,t+1}^{m} - r_{j,t+1}^{m}, \forall t, j = 1,2,..J - MDR \quad (6.15)$$

Constraint equation (6.14) insures that platform machine type "*j*" is available in all production periods. Constraint equation (6.15) relates the non-platform machine type "*j*" in production period "*t+1*" with the non-platform machine type "*j*" in production period "*t*" as well as the addition or removal of machine "*j*" in production period "*t+1*". The range for the index "*j=1,2,..J-MDR*" is chosen in such a manner since machine "*j*" is machine structure. Even when considering machine type "*a*", it is considered machine type "*j*" with machining axis.

In addition, two more constraint equations are introduced such that:

$$x^{m}_{j,t=T_0} = 0, j = J - MDR + 1, \ldots, J \tag{6.16}$$

$$y^{m}_{j,t=T_0} = 0, j = J - MDR + 1, \ldots, J \tag{6.17}$$

The two constraint equations (6.16) and (6.17) constrains the mathematical model to choose within the initial configuration machine types "*j=1,2..J-MDR*" in the first production period "$t=T_0$". The machining axes addition and removal takes place in the subsequent production periods "*t>1*".

6.3 Computational Verification Using Mathematical Example

An example is used to demonstrate the use of the developed mathematical model. A simple product family consisting of four product variants (*i=1,2,3,4*) and a total of four product features (*f=1,2,3,4*) and machining operations (*o=1,2,3,4*). The different product variants and their product features are given in Figure 6.3. The different input parameters for the product, features, operations and demand are given Table 6.1, Table 6.2 and Table 6.3. In Figure 6.3, the ratio between the length of hole an its diameter (L/D) determines the type machine which process these holes. According to [120], when the ratio between the length of hole and its diameter (L/D) is less than 300, deep drilling machine is used with drill gun tool. When the ratio between the length of hole and its diameter is less than 50, a drilling machine with twist drill is used.

Table 6.1: Product feature-machining operations matrix ($\gamma_{f,o}$)

		Operations 1	2	3	4
Features	*1*	1	0	0	0
	2	0	1	0	0
	3	0	0	1	0
	4	0	0	0	1

Table 6.2: Product variant-product feature matrix ($\rho_{i,f}$)

		Features 1	2	3	4
Product variants	*1*	1	0	0	0
	2	1	1	0	0
	3	1	0	1	0
	4	1	0	0	1

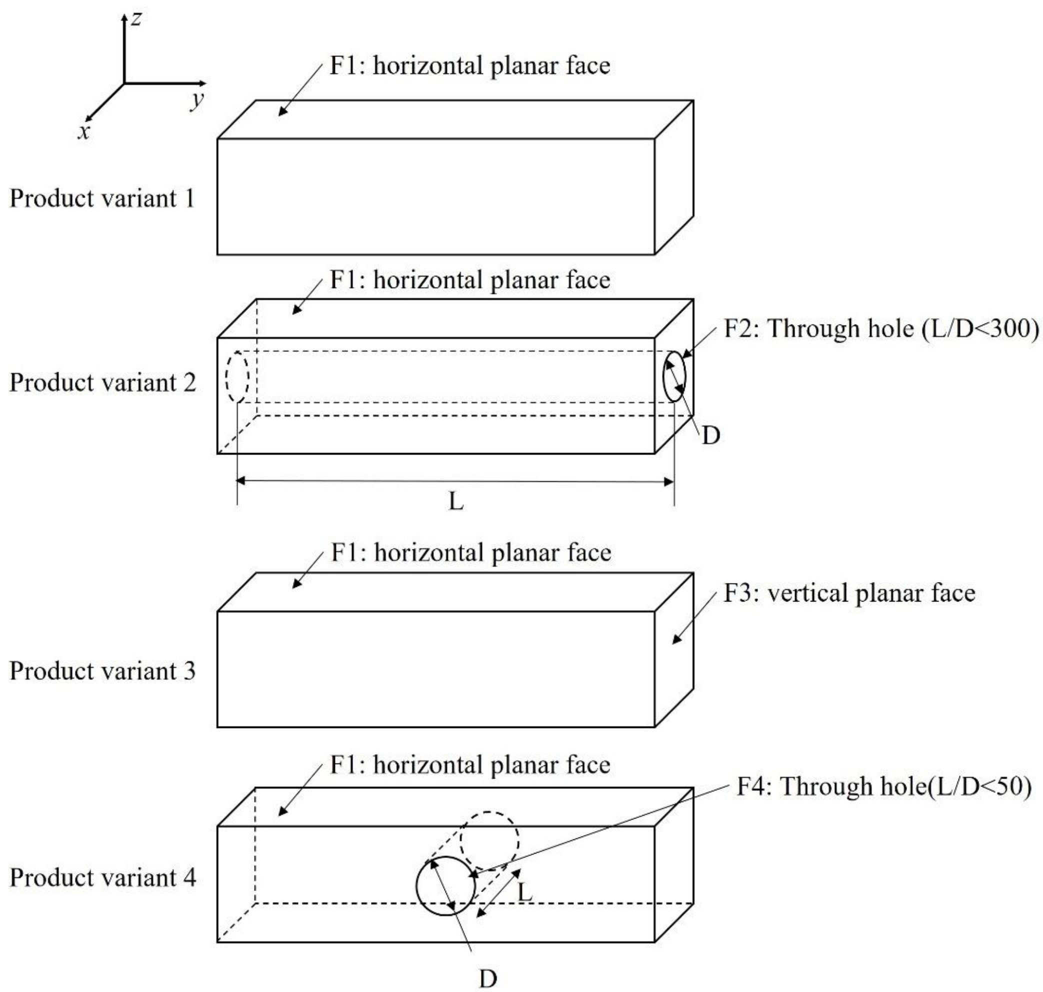


Figure 6.3 The different product variants for the numerical example and their features

Table 6.3: product variant-production period matrix ($z_{i,t}$) and product demand in each production period ($demand_{i,t}$) in units/day

		Production periods		
		1	*2*	*3*
Product variants	*1*	1(2000)	0	1(1500)
	2	0	0	0
	3	0	1(1000)	0
	4	0	1(3000)	0

The input parameter concerning the machine side is given in Table 6.4. This example consists of four machines ($j=1,2,3,4$) with two modular architecture machines ($j=1,2$). When adding two extra machining axis to 3-axis CNC machine type 1, the new configuration of the 3-axis CNC machine type 1 is changed to 5-axis CNC machine type 5. When adding machining axis to deep hole drilling machine type 2 which can drill in the y-axis direction as shown in Figure 6.3, the new configuration of deep hole drilling machine type 2 is changed to deep hole drilling machine type 6 which can drill in the x-axis direction as shown in Figure 6.3. The number of hours available per day "*NHD*" is assumed as 24 hrs.

Table 6.4: Machine-machining operations matrix ($McOp_{j,o}$), processing time of operations on machines ($ptime_{j,o}$) in seconds and purchase cost of each machine

Operations		Machines					
		1 (3-axis CNC)	*2 (Deep hole drilling machine)*	*3 (horizontal milling machine)*	*4 (horizontal milling machine)*	*5 (5-axis CNC)*	*6 (Deep hole drilling machine)*
Milling on horizontal plane	*1*	1(222)	0	0	0	1(160)	0
Deep hole drilling	*2*	0	1(132)	1(156)	1(210)	0	0
Milling on vertical plane	*3*	0	0	0	0	1(144)	0
Hole drilling	*4*	0	0	0	0	1(210)	1(186)
Purchase cost ($\$\times10^3$)		170	157	461	162	33	80

According to Table 6.4, 3-axis CNC machine type 1 is only capable of performing operation 1. On adding extra two machining axis to 3-axis CNC machine type 1, the new machine configuration of 3-axis CNC machine type 1 is changed to 5-axis CNC machine type 5 which can process operations 1, 3 and 4. In addition, deep hole drilling machine type 2 can only process operation 2 on the xz plane. On adding one extra machining axis to machine 2, the new configuration of deep hole drilling machine 2 is changed to deep hole drilling machine type 6 which can perform operation 4 on the yz plane. The main result for the mathematical example is shown in Figure 6.4.

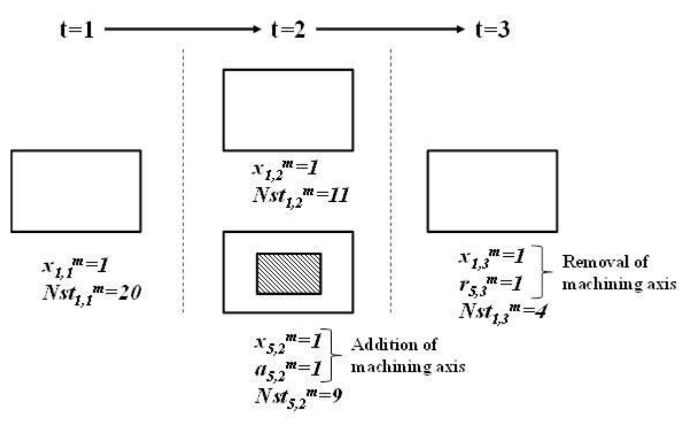


Figure 6.4 Results for the mathematical example

In production period 1, only product variant 1 is produced according to Table 6.3 Product variant 1 consists of product feature 1 (horizontal planar face) which requires machining operation 1.

According to the machine-machining operation matrix in Table 6.4, 3-axis CNC machine type 1 as well as 3-axis CNC machine type 1 with two extra machining axis added (i.e. 5-axis CNC machine type 5) possess the machining capability required to process operation 1. Since the mathematical model aims to minimize the cost, it chooses 3-axis CNC machine type 1 to process the machining operation 1 since 3-axis CNC machine type 1 initial configuration costs $170,000 while 3-axis CNC machine type 1 with two extra machining axis added (i.e. 5-axis CNC machine type 5) costs $170,000 for the addition of the machine as well as $33,000 for the machining axis purchase.

In production period 2, product variant 3 and product variant 4 are produced. Product variant 3 contains product feature 1 (horizontal planar face) which requires machining operation 1 and product feature 3 (vertical planar face) which requires machining operation 3. Product variant 4 is composed of product feature 1 (horizontal planar face) which requires machining operation 1 and product feature 4 (through hole) which requires machining operation 4. Only 5-axis CNC machine type 5 (which is 3-axis CNC machine type 1 with extra two machining axes) possess the machining capability required to perform machining operation 3 and machining operation 4. Therefore, the model adds a two extra machining axes to 3-axis CNC machine type 1 in production period 2 to change its configuration to 5-axis CNC machine type 5. In addition, 3-axis CNC machine type 1 within its initial configuration is also available in production period 2 in order to process machining operation 1.

In production period 3, product variant 1 is being produced which contains only product feature 1 (horizontal planar face) and requires machining operation 1. Two Machining axes are removed from the 5-axis CNC machine type 5 (which is 3-axis CNC machine type 1 with two extra machining axes) in production period 3 and the 3-axis CNC machine type 1 is only used in production period 3.

6.4 Case Study: Machining of cylinder blocks taken from Mitsubishi Heavy Industries

The case study applied in this chapter is taken from Mitsubishi automotive cylinder block manufacturer [112]. The relationship between the product variants and product features is taken from Table 5.1 and the relationship between product feature and machining operation is taken from Table 5.2, respectively. The rest of the input parameter are taken from Table 6.5 and Table 6.6. In this case study, it is required to synthesize the manufacturing system required in the different production periods taking into consideration the machine and system level cost of change based on co-platforming. In addition, the effect of maintaining a common core of machines within a manufacturing system on the investment cost will be investigated.

Table 6.5: Product variant-product features matrix and demand of each product in each production period (units/day)

		Product features									Production periods		
		1	2	3	4	5	6	7	8	9	1	2	3
Product variants	4A-GEU 1587cc	1	0	1	0	0	1	0	1	1	0	0	0
	711 M 1691 cc	1	0	1	0	1	0	0	1	1	500	0	0
	QR20DE 1998 cc	1	0	1	0	0	0	1	1	0	800	0	0
	Mopar 2360 cc	1	0	1	0	0	1	1	1	1	0	0	0
	Cosworth 2935 cc	0	1	0	1	0	1	1	1	0	0	800	0
	Buick215 2900 cc	0	1	0	1	1	1	1	1	0	0	900	0
	Cyclone 3496 cc	0	1	0	1	0	1	0	1	1	0	0	400
	LN3 3800 cc	0	1	0	1	1	1	1	1	1	0	0	500

Table 6.6: Machine-machining operation matrix

OP ID	KX50M (CNC-M1) Config-01	KX10i (CNC-M2) Config-01	KXG45-14 (CNC-M3)	K2X10 (CNC-M4)	KX50L (CNC-M5)	Vertical boring machine (M6)	Horizontal milling machine (M7)	LBM2500 (Hori. Honing-M8)	VCB1500V (Verti. Honing-M9)	LBM1500 (Hori.Honing-M10)	KX50M (CNC-M1) Config-02	KX10i (CNC-M2) Config-02
OP01	222	156	234	156	240	0	150	0	0	0	222	156
OP02	138	0	0	210	132	0	0	0	0	0	0	132
OP03	132	0	288	0	144	0	0	0	0	0	0	180
OP04	216	0	0	0	210	0	0	0	0	0	0	126
OP05	162	0	0	162	294	216	0	0	0	0	0	180
OP06	132	0	0	0	258	0	0	0	282	0	0	144
OP07	294	0	0	0	216	0	0	0	0	0	0	240
OP08	0	0	0	0	240	0	0	0	240	0	0	0
OP09	222	0	0	0	282	0	0	0	0	0	0	282
OP10	0	0	0	0	294	0	0	282	0	0	0	0
OP11	270	0	0	0	264	0	0	0	0	0	0	150
OP12	0	0	0	0	0	0	0	144	0	186	0	0
OP13	246	0	0	0	150	0	0	0	0	0	0	246
OP14	216	0	0	0	138	0	0	0	0	0	0	168
OP15	198	0	0	0	222	0	0	0	0	0	0	126
OP16	288	0	0	0	150	0	0	0	0	0	0	234
OP17	180	0	0	0	120	0	0	0	0	0	0	126
OP18	210	0	0	0	186	0	0	0	0	0	0	276
Cost (x10^3$)	270	157	461	162	336	80	10	100	50	80	30	30
Working envelop ($\times 10^6$ mm^3)	2626	393	6435	460	3939	-	-	-	-	-	2626	393

In this case study, it is required to synthesize the manufacturing system required in the different production periods (I-4 in production period 1, V-8 in production period 2 and V-6 in production period 3) taking into consideration the machine and system level cost of change based on co-platforming. In addition, the effect of maintaining a common core of machines within a manufacturing system on the investment cost will be investigated. Salvage cost of machines is assumed to be 1% of the purchase cost [18]. Base cost of integration and testing is calculated as $400 (fifteenth term in equation 21) [18]. Available one time budget is $50,000,000. Number of available hours per day “NHD” is 21hrs. In this case study, it is assumed that two machines are of modular structure (i.e *MDR=2*) and eight machines are of integrated structure. Therefore, according to Table 6.6, machine type 11 is composed of machine type 1 with machining axis added. Similarly, machine type 12 is composed of machine type 2 with machining axis added. Machines type 2 to 10 are of integrated architecture.

6.5 Results and Discussion

The mathematical programming model is written using AMPL (http://ampl.com/) and solved by Gurobi Mixed Integer Linear Programming (MILP) in NEOS in 1807.95 seconds (for 3 production periods, 8 product variants, 18 operations, 9 features and 12 machines). The optimum value for the objective function (initial investment cost in machines, addition and removal cost of machines and machining axes as well as integration and testing cost) equation (6.1) is $8,504,000.

Based on the products produced in each production period, the developed model determines the product platform and non-platform features. The product platform feature in these cylinder blocks is product platform feature 8 (cylinder side wall planar face) due to its presence in the I-4, V-8 and V-6 cylinder blocks produced during the considered three different production periods. The results obtained using the co-platforming optimization model are shown in Figure 6.5. The 5-axis CNC machines type 1 and 5 are platform machines since they possess the machining capabilities required to process the roughing and finishing machining operations for the product platform feature 8 (cylinder side wall planar face). These two machines are available in production periods 1, 2 and 3. These two machines do not require addition of further capabilities such as machining axes.

The 3-axis CNC machine 2 is selected in production period 1 in order to process the rough cutting operations for product feature 1 (horizontal deck planar face). However, due to the introduction of V-8 and V-6 in production periods 2 and 3, the 3 machining axis capability cannot process the intricate product features in the V-6 and V-8 such as product feature 2 (inclined deck planar face) and product feature 4 (hole on inclined plane). For this reason, two more machining axes are added to the existing 3-axis CNC machine type 2 available in production period 1 and changed to the 5-axis CNC machine type 12 in production period 2. It is worth noting that the base structure of 3-axis CNC machine type 2 remains unaltered in the three production periods, however adding extra two machining axes is required in production periods 2 and 3 in order to change the configuration of 3-axis CNC machine type 2 in production period 1 into 5-axis CNC machine type 12. The 3-axis CNC machine type 2 is considered a platform machine since it possesses the machining capability required to process the roughing operation of product platform feature F8 (cylinder side wall planar face).

Horizontal honing machine type 8 is a non-platform machine since it is does not possess the machining capability required to process any product platform features. Machine type 8 is used to process finish cutting operation for the non-platform product features 5 (camshaft bore) and 6 (crankshaft bore) in production period 2 and production period 3. This machine is not required in production period 1.

Finally, vertical honing machine type 9 is a non-platform machine since it does not possess the machining capability required to process any of the product platform features. Machine type 9 is used to process the finish cutting operation for the non-platform product features 3 (cylinder bore on horizontal surface) in production period 1 and non-platform product feature 4 (cylinder bore inclined surface) in production period 2. Machine type 9 is not required in production period 3 and for this reason, it is removed from the manufacturing system in production period 3.

In production period 1, machine type 1 is used to process the finish cutting operations for product feature 1 (horizontal deck planar face) and the rough cutting operations for product features 3 (cylinder bore on horizontal surface), 5 (camshaft bore) and 8 (cylinder side wall planar face) within product variant 2 (711M1691cc). In addition, in production period 1, machine type 1 is used to process the rough cutting operations for product features 3 (cylinder bore on horizontal surface) and finish cutting operations for product feature 1 (horizontal deck planar face) within product variant 3 (QR20DE1998cc). The demand for product variant 2 is 500units/day and the demand for product variant 3 is 800units/day. According to the processing time for each product feature in Table 6.6 and the demand for each product variant, the number of machine types 1 is 7 in production period 1, which is calculated using equation (5.40) and illustrated as shown in Figure 6.6.

In production period 2, machine type 1 is used to process the rough cutting operations for product features 2 (inclined deck planar face) and 8 (cylinder side wall planar face) within product variant 5 (Cosworth2935cc) as well as the rough cutting operations for product features 2 (inclined deck planar face) and 5 (camshaft bore) within product variant 6 (Buick2152900cc). The demand for product variant 5 is 800units/day and the demand for product variant 6 is 900units/day. According to the processing time for each product feature in Table 6.6 and the demand for each product variant, the number of machine type 1 is 7 in production period 2 as calculated using equation (5.40) and illustrated as shown in Figure 6.6. Although the total demand in production period 2 exceeds that in production period 1, the number of machine type 1 does not change (7 in both production periods). This is due to the number of operations being processed in production period 1 (four product features for variant 2 and two product features for variant 3) which exceeds the number of operations being processed in production period 2 (two product features for variant 5 and two product features for variant 6). However, the number of machine type 1 is reduced to 6 machines in production period 3 which can be attributed to the reduction in demand in production period 3 as given in Table 6.5. The rest of results for the number of machine types are shown in Figure 6.5.

The effect of maintaining a common core of platform machines within the different production periods on the objective function equation (6.1) is determined taking into consideration the system and machine level change (in chapter 5, only the system level was considered). The plot in Figure 6.7 shows the effect of "α_{av}" on the x-axis, which is the average value of "α_t^m" in production periods 1, 2 and 3 and the objective function in equation (6.1) on the y-axis. The steps for plotting the graph in Figure 6.7 is the same as the graph plotting in Figure 5.6 by varying the value of "α_t^m" from 0 to 1 and capturing the corresponding optimum cost objective function.

At "α_{av}" lies between 0 and 1, a group of common core or platform machines are maintained. In this bandwidth, the minimum cost of $8,504,000 is achieved at a value of "α_{av}" equal to 0.47. Based on this case study, it can be concluded from Figure 6.7 that co-platforming can lead to cost savings relative to the two extreme cases where "$\alpha_{av}=0$" corresponding to the use of different manufacturing system (in which there is no platform machines) in each production period and "$\alpha_{av}=1$" corresponding to the use flexible manufacturing system when considering the change in machine level and system level.

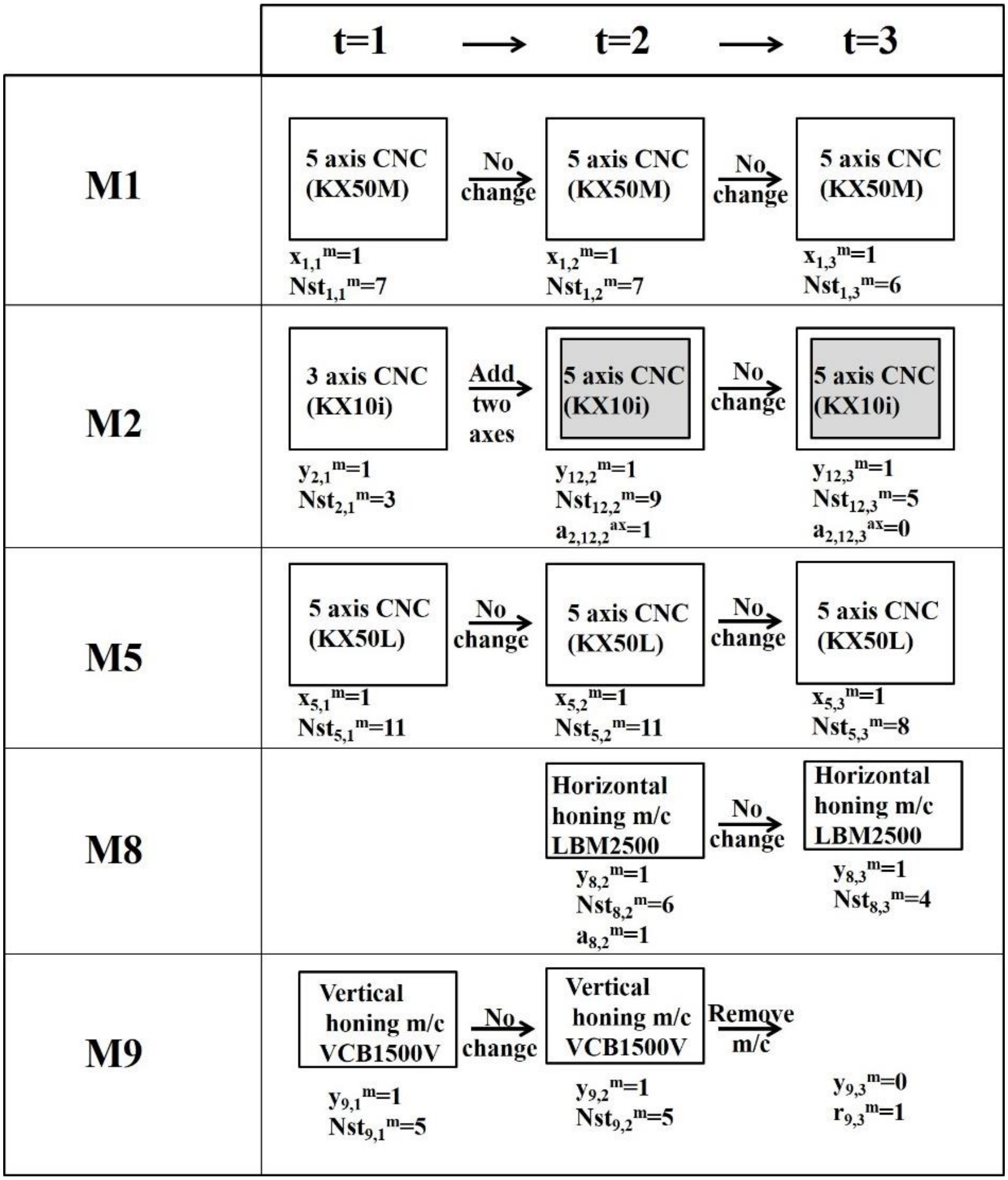


Figure 6.5 Illustration of Mathematical model results showing the different machine types in each production period as well as the added/removed machining axes

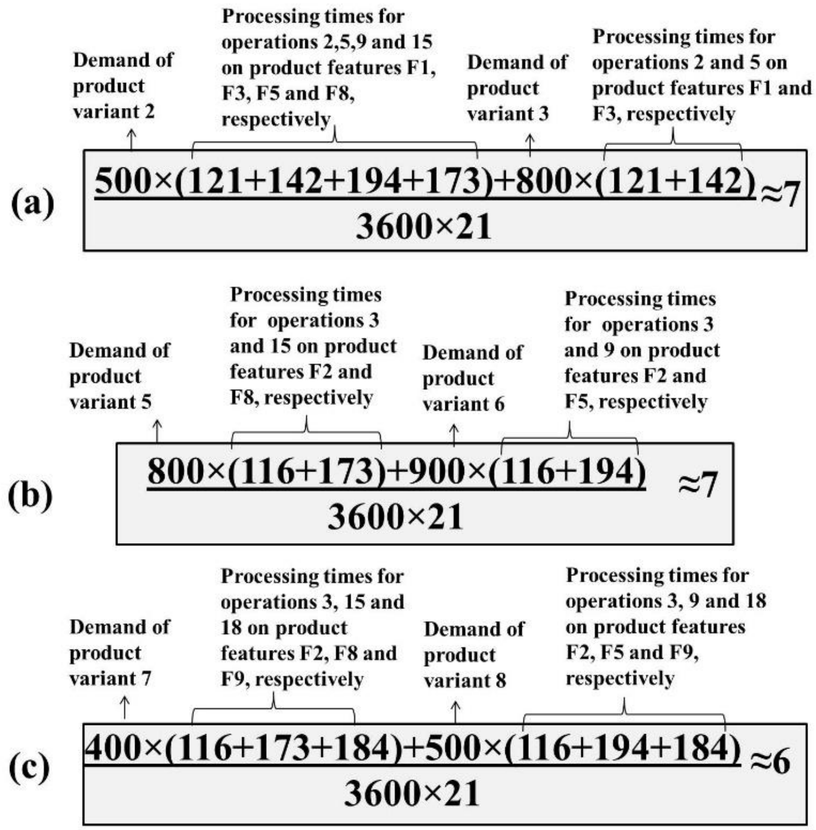


Figure 6.6 Illustration of calculation of number of machines in each production period applied to machine M1-KX50M (a) production period 1, (b) production period 2 and (c) production period 3

6.6 Limitations

The introduced mathematical programming model has some limitations on the physical level as well as on the computational level. In the physical level, the mathematical model in this form is applied mainly on automated manufacturing systems. However, the model is flexible and can be extended to take into consideration manual manufacturing systems by taking into consideration worker related types of capabilities that can be performed on the product by the worker which includes handheld tools, setups, learning curve…etc. In addition, the model addressed in this dissertation is mainly applied on machine tools as manufacturing system components. Other manufacturing system components such as buffers and material handling units can be taken into consideration within the model with minor modifications. On the computational level, various scenarios have been applied as indicated in Table 6.7.

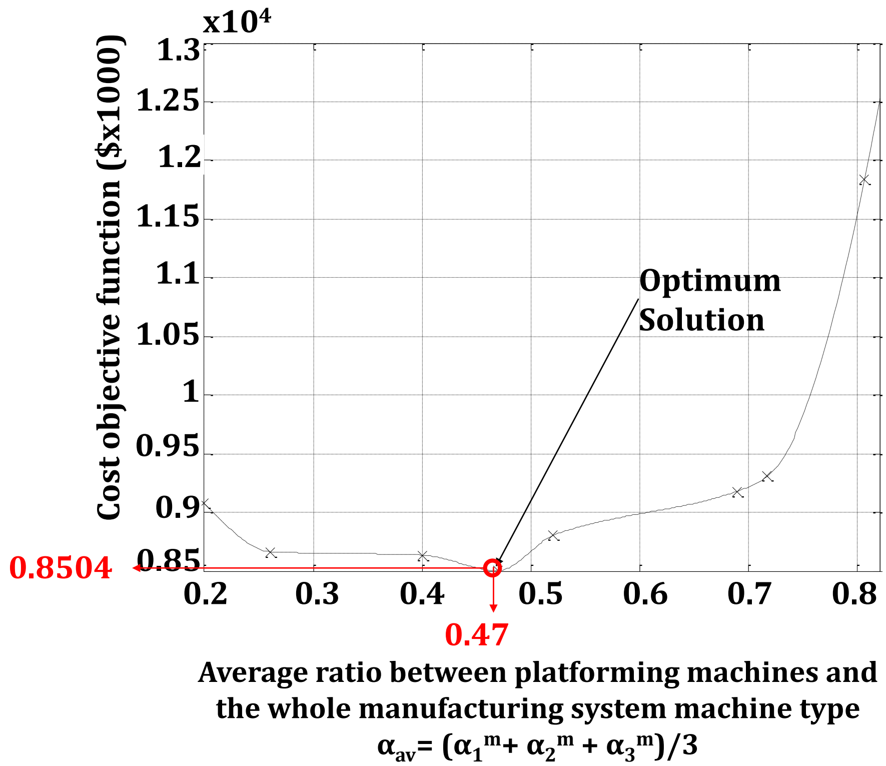


Figure 6.7 Effect of maintaining a common platform machines on the cost within the system level and machine level

Table 6.7: Computational time for different scenarios

Number of					Computational time (sec)	Solution status
Periods	Products	Operations	Components or features	Machines		
3	4	4	4	6	<1	Optimal solution
2	8	18	9	12	182.94	Optimal solution
2	4	30	20	10	1057.66	Optimal solution
3	8	18	9	12	1807.95	Optimal solution
2	4	54	20	12	N/A	No solution

For small problem sizes such as the first scenario, the computational time is less than 1 second. The computational time increases to 182.94 seconds when solving a problem size of periods=2, products=8, operations=18, features=9 and machines=12. The computational time increases to 1057.66 seconds when solving a problem size of periods=2, products=4, operations=30, features=20 and machines=10. When solving a problem size of periods=3, products=8, operations=18, features=9 and machines=12, computational time increases to 1807.95 seconds. When increasing the number of operations to 54 as seen in the last scenario, the mathematical model is not solved. Hence, it is proposed to reformulate the model and solve it through metaheuristics methods such as genetic algorithm, stimulated annealing or particle swarm. However, this approach will not guarantee a global optimum solution.

6.7 Conclusion

This chapter extends the co-platforming strategy to a new level where changes at the machine level (i.e. addition or removal of machining axes, change of setup) and at the system level (i.e. addition or removal of machines) are considered. This chapter is focused functional synthesis of the manufacturing systems based on co-platforming taking into consideration the machine level and system level. This objective is achieved by using a mixed integer linear programming model to minimize the total machine level investment cost, including initial investment cost in machines, cost of adding and removing machines and machine axes as well as the cost of their subsequent integration and testing, when switching from one product family to another.

The mathematical model is applied to a simple numerical example for verification purposes. In addition, it is applied to a case study based on data from an automotive cylinder block manufacturer. It determines the required types and numbers of each machine. It also selects three platform machines two of which are of modular architecture and the third is of and integrated architecture. The modular architecture machine starts with an initial configuration with limited number of machining axes (e.g. 3 machining axis) such as 3-axis CNC machine type 2 in the case study and according to the change in demand and functionality of the product, extra machining axes (e.g. 5-axis machining axis) such as 5-axis CNC machine type 12 are added.

Finally, the savings in change cost when applying the co-platforming methodology on the machine and system levels has been investigated. It was demonstrated that through co-platforming, the investment cost is reduced when maintaining a common core of machines (platform) in the different production periods compared to the investment cost for the same products and production periods without system platform. The comparison has been done as shown in Figure 6.7. The ratio the platform machine types to the sum of platform and non-platform machine types has been altered. When this ratio is zero, it indicates that there are no platform machines. When this ratio is one, it indicates that all machines are platform.

CHAPTER 7. PHYSICAL SYNTHESIS OF MANUFACTURING SYSTEMS USING CO-PLATFORMING

7.1 Overview

This chapter introduces a mathematical mixed integer linear programming model for the physical synthesis of manufacturing systems (i.e. manufacturing system configuration) based on the co-platforming strategy. The manufacturing system configuration problem involves determining the number of stages, type of machines in each stage and the number of identical machines in each stage [46]. The objective function is to minimize the overall investment cost of machines within the manufacturing system. The mathematical model is implemented on a case study from an automotive cylinder block manufacturer.

The IDEF0 of the mathematical model proposed in this chapter is shown in Figure 7.1. The main output from the proposed model is the number and type of each machine in each stage as well as the number of stages. Additional auxiliary outputs from the model also includes the platform and non-platform machines which are already obtained in the mathematical model in chapter 5.

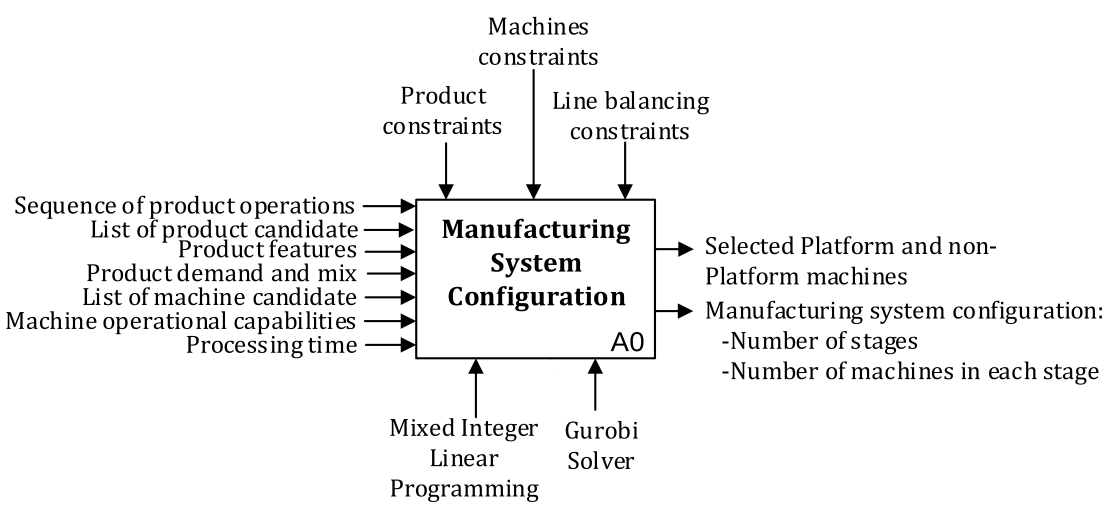


Figure 7.1 IDEF0 of the mathematical model for physical synthesis of the manufacturing system

7.2 Model Development

7.2.1 Input Parameters

The list of input parameters is given as:

$$z_{i,t} = \begin{cases} 1, if\ product\ i\ is\ available\ in\ production\ period\ t \\ 0, otherwise \end{cases} \quad (7.1)$$

$$\rho_{i,f} = \begin{cases} 1, if\ feature\ f\ is\ available\ in\ product\ variant\ i \\ 0, otherwise \end{cases} \quad (7.2)$$

$$\gamma_{f,o} = \begin{cases} 1, if\ operation\ o\ is\ required\ by\ product\ feature\ f \\ 0, otherwise \end{cases} \quad (7.3)$$

$$McOp_{j,o} = \begin{cases} 1, if\ machine\ j\ can\ perform\ operation\ o \\ 0, otherwise \end{cases} \quad (7.4)$$

$$prec_{i,o1,o2} = \begin{cases} 1, if\ operation\ o1\ preceeds\ operation\ o2\ within\ product\ variant\ i \\ 0, otherwise \end{cases} \quad (7.5)$$

$$purcost_j: Purchase\ cost\ of\ machine\ type\ j \quad (7.6)$$

$$sellcost_j: Salvage\ cost\ of\ machine\ type\ j \quad (7.7)$$

$$ptime_{o,j}: Processing\ time\ of\ operation\ o\ on\ machine\ j \quad (7.8)$$

$$demand_{i,t}: Demand\ of\ product\ variant\ i\ in\ production\ period\ t \quad (7.9)$$

7.2.2 Decision Variables

The list of decision variables are:

$$x_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ a\ platform\ machine\ in\ production\ period\ t \\ 0, otherwise \end{cases} \quad (7.10)$$

$$y_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ a\ non\ platform\ machine\ in\ production\ period\ t \\ 0, otherwise \end{cases} \quad (7.11)$$

$$a_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ added\ as\ non\ platform\ machine\ in\ prodution\ period\ t \\ 0, otherwise \end{cases} \quad (7.12)$$

$$r_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ removed\ from\ non\ platform\ machines\ in \\ \quad production\ period\ t \\ 0, otherwise \end{cases} \quad (7.13)$$

$$x^{p}_{f,t} = \begin{cases} 1, if\ product\ feature\ f\ is\ a\ product\ platform\ feature\ in \\ \quad production\ period\ t \\ 0, otherwise \end{cases} \tag{7.14}$$

$$y^{p}_{f.t} = \begin{cases} 1, if\ product\ feature\ f\ is\ non-platform\ product\ feature \\ \quad in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{7.15}$$

$$\varphi_{i,j,o,f,t} = \begin{cases} 1, if\ operation\ o\ required\ for\ product\ feature\ f\ in\ product \\ \quad variant\ i\ in\ production\ period\ t\ is\ assigned\ to\ machine\ j \\ 0, otherwise \end{cases} \tag{7.16}$$

$$\psi_{o,f,t} = \begin{cases} 1, if\ product\ feature\ f, which\ is\ available\ within\ all\ product \\ \quad variants, requires\ operation\ o\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{7.17}$$

$$\varepsilon_{f,t} = \begin{cases} 1, if\ product\ feature\ f\ is\ available\ in\ all\ product\ produced\ in \\ \quad production\ period\ t \\ 0, otherwise \end{cases} \tag{7.18}$$

$$\delta_{f,t} = \begin{cases} 1, if\ product\ feature\ f\ is\ available\ in\ at\ least\ one\ product\ variant \\ \quad in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{7.19}$$

$$\sigma_{o,f} = \begin{cases} 1, if\ operation\ o\ required\ by\ product\ feature\ f\ is\ available\ in\ all \\ \quad production\ periods \\ 0, otherwise \end{cases} \tag{7.20}$$

$$\vartheta_{i,j,o,f,l,t} = \begin{cases} 1, if\ operation\ o\ for\ product\ feature\ f\ in\ product\ variant\ i\ in \\ \quad production\ period\ t\ is\ assigned\ to\ machine\ j\ within\ stage\ l \\ 0, otherwise \end{cases} \tag{7.21}$$

$$opst_{i,j,o,l,t} = \begin{cases} 1, if\ operation\ o\ in\ product\ variant\ i\ in\ production\ period\ t \\ \quad is\ assigned\ to\ machine\ j\ within\ stage\ l \\ 0, otherwise \end{cases} \tag{7.22}$$

$$Nst_{j,t}: Total\ number\ of\ machine\ type\ j\ in\ production\ period\ t \tag{7.23}$$

$$nst_{j,l,t}: Number\ of\ machine\ type\ j\ in\ stage\ l\ in\ production\ period\ t \tag{7.24}$$

7.2.3 Constants and Indices

The model contains two constants, namely "*M*" which is a large value number and "ϵ" which is small value number larger than 0 and less than 1 (e.g. 0.1) which are used for the same purpose as illustrated in chapter 5. The constant "T_0" is the initial production period ($T_0=1$). In addition, the model contains a number of sets, namely:

F [1,...,s,...], [1,...,ŝ,...], [1,...,q,...], [1,...,f,...] = set of product features

J [1,...,a,...], [1,...,b,...], [1,...,b̂,...], [1,...,j,...] = set of machines

O [1,...,o,...], O [1,...,o1,...], O [1,...,o2,...] = set of operations

T [1,...,t,...] = set of production periods

I [1,...,i,...] = set of product variants

L [1,...,l,...], [1,...,l1,...] , [1,...,l2,...] = set of manufacturing stages

7.2.4 Objective function

The objective function equation (7.25) is related to the investment cost in manufacturing system which includes the machines' addition and removal as well as integration and testing cost. The first, second, third, fourth, fifth and sixth terms in equation (7.25) are similar to the corresponding terms in (5.21) and hence, illustration of these terms will not be discussed in this chapter.

$Minimize$:

$$
\begin{aligned}
&\sum_{j=1}^{J} purcost_j Nst_{j,t=T_0} x_{j,t=T_0}^{m} \\
&+\sum_{j=1}^{J} purcost_j Nst_{j,t=T_0} y_{j,t=T_0}^{m} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J} \max(0, Nst_{j,t+1} - Nst_{j,t}) purcost_j x_{j,t+1}^{m} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J} \min(0, Nst_{j,t+1} - Nst_{j,t}) sellcost_j x_{j,t}^{m} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J} \max(0, Nst_{j,t+1} - Nst_{j,t}) purcost_j y_{j,t+1}^{m} \\
&+\sum_{t=1}^{T}\sum_{j=1}^{J} \min(0, Nst_{j,t+1} - Nst_{j,t}) sellcost_j y_{j,t}^{m} \\
&+\sum_{t=1}^{T} \frac{A_{0,t}^{m} B^{m}}{I_0^{m} \alpha_t^{m}}
\begin{bmatrix}
\sum_{b=1}^{J} \sum_{\substack{\hat{b}=1 \\ |l1-l2|=1}}^{J} st_{b,l1,t} st_{\hat{b},l2,t} d^{f_{b,\hat{b}}-1}\, y_{\hat{b},t}^{m} r_{b,t}^{m} \\
+\sum_{b=1}^{J} \sum_{\substack{\hat{b}=1 \\ |l1-l2|=1}}^{J} st_{b,l1,t} st_{\hat{b},l2,t} d^{f_{b,\hat{b}}-1}\, y_{\hat{b},t}^{m} a_{b,t}^{m} \\
+\sum_{a=1}^{J} \sum_{\substack{b=1 \\ |l1-l2|=1}}^{J} st_{a,l1,t} st_{b,l2,t} d^{f_{a,b}-1}\, x_{b,t}^{m} r_{a,t}^{m} \\
+\sum_{a=1}^{J} \sum_{\substack{b=1 \\ |l1-l2|=1}}^{J} st_{a,l1,t} st_{b,l2,t} d^{f_{a,b}-1}\, x_{b,t}^{m} a_{a,t}^{m}
\end{bmatrix} \\
&+1000 \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} \left| st_{j,l,t+1} - st_{j,l,t} \right| \\
&+10 \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} nst_{j,l,t}
\end{aligned}
\tag{7.25}
$$

The seventh term is the integration and testing cost of adding non-platform machines to the existing platform machines. The different parameter within the seventh term in equation (7.25) are illustrated as in subsection 5.2.4.

The term "$\sum_a \sum_b st_{a,l1,t} st_{b,l2,t} d^{f_{a,b}-1} x_{b,t}^m r_{a,t}^m$" is considered in order to illustrate the seventh term in equation (7.25). The term "$st_{b,l2,t}$" is a decision variable which equals to 1 if machine "*b*" is at stage "*l2*" in production period "*t*" and 1 otherwise. The condition "|*l1*-*l2*|=*1*" insures that machine type "*a*" is either downstream to machine type "*b*" or upstream to machine type "*b*". The multiplication of the terms "$st_{a,l1,t}$" and "$st_{b,l2,t}$" with the condition "|*l1*-*l2*|=*1*" is equal to 1 if machines type "*a*" and "*b*" are in two consecutive stages. An integration and testing cost will be incurred if non-platform machine type "*a*" is removed from the manufacturing system in production period "*t*" (i.e. $r_{a,t}^m$=1) and at the same time, platform machine type "*b*" is available within the manufacturing system in production period "*t*" (i.e. $x_{b,t}^m$=1) and machines type "*a*" and "*b*" are in two consecutive stages (i.e. $st_{a,l1,t} \times st_{b,l2,t}$ =1 where |*l1*-*l2*|=*1*). Therefore, an integration and testing cost is incurred. The eighth term adds a penalty value whenever a stage is required in period "*t+1*"compared to period "*t*".

The eighth term is a penalty term to minimize the number of stages in each production period (i.e. $st_{j,l,t+1}$) compared to the preceding production period (i.e. $st_{j,l,t}$) in order to encourage using stages in certain production period similar to the preceding production period, hence, reducing the cost of change. The ninth term applies a penalty to the number of machines within all stages the in order to insure that only the exact number of machines required are selected when synthesizing the manufacturing system. The eighth and ninth terms are not part of the cost, however, they are penalty terms used during optimization. The rest of the design variables and parameters in equation (7.25) are defined as:

$$\alpha_t^m = \frac{\sum_{j=1}^{J} x_{j,t}^m}{\sum_{j=1}^{J} x_{j,t}^m + \sum_{j=1}^{J} y_{j,t}^m}, \forall t \quad (7.26)$$

$$I_0^m = \sum_{j=1}^{J} purcost_j Nst_{j,t} x_{j,t}^m \;, t = T_0 = 1 \quad (7.27)$$

7.2.5 Constraints

This section is concerned with the constraints for the product and manufacturing system side. Several constraints concerning the product and system side are introduced in this subsection. Constraint equations (7.28) to (7.44) are the same as the constraints sets in the mathematical model in chapter 5 and accordingly, the illustration of the constraints will not be duplicated. However, several new constraints sets will be considered in this chapter.

$$a_{j,t+1}^m \le \sum_{i=1}^{I} \sum_{o=1}^{O} \sum_{f=1}^{F} \varphi_{i,j,o,f,t+1} (1 - y_{j,t}^m)(1 - x_{j,t}^m) \le M a_{j,t+1}^m, \forall j, t \quad (7.28)$$

$$r_{j,t+1}^{m} \le \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{f=1}^{F} y_{j,t}^{m}(1-\varphi_{i,j,o,f,t+1}) \le Mr_{j,t+1}^{m}\ \forall j,t \tag{7.29}$$

$$M\sigma_{o,f} - M + 1 \le 1 - T + \sum_{t=1}^{T}\psi_{o,f,t} \le (1-\epsilon)\left(1-\sigma_{o,f}\right) + \sigma_{o,f}, \forall o,f \tag{7.30}$$

$$x_{j,t}^{m} \le \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{f=1}^{F}\varphi_{i,j,o,f,t}\sigma_{o,f} \le Mx_{j,t}^{m}, \forall j,t \tag{7.31}$$

$$a_{j,t}^{m} + r_{j,t}^{m} \le 1, \forall j,t \tag{7.32}$$

$$x_{j,t}^{m} = x_{j,t+1}^{m}, \forall j,t \tag{7.33}$$

$$x_{j,t}^{m} + y_{j,t}^{m} \le 1, \forall j,t \tag{7.34}$$

$$y_{j,t+1}^{m} = y_{j,t}^{m} + a_{j,t+1}^{m} - r_{j,t+1}^{m}, \forall j,t \tag{7.35}$$

$$M\psi_{o,f,t} - M + 1 \le 1 + \left(\sum_{i=1}^{I} z_{i,t}\gamma_{f,o}\rho_{i,f} - \sum_{i=1}^{I} z_{i,t}\right) \le (1-\epsilon)\left(1-\psi_{o,f,t}\right) + \psi_{o,f,t}, \forall t,f,o \tag{7.36}$$

$$M\varepsilon_{f,t} - M + 1 \le 1 + \left(\sum_{i=1}^{I} z_{i,t}\rho_{i,f} - \sum_{i=1}^{I} z_{i,t}\right) \le (1-\epsilon)\left(1-\varepsilon_{f,t}\right) + \varepsilon_{f,t}, \forall f,t \tag{7.37}$$

$$Mx_{f,t=T_0}^{p} - M + 1 \le 1 + \left(\sum_{t=1}^{T}\varepsilon_{f,t} - T\right) \le (1-\epsilon)\left(1 - x_{f,t=T_0}^{p}\right) + x_{f,t=T_0}^{p}, \forall f,t \tag{7.38}$$

$$\delta_{f,t} \le \sum_{i=1}^{I} z_{i,t}\rho_{i,f} \le M\delta_{f,t}, \forall f,t \tag{7.39}$$

$$\left(x_{f,t}^{p} + y_{f,t}^{p}\right) = \delta_{f,t}, \forall f,t \tag{7.40}$$

$$x_{f,t}^{p} = x_{f,t+1}^{p}, \forall p,t \tag{7.41}$$

$$\sum_{j=1}^{J}\varphi_{i,j,o,f,t} = z_{i,t}\rho_{i,f}\gamma_{f,o}, \forall\ i,o,f,t \tag{7.42}$$

$$\varphi_{i,j,o,f,t} = z_{i,t}\rho_{i,f}\gamma_{f,o}McOp_{j,o}\mu_{i,j,o,f,t}\left(x_{j,t}^{m} + y_{j,t}^{m}\right), \forall\ i,j,o,f,t \tag{7.43}$$

$$\sum_{j=1}^{J}\mu_{i,j,o,f,t} = 1, \forall\ i,o,f,t \tag{7.44}$$

Constraint equation (7.45) is related to line balancing which restrains the number of each machine type "*j*" in stage "*l*" according to the product demand.

$$\sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{f=1}^{F} demand_{i,t}\times ptime_{o,j}\times\vartheta_{i,j,o,f,l,t} \le 3600\times NHD\times\left(x_{j,t}^{m} + y_{j,t}^{m}\right)nst_{j,l,t}, \forall i,j,t,l \tag{7.45}$$

Constraint equation (7.46) requires that the total number of machine type "*j*" is the summation of machine type "*j*" in each stage.

$$\sum_{l=1}^{L} nst_{j,l,t} = Nst_{j,t}, \forall j, t \tag{7.46}$$

Constraint equation (7.47) restrains the maximum number of machines in each stage according to the area of the layout.

$$nst_{j,l,t} \leq n_{max}, \forall j, l, t \tag{7.47}$$

Where the constant "n_{max}" is the total number of identical machines that can be inserted in one stage. This value is constrained by the facility layout. Constraint equation (7.48) is concerned with assigning operation "*o*" required to produce feature "*f*" within product variant "*i*" to machine type "*j*" to only one stage.

$$\sum_{l=1}^{L} \vartheta_{i,j,o,f,l,t} = \varphi_{i,j,o,f,t}, \forall j, t \tag{7.48}$$

Constraint equation (7.49) is concerned with defining the decision variable "$opst_{i,j,o,l,t}$".

$$opst_{i,j,o,l,t} \leq \sum_{f=1}^{F} \vartheta_{i,j,o,f,l,t} \leq M \ \ opst_{i,j,o,l,t}, \forall j, t \tag{7.49}$$

Constraint equation (7.50) states if at least one operation "*o*" required for product feature "*f*" in product variant "*i*" is assigned to machine "*j*" in stage "*l*" (i.e. $\upsilon_{i,j,o,f,l,t}=1$), therefore, machine type "*j*" is assigned to stage "*l*" in production period "*t*" (i.e. $st_{j,l,t}=1$).

$$st_{j,l,t} \leq \sum_{i=1}^{I} \sum_{o=1}^{O} \sum_{f=1}^{F} \vartheta_{i,j,o,f,l,t} \leq M \ \ st_{j,l,t}, \forall j, l, t \tag{7.50}$$

Constraint equation (7.51) represents the precedence constraint. This constraint is illustrated as follows; if operation "*o1*", which is required for product variant "*i*" and is processed on machine "*j*" in production period "*t*", precedes operation "*o2*", therefore, operation "*o1*" must be performed within an earlier (or at least same) stage than operation "*o2*".

$$\sum_{j=1}^{J} \sum_{l=1}^{L} l \times opst_{i,j,o1,l,t} \times prec_{i,o1,o2} \leq \sum_{j=1}^{J} \sum_{l=1}^{L} l \times opst_{i,j,o2,l,t} \times prec_{i,o1,o2}, \forall i, t, o1, o2 \tag{7.51}$$

7.3 Computational Verification Using Mathematical Example

A simple example is used to demonstrate the use of the mathematical model. A simple product family consisting of two product variants (*i=1,2*) and a total of four product features (*f=1,2,3,4*) and machining operations (*o=1,2,3,4*). The different input parameters for the product, features, operations and demand are given in Table 7.1, Table 7.2 and Table 7.3.

Table 7.1: Product feature-machining operations matrix ($\gamma_{f,o}$)

		Operations			
		1	*2*	*3*	*4*
Product features	*1*	1	0	0	0
	2	0	1	0	0
	3	0	0	1	0
	4	0	0	0	1

Table 7.2: Product variant-product feature matrix ($\rho_{i,f}$)

		Product features			
		1	*2*	*3*	*4*
Product variants	*1*	1	1	0	0
	2	1	0	1	1

Table 7.3: product variant-production period matrix ($z_{i,t}$) and product demand in each production period ($demand_{i,t}$) in units/day

		Production periods	
		1	*2*
Product variants	*1*	1(850)	0
	2	0	1(1096)

The input parameter concerning the machine side is given in Table 7.4. This example consists of four machine types (*j=1,2,3,4*). The numbers between the brackets in Table 7.4 refer to the processing time of operation "*o*" on machine type "*j*" in seconds.

Table 7.4: Machine-machining operations matrix ($McOp_{j,o}$), processing time of operations on machines ($ptime_{j,o}$) in seconds and purchase cost of each machine

		Machines			
		1	*2*	*3*	*4*
Operations	*1*	1(37)	0	0	0
	2	0	1(26)	0	0
	3	0	0	1(30)	0
	4	0	0	0	1(36)
Purchase cost ($\times 10^3$)		100	200	150	300

The operations precedence matrix for the different product variants is given in Figure 7.2. For product variant 1, operation 1 precedes operation 2 and for this reason, the element "$prec_{1,1,2}$" is equal to 1.

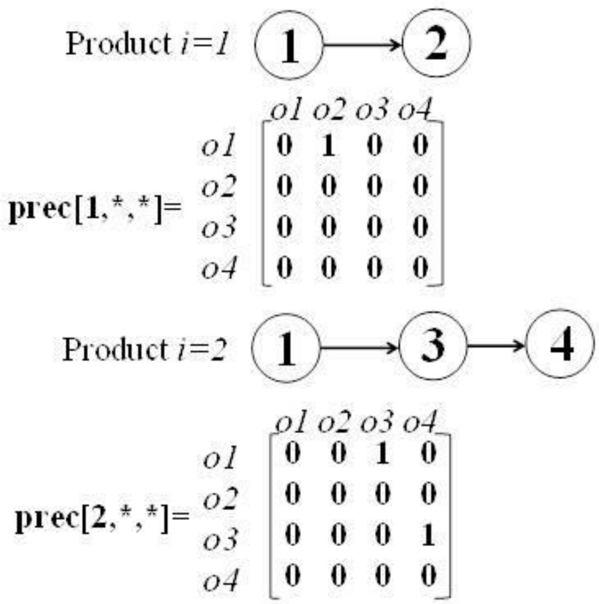


Figure 7.2 Operations precedence matrix for the different product variants for the mathematical example

According to the input parameters in Table 7.2, product feature 1 is available in product variants 1 and 2. Therefore, product feature 1 is a product platform feature. Product feature 1 requires machining operation 1 which can only be processed by machine 1. Therefore, machine type 1 is a platform machine since it possesses the machining capability to process product platform feature 1. In addition, product variant 1 contains product feature 2 in its composition according to Table 7.2. However, product feature 2 is not available in product variant 2 and therefore, product feature 2 is non-platform product feature. Since platform machine type 1 does not possess the machining capability to process operation 2 required for non-platform product feature 2, non-platform machine type 2 is added to the manufacturing system in production period 1. In production period 2, product variant 2 is required which is composed of product features 3 and 4 (in addition to platform product feature 1). Product features 3 and 4 are not available in production period 1 and therefore product features 3 and 4 are non-platform product features. Since platform machine type 1 does not possess the machining capability to process neither operation 3 nor 4 required for non-platform product feature 3 and 4, respectively, therefore, non-platform machines type 3 and 4 are added to the manufacturing system in production period 2.

The co-platforming mapping results of machines and product features from the output of the mathematical model is shown in Figure 7.3 and they conform to the explanation presented in the previous paragraph.

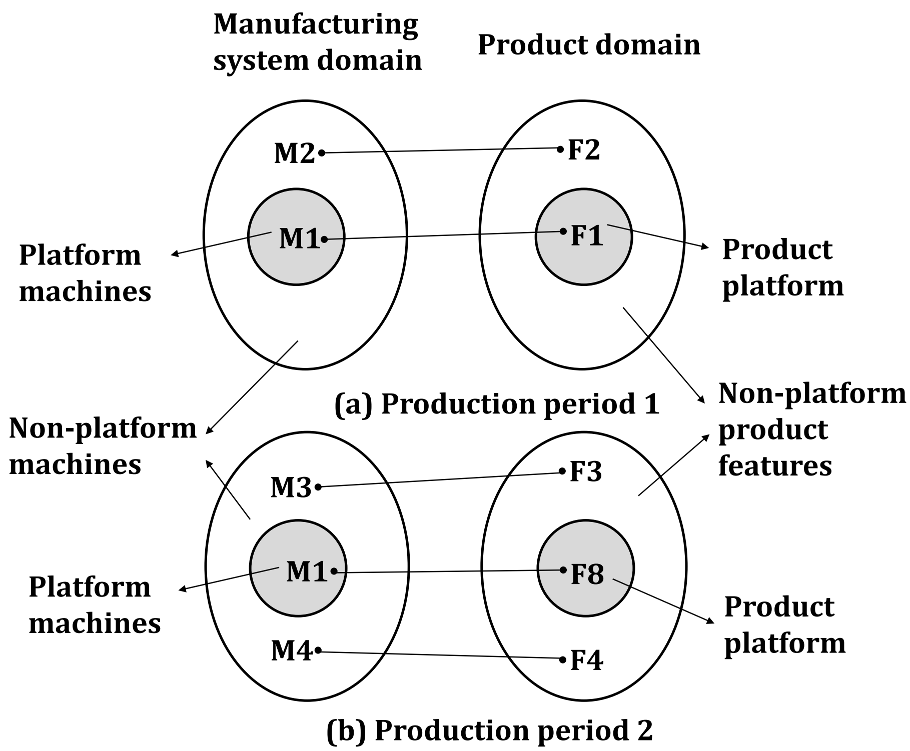


Figure 7.3 Co-platforming mapping results of machines and product features for the verification example

The generated manufacturing system configuration according to the mathematical model is shown in Figure 7.4. In production period 1, and according to the operational precedence matrix in Figure 7.2, operation 1 precedes operation 2. According to Table 7.4, machine type 1 can process machining operation 1 and machine 2 can process machining operation 2. Hence, the first stage contains machine type 1 followed by machine type 2.

In production period 2, and according to the operational precedence matrix in Figure 7.2, machining operation 1 precedes machining operation 3 and machining operation 3 precedes machining operation 4. According to Table 7.4, machine type 1 can process machining operation 1, machine type 3 can process machining operation 3 and machine type 4 can process machining operation 4. Hence, the first stage contains machine type 1 followed by machine type 3 followed by machine type 4.

Finally, it is required to find the number of machines in each stage. According to the mathematical programming model, the number of machines type 1 and 2 in production period 1 is 1 each. In addition, the number of machines type 1, 3 and 4 in production period 2 is 1 each.

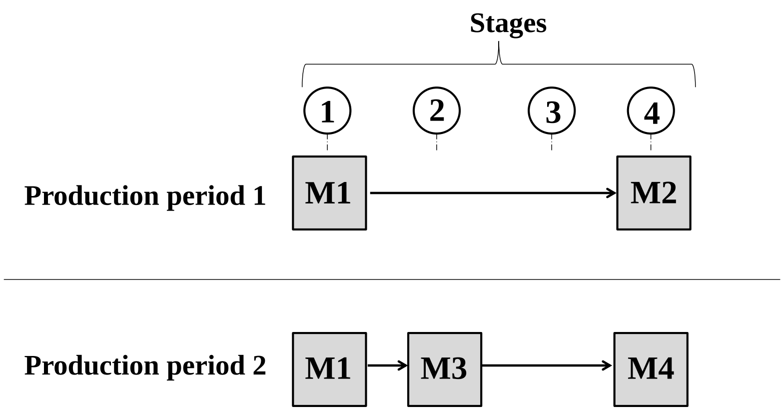


Figure 7.4 Manufacturing system configuration for the verification example

To verify these results, Table 7.5 provides the different processing time in seconds for each machining operation on each machine. By using constraint equation (7.45), the number of each machine type "*j*" in each stage "*l*" in production period "*t*" (i.e. $nst_{j,l,t}$) is calculated as shown in the equations set (7.52) as:

$$nst^{m}_{1,1,1} = \frac{850\times37}{3600\times24} \approx 1,\ nst^{m}_{2,4,1} = \frac{850\times26}{3600\times24} \approx 1,\ nst^{m}_{1,1,2} = \frac{1096\times37}{3600\times24} \approx 1$$
$$nst^{m}_{3,3,2} = \frac{1096\times30}{3600\times24} \approx 1,\ nst^{m}_{4,4,2} = \frac{1096\times36}{3600\times24} \approx 1 \qquad (7.52)$$

Table 7.5: Results from the mathematical model for the verification mathematical example

Product variant 1 (demand=850 units/day)					Product variant 2 (demand=1096 units/day)				
Feature	Machine	Stage	Operation	Processing time (sec)	Feature	Machine	Stage	Operation	Processing time (sec)
1	1	1	1	*37*	1	1	1	1	*37*
2	2	4	2	*26*	3	2	2	3	*30*
					4	4	4	4	*36*

7.4 Case Study: Machining of cylinder blocks taken from Mitsubishi Heavy Industries

The same case study from chapter 5 will be considered in this chapter. The input parameters are taken from Table 5.1, Table 5.2 and Table 5.3 from chapter 5 as well as Figure 7.5 which is the operations precedence constraint.

prec[1,*,*]=

Op01	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Op02	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Op03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op05	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Op06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Op12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Op13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Op16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Op17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

prec[2,*,*]=

Op01	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Op02	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Op03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op05	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Op06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Op10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Op11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Op16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Op17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

prec[3,*,*]=

Op01	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Op02	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Op03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op05	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Op06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Op14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Op15	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op16	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Op17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

prec[4,*,*]=

Op01	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Op02	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Op03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op05	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Op06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op11	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Op12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Op13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Op14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Op15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Op16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Op17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

prec[5,*,*]=

Op01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op03	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Op04	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Op05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op07	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Op08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op11	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Op12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Op13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Op14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Op15	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op16	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Op17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

prec[6,*,*]=

Op01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op03	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Op04	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Op05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op07	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Op08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op09	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Op10	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Op11	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Op12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Op13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Op14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Op15	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op16	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Op17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

prec[7,*,*]=

Op01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op03	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Op04	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Op05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op07	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Op08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Op12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Op13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Op16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Op17	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op18	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

prec[8,*,*]=

Op01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op03	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Op04	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Op05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op07	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Op08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op09	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Op10	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Op11	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Op12	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Op13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Op14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Op15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Op16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Op17	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Op18	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 7.5 Operations precedence matrix for the different product variants for the case study

7.5 Results and Discussion

The mathematical programming model is written using AMPL (http://ampl.com/) and solved by Gurobi Mixed Integer Linear Programming (MILP) in NEOS [117, 118, 119] in 1068.9 seconds for 2 production periods, 8 product variants, 18 operations, 9 features and 10 machines. The objective function (initial investment cost of machines, addition, removal cost as well as integration and testing cost including the penalty terms) equation (7.25) is 15496400 with an optimality gap of 2.9%. By excluding the last two terms in equation (7.25) since they are not part of the manufacturing system total cost, the total investment cost including the addition, removal and integration cost of machines is $12,726,400.

The mapping between machines and product features is shown in Figure 7.6. The proposed manufacturing system is shown in Figure 7.7. In Figure 7.7(a), the synthesized manufacturing system is for I-4 cylinder blocks while in Figure 7.7(b), the synthesized manufacturing system is for V-6 and V-8 cylinder blocks.

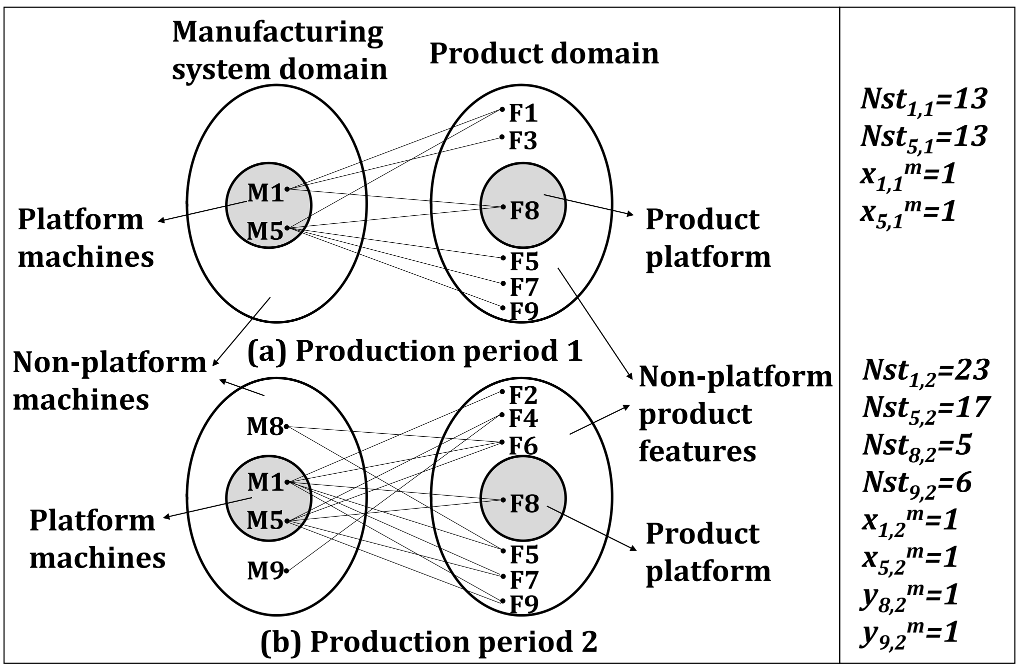


Figure 7.6 Co-platforming results

The developed model determines, based on the products produced in each period, the product platform and non-platform product features. The product platform features in this case study is product feature F8 (cylinder side wall planar face) since it is present in the I-4, V-6 and V-8 cylinder blocks produced during the considered two production periods. The rest of the non-platform cylinder blocks features in production periods 1 and 2 are either present in all products in only one of the production periods or present in both production periods but not in all product variants.

According to Figure 7.6, in production period 1, 5-axis CNC platform machines type 1 and 5 possess the machining capabilities to process the roughing and finishing machining operations for product platform feature 8 (i.e. cylinder side wall planar face). However, the model also maps 5-axis CNC platform machine type 1 to the machining operations required for some of the non-platform product features such as feature 1 (horizontal deck planar face) and feature 3 (cylinder bore on horizontal surface). This is because it possesses the machining capabilities to process non-platform product features 1 and 3 and to minimize the number and types of used machines. The 5-axis CNC platform machine type 5 is mapped to non-platform product features 1 (horizontal deck planar face), 5 (camshaft bore), 7 (water pump mount planar face) and 9 (oil pump mount planar face) since it possesses the machining capabilities required to process required operations for these non-platform product features.

5-axis CNC platform machines type 1 and 5 possess the machining capabilities to process the rough and finish machining operations for product platform feature 8 (cylinder side wall planar face) as in production period 1. In addition, the model maps platform 5-axis CNC machine type 1 to machining operations required for non-platform product features 2 (inclined deck planar face), 7 (water pump mount planar face) and 9 (oil pump mount planar face) as well as the rough operation for non-platform product features 5 (camshaft bore) and 6 (crankshaft bore) since it possesses the capability required to process these non-platform product features for the reasons mentioned in the previous paragraph. Furthermore, the 5-axis CNC platform machine type 5 is mapped to non-platform product features 4 (cylinder bore inclined surface), 6 (crankshaft bore), 7 (water pump mount planar face) and 9 (oil pump mount planar face).

The finishing operation of the non-platform product features 5 (camshaft bore) and 6 (crankshaft bore) is mapped to non-platform horizontal honing machine 8 (LBM2500). In addition, the finish operation of the non-platform product feature 4 (cylinder bore inclined surface) is mapped to non-platform vertical honing machine 9 (VCB1500V).

It is worth noting that real implementation of the case study from Mitsubishi [112] involves performing the rough cutting operations and finish cutting operations for the V-6 and V-8 on 5-axis CNC machines which is different from the solution proposed in this dissertation which maps non-platform product feature 6 (crankshaft bore) to a special purpose machine for honing operation (LBM2500). This difference is due to the special design of the 5-axis CNC machines implemented by Mitsubishi [112] which is equipped with the tool required for honing operations. The machine tools chosen in this dissertation are taken from standard catalogues.

In production period 1, 5-axis CNC machine type 1 can process the three product features 1, 3 and 8 with a total number of units of 1300 units (500 for the I-4 cylinder block models 711M1691cc and 800 for QR20DE1998cc) per day. In production period 2, 5-axis CNC machine type 1 processes operations for the six product features 2, 5, 6, 7, 8 and 9 with a total of 2100 units per day (for the V-configuration cylinder blocks 800 for Cosworth2935cc, 900 for Cyclone3496cc and 400 for LN33800cc). Due to the increase in number of product features that require processing by 5-axis CNC machine type 1 increased from three to six and the increase in total production demand from 1300 units (500 for the I-4 cylinder block models 711M1691cc and 800 for QR20DE1998cc) to 2100 units (for the V-configuration cylinder blocks 800 for Cosworth2935cc, 900 for Cyclone3496cc and 400 for LN33800cc), the number of required 5-axis CNC machines 1 increased from 13 to 23 in the second period.

In production period 1, 5-axis CNC machine type 5 processes operations for the five product features 1, 5, 7, 8 and 9 with a total number of units of 1300 units per day. In production period 2, machine 5 processes operations for the four product features 4, 6, 7, 8 and 9 with a total number of units of 2100 units per day. Therefore, the number of 5-axis CNC machines type 5 increased from 13 in production period 1 to 17 in production period 2.

The proposed manufacturing system is shown in Figure 7.7. In Figure 7.7(a), the synthesized manufacturing system is for I-4 cylinder blocks while in Figure 7.7(b), the synthesized manufacturing system is for V-6 and V-8 cylinder blocks. The machine type selection according to the mathematical model in this chapter is identical to the machine type selection in the mathematical model in chapter 6. However, there is a difference in the number of machine type in the mathematical model in this chapter compared to the mathematical model in chapter 5. This difference occurs specifically within constraint equation (5.40) in chapter 5 and constraint equation (7.45) in this chapter. After calculating the number of machines in the whole system according to constrain equation (5.40), the final solution is rounded once and released as an output. However, for constraint equation (7.45), after calculating the number of machines in each stage according to constrain equation (7.45), the final solution is rounded for each stage and the summation of the rounded values is released as an output.

In Figure 7.7, the rectangular dashed lines within some stages such stages 03, 05 and 06 represent empty positions which can be used in subsequent production periods to add machines. For example, there are two machines in stage 02 in production period 1 and three in production period 2. In addition, consider stages 12 and 18 which are completely empty as no machines are required in stages 12 and 18 in production period 1. However, new machines are added in production period 2 in stages 12 and 18. The penalty term "$1000 \sum_j \sum_l \sum_t \left| st_{j,l,t+1} - st_{j,l,t} \right|$" in the objective function equation (7.25) which minimizes the number of stages in each production period (i.e. $st_{j,l,t+1}$) compared to the preceding production period (i.e. $st_{j,l,t}$) by minimizing the penalty term.

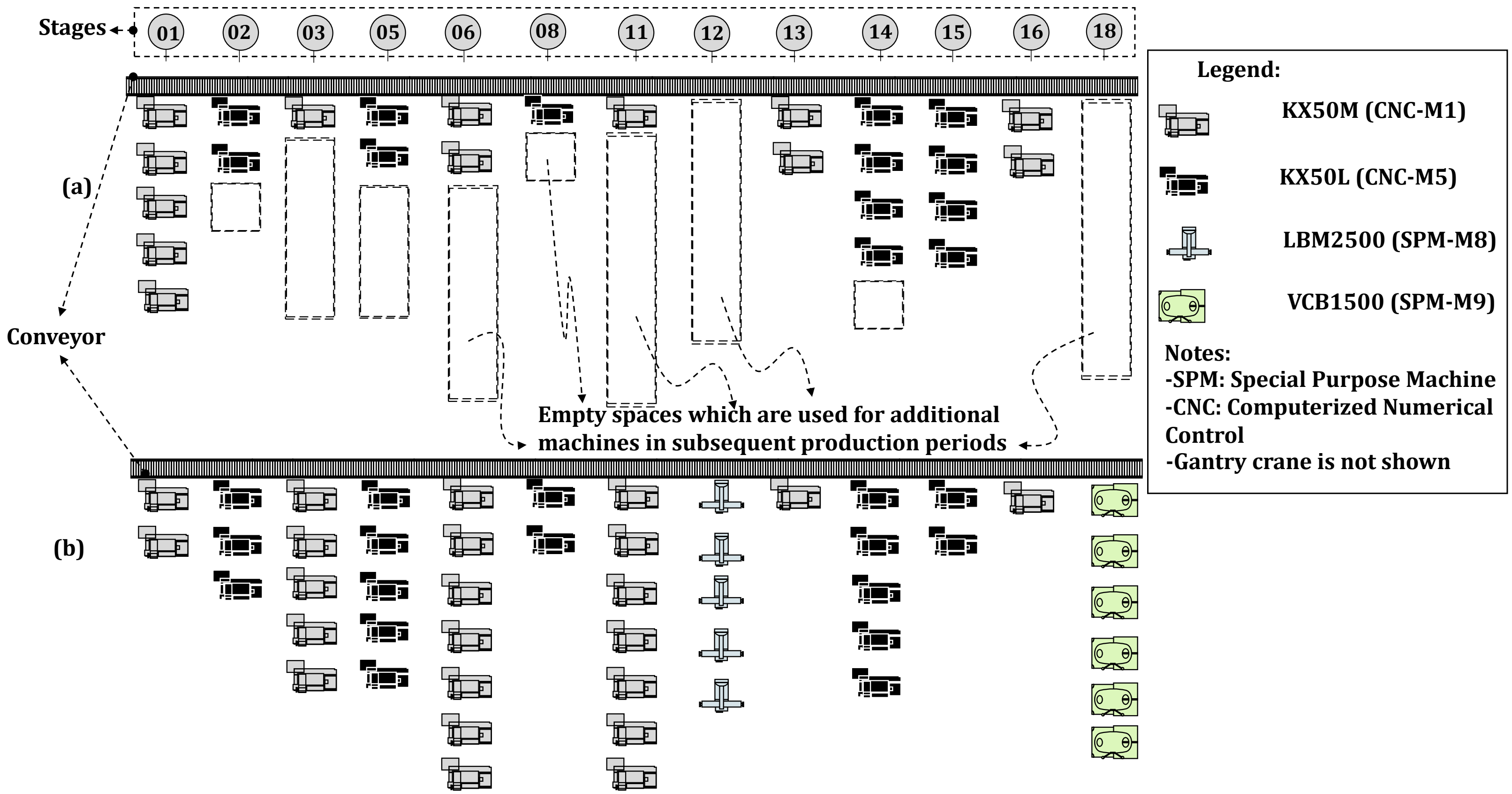


Figure 7.7 Manufacturing system configuration in (a) I-4 cylinder blocks in production period 1 and (b) V-6 and V-8 cylinder blocks in production period 2

7.6 Limitations

The mathematical programming model introduced in this chapter has limitations on the physical level as well as on the computational level. On the physical level, the same limitations of the model in chapter 5 is applied which is concerned with automated manufacturing systems as well as the types of manufacturing system components considered (such as buffers material handling units are not considered). Though the model in this chapter provides optimal solution in terms of number and types of machines, yet the computational time might cause restrictions on the size of the model as shown in Table 7.6. The maximum problem size achieved is periods=2, products=8, operations=18, features=9 and machines =10 at 1068.9 seconds. The reason for such large computational time relative to computational times in the previous chapters is the manufacturing configuration determination which requires satisfying the precedence or order of the machining operations when selecting machines within each stage. For future work, the mathematical model can be modified by re-defining the decision variables as well as rewriting the objective function.

Table 7.6: Computational time for different scenarios

Number of						Computational time (sec)	Solution status
Periods	Products	Operations	Features	Machines	MIPgap (%)		
2	2	4	4	4	0	<1	Optimal solution found
2	4	9	9	8	2.1163	90.64	Optimal solution found
2	4	9	9	10	2.83	124.63	Optimal solution found
2	2	24	9	8	1.618	396.24	Optimal solution found
2	8	18	9	10	2.9	1068.9	Optimal solution found
3	8	18	9	10	3.73	6383	No optimal solution

When solving a problem size of periods=2, products=4, operations=30, features=20 and machines=10, the model cannot provide optimal solution. This is due to the increase in the number of operations and features relative to scenarios one, two and three.

7.7 Conclusion

A mixed integer programming model to synthesize optimal manufacturing systems configuration (physical system) based on co-platforming has been presented. The total investment cost including initial investment cost, and the cost of addition, removal, integration and testing of machines within the manufacturing system are minimized within the objective function. Constraints such as line balancing and precedence constraints are taken into consideration in order to synthesize an optimal manufacturing system configuration.

The developed model is applied to a case study from the automotive industry. Different configurations were generated depending on the cylinder block model required according to the customers' demand. Several conclusions can be made. The developed co-platforming methodology allows the manufacturing system configuration to be synthesized simultaneously or concurrently with the product design by mapping product platform features to platform machines, and non-product platform features to non-platform machines. Platform product and system components remain unchanged throughout the different production periods while non-platform product and system components are modified according to the change in product design which arises from changes in customer requirements. The platform machines are chosen with relatively higher machining capabilities than the non-platform machines. Platform machines mainly process all product platform features. However, in some cases, platform machines are also assigned to process non-platform product features and components if they possess the sufficient machining capabilities and available production capacity to maximize machine utilization.

Additional manufacturing system components such as material handling units and buffers and system performance analysis using simulation are candidates for inclusion in future work.

CHAPTER 8. ASSEMBLY SYSTEM SYNTHESIS USING CO-PLATFORMING

8.1 Integrated co-platforming methodology

In this chapter, the co-platforming methodology is solved in three phases as shown in Figure 8.1. Phase 1 is the functional synthesis of generic assembly machine candidates. In this phase, a matrix based formulation is used in order to find the candidate platform and non-platform assembly machines. This approach is useful since large problem sizes can be handled due to the relatively low computational time required and accordingly, it can handle real size problems. This phase is cost independent.

Phase 2 is the functional synthesis of assembly machine types and numbers of each type. In this phase, a mixed integer linear programming model is developed in which the optimum type of assembly machines and their number are the main output. This phase is cost dependent. Phase 3 is the synthesis of assembly system configuration in which the number of stages and the number of assembly machines in each stage is determined. In this phase, a mixed integer linear programming model is proposed. This phase is cost dependent.

8.2 Functional synthesis of generic machine candidates

This section is concerned with the functional synthesis of generic assembly machine candidates using co-platforming methodology, which is matrix-based mapping. Figure 8.2 illustrates main elements required to formulate the matrix model for the functional synthesis of assembly machine candidates. The methodology consists of three main parts; the first part is the mapping matrix which consists of several input matrices, the second part is the input vector which is a binary vector describing the product platform components and finally, the third part is the output vector which describes the assembly system platform assembly machines. In the following subsections, a detailed mathematical formulation for each matrix and vector is included.

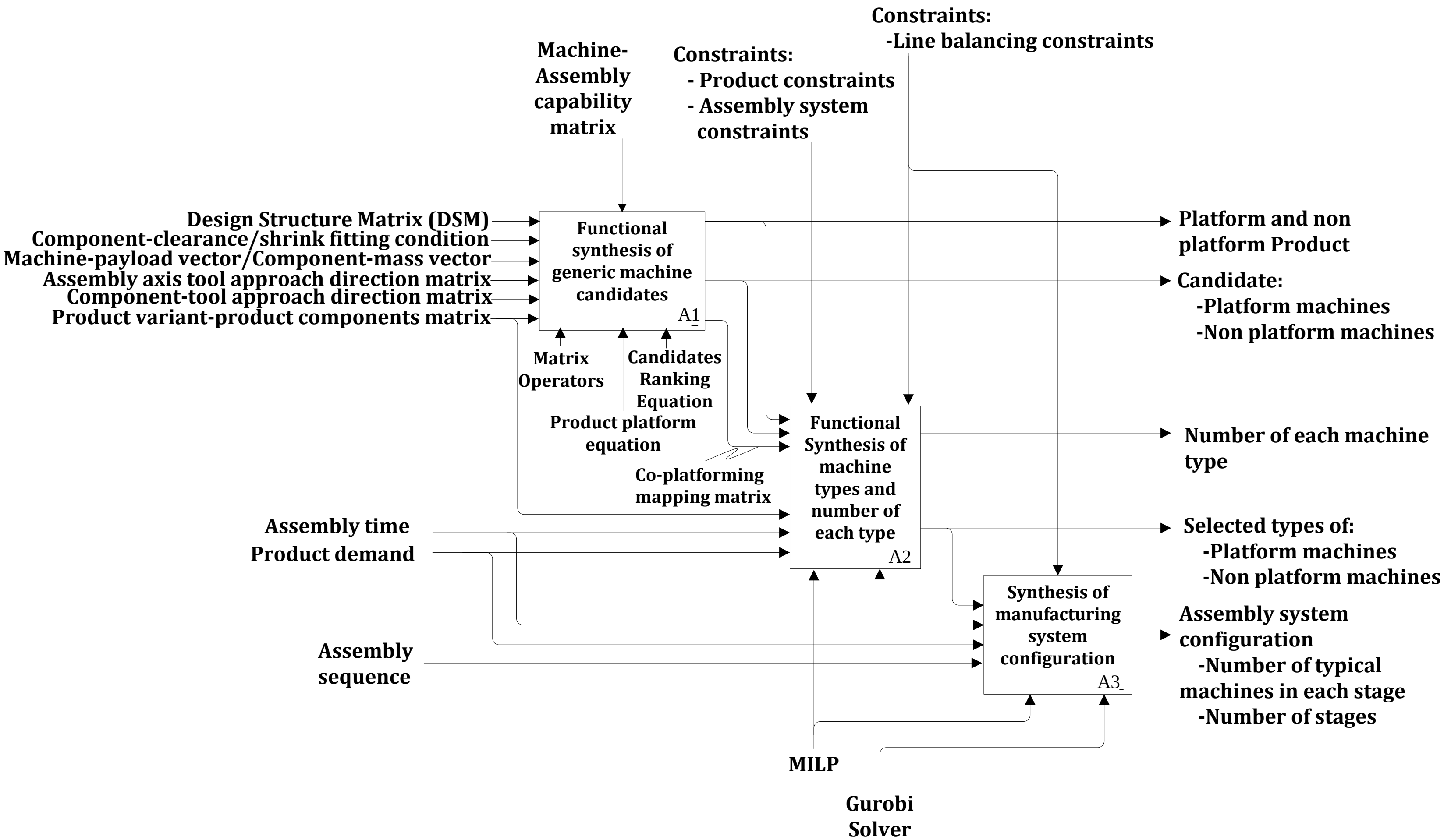


Figure 8.1IDEF0 representation of the integrated co-platforming methodology

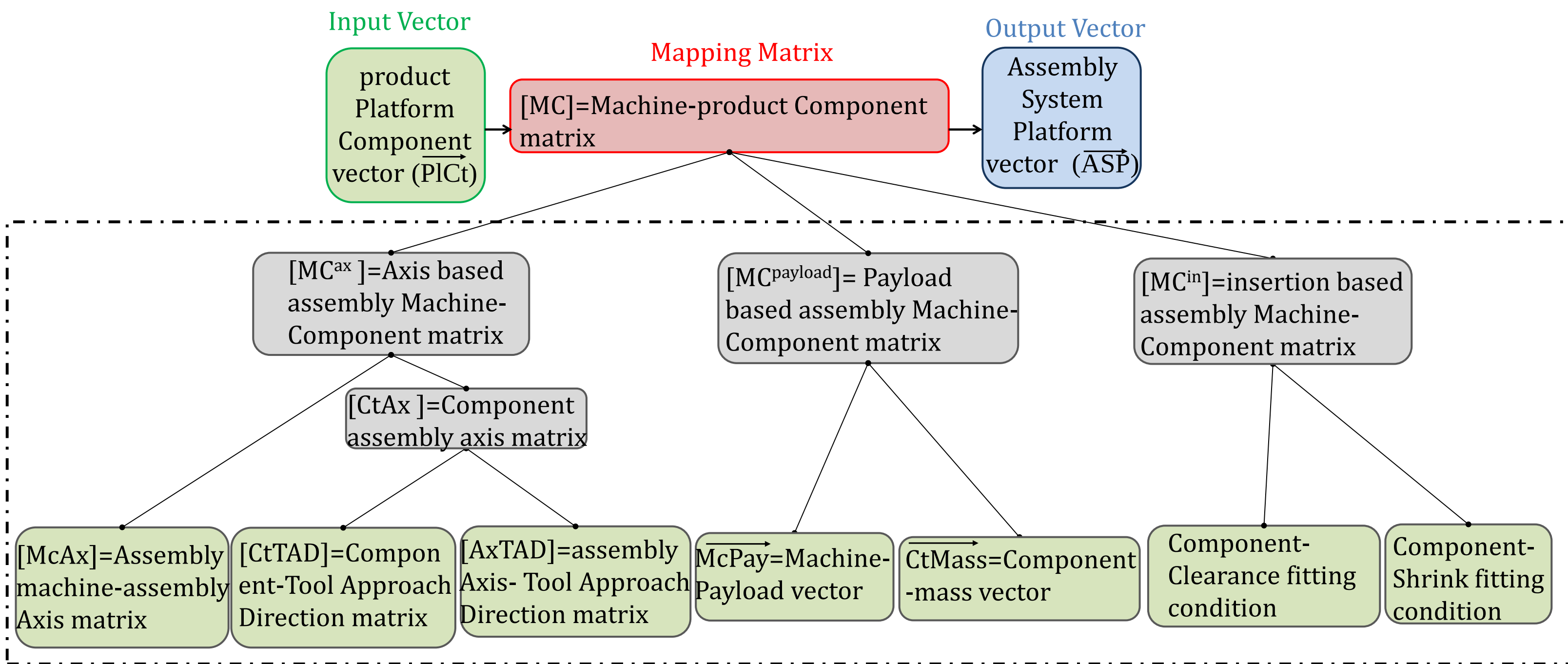


Figure 8.2 Matrix based formulation of the functional synthesis of machine candidates through co-platforming using matrix based formulation

In the previous chapters, machining operations were considered and accordingly, features characteristics were applied such as orientation of the feature, dimensional and geometric tolerance, required cutting power and surface finish. In this chapter, assembly operations are considered. In assembly operations, components apply instead of features. Therefore, in this chapter, components characteristics are considered such as the relationship between components (in the form of design structure matrix), orientation of components, required insertion force of components, mass of component (which determines the payload required by the assembly machine/robot), types of fits and mating conditions between each component.

8.2.1 Design Structure Matrix

Design Structure Matrix (DSM) is a tool used to represent the elements of a system and the interaction between the elements. A DSM is a square matrix in which the rows and columns describe the elements of a system and each cell is filled according the interaction between the elements of the matrix [121]. Figure 8.3 illustrates the Design Structure Matrix (DSM) since it will be used through this chapter. An example is shown in Figure 8.3a to illustrate the construction of DSM. The elements of DSM are defined as:

$$dsm_{f,q} = \begin{cases} 1, if\ component\ q\ is\ assembled\ to\ component\ f \\ 0, otherwise \end{cases}, \forall f, q \quad (8.1)$$

Where *f,q={1,2…F}* are the set of product features. The interaction between components within a product can be described through a matrix form (DSM) (Figure 8.3b).

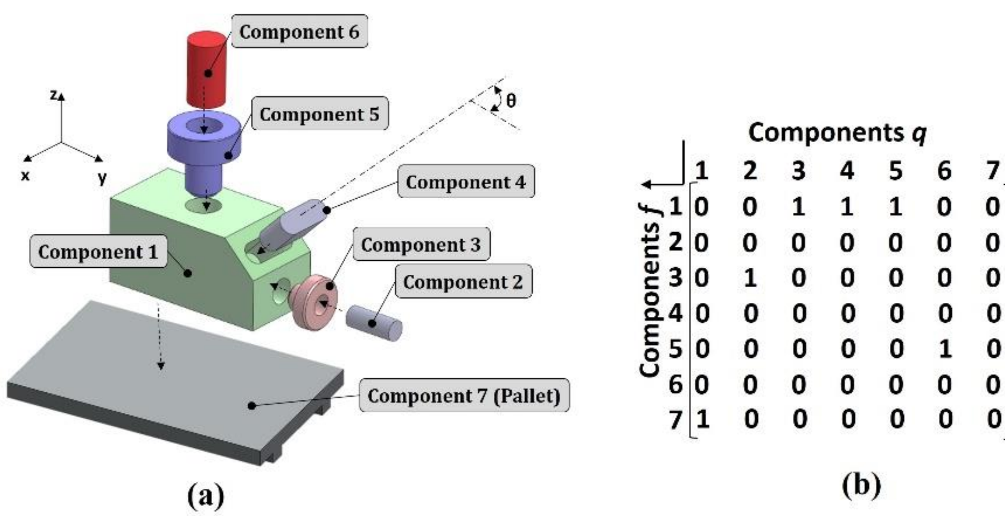


Figure 8.3 (a) Simple example illustrating the Design Structure Matrix (DSM) (b) Design Structure Matrix (DSM)

Table 8.1: Component-Tool Approach Direction matrix for illustrating example Figure 8.3

Component (*f*)	Component-tool approach direction matrix [*CtTAD*]
1	$cttad_{1,k(=1,2,3,4,5,6),i}=[0\ 0\ 0\ 0\ 0\ cos(0)]$
2	$cttad_{2,k(=1,2,3,4,5,6),i}=[0\ 0\ 0\ cos(0)\ 0\ 0]$
3	$cttad_{3,k(=1,2,3,4,5,6),i}=[0\ 0\ 0\ cos(0)\ 0\ 0]$
4	$cttad_{4,k(=1,2,3,4,5,6),i}=[0\ 0\ 0\ cos(\theta)\ 0\ cos(90-\theta)]$
5	$Cttad_{5,k(=1,2,3,4,5,6),i}=[0\ 0\ 0\ 0\ 0\ cos(0)]$
6	$Cttad_{6,k(=1,2,3,4,5,6),i}=[0\ \ 0\ 0\ 0\ 0\ cos(0)]$
7	$Cttad_{7,k(=1,2,3,4,5,6),i}=[0\ 0\ 0\ 0\ 0\ 0]$

8.2.2 Axis Based Machine-Component Matrix

The axis based machine-component matrix [MCt^{ax}] is calculated as:

$$mct_{j,f}^{ax} = \bigcup_{i=1}^{I} \overline{mct}_{j,f,i}^{ax}, \forall j,f \tag{8.2}$$

The different terms in equation (8.2) are calculated as:

$$\overline{mct}_{j,f,i}^{ax} = \sum_{p=1}^{P} ctax_{p,f,i} \times mcax_{j,p}, \forall j,f,i \tag{8.3}$$

$$ctax_{p,f,i} = \begin{cases} 1, if \ \frac{1}{\sum_{k=1}^{K} cttad_{f,k,i}^{2}} \sum_{k=1}^{K} cttad_{f,k,i} \times axtad_{p,k} \geq 1 \\ 0, otherwise \end{cases} \tag{8.4}$$

$$axtad_{p,k} = cos\theta_{f,k,i}, \forall f,k,i, \theta_{f,k,i} \epsilon [0,90] \tag{8.5}$$

$$cttad_{f,k,i} = cos\theta_{f,k,i}, \forall f,k,i, \theta_{f,k,i} \epsilon [0,90] \tag{8.6}$$

$$mcax_{j,p} = \begin{cases} 1, if \ machine \ j \ possesses \ assembly \ axis \ type \ p \\ 0, otherwise \end{cases}, \forall j,p \tag{8.7}$$

where $p=\{1,2,\ldots P\}$ is the set of assembly axis types. For example, if 3, 4 and 5 axis are considered, therefore, p=*1,2,3* for 3-axis, 4-axis and 5-axis, respectively. In addition, $j=\{1,2,\ldots J\}$ is the set assembly machines. Furthermore, $i=\{1,2\ldots I\}$ is the set of product variants. The component-Tool Approach Direction matrix [*CtTAD*] for the example in Figure 8.3 is deducted from Table 8.1.

8.2.3 Insertion based machine-component matrix

An important task in automated assembly is the process of insertion of peg into a hole considering clearance as well as interference type of fit. In clearance fit, three steps in which the assembly task is accomplished as shown in Figure 8.4; chamfer-crossing, one-point contact and two-point contact [122]. In interference fit, the axial force induced due to assembly of two components must be less than or equal to the axial force applied by the assembly machine [123]. The insertion-based machine-component matrix is derived as:

$$\overline{mct}_{j,f,q}^{in} = \begin{cases} 1\{\varepsilon_{0j} \le L_{chamfer}\} \wedge 1\left\{\left|\theta_{0j} + s_j\varepsilon_{0j}\right| \le \dfrac{c_{q,f}}{\mu}\right\} \\ \qquad \wedge 1\{max(F_{1f,q}^{c}, F_{2f,q}^{c}, F_{3f,q}^{c}) \le F_j^{ax}\}, if\ \Delta_{f,q} > 0\ and\ dsm_{f,q} = 1 \\ 1\{0.5\mu\pi l_{f,q} E\left|\Delta_{f,q}\right| \le F_j^{ax}\}, if\ \Delta_{f,q} < 0\ and\ dsm_{f,q} = 1 \\ dsm_{f,q}, if\ \Delta_{f,q} = 0 \end{cases} \tag{8.8}$$

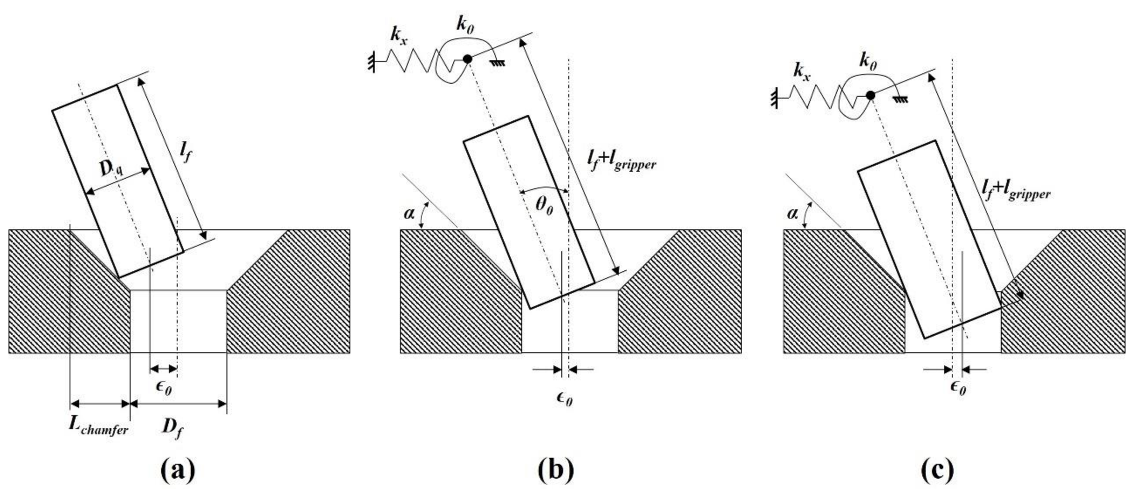


Figure 8.4 Peg insertion assembly task for (a) chamfer crossing and (b) one-point contact (c) two-point contact

Where "$l_{f,q}$" is the length of component f, when inserted in component q, "$l_{gripper}$" is the length of gripper, "k_{xj}" is the compliance device stiffness in the x-direction, "$k_{\theta j}$" is the compliance device torsional spring stiffness in the θ-direction and "$\Delta_{f,q}$" is element of the fit matrix "Δ" which corresponds to row f and column q. In addition, "E" is the modulus of elasticity, "F_j^{ax}" is the maximum axial force applied by assembly machine "j", "ε_{0j}" is the repeatability of assembly machine "j" and $L_{chamfer}$ is the width of chamfer (taken as 2mm). The rest of the terms in equation (8.8) are given as:

$$s_{f,j} = \frac{l_{f,q}+l_{gripper}}{(l_{f,q}+l_{gripper})^2+\frac{k_{\theta j}}{k_{xj}}}, \forall j \tag{8.9}$$

$$c_{f,q} = \frac{\Delta_{f,q}}{D_{f,q}}, \Delta_{f,q} > 0, \forall f, q, \tag{8.10}$$

$$F^c_{1j,f,q} = k_{xj}\varepsilon_{0j}\frac{cos\alpha + \mu sin\alpha}{sin\alpha - \mu cos\alpha} \tag{8.11}$$

Where "α" is the chamfer angle. For one-point contact:

$$F^c_{2j,f,q} = \mu k_{xj}\varepsilon_{0j} \tag{8.12}$$

Where "μ" is the coefficient of friction between components "f" and "q". For two-point contact:

$$F^c_{3j,f,q} = 2\mu\left(\theta_{0j} - \frac{\Delta_{f,q}}{l_{f,q}}\right)\frac{k_{\theta j}}{l_{f,q}} \tag{8.13}$$

Equation (8.8) is composed of three ranges. The first range is used when the type of fit between components "f" and "q" is clearance. The second range is used when the type of fit between components "f" and "q" is interference. The third range is used otherwise. The indicator function in equation (8.8) is equal to 1 if the condition within the braces is satisfied and 0 otherwise. Finally, the insertion- based machine-component matrix is derived as:

$$mct^{in}_{j,f} = \min\{1, \sum_{q=1}^{F} \overline{mc}^{in}_{j,f,q}\}, \forall j, f \tag{8.14}$$

8.2.4 Payload based machine-component matrix

The payload based machine-component matrix is required in order to decide on whether the assembly machine can carry a certain component or not. In order to derive the payload based machine-component matrix [$MCt^{payload}$], the mass of each component is defined in the form of vector called *CtMass* as:

$$ctmass_f = mass_f, \forall f \tag{8.15}$$

In addition, machine payload is defined in the form of a vector called *McPay* which is defined as:

$$mcpay_j = payload_j, \forall f \tag{8.16}$$

Finally, the payload based machine-component matrix is calculated as:

$$mct^{payload}_{j,f} = 1\{mcpay_j \geq ctmass_f\}, \forall j, f \tag{8.17}$$

Each element in the payload based machine-component matrix [$MCt^{payload}$] is equal to 1 if the payload of assembly machine type *j* is greater than the mass of component *f* and 0 otherwise as shown in equation (8.17).

8.2.5 Machine-component mapping matrix

This section is concerned with the calculation of the machine-component mapping matrix [*MCt*]. The elements of the machine-component mapping matrix are calculated as:

$$mct_{j,f} = mct_{j,f}^{ax} \wedge mct_{j,f}^{in} \wedge mct_{j,f}^{payload}, \forall j, f \tag{8.18}$$

The machine-component mapping matrix [*MCt*] in equation (8.18) is equal to 1 if component *f* is oriented within the assembly axis reach of assembly machine type "j" (i.e. $mc_{j,f}^{ax}=1$) and assembly machine type "j" satisfies the insertion conditions of component "f" (i.e. $mct_{j,f}^{in}=1$) and the payload of assembly machine type "j" is greater than the mass of component "f" (i.e. $mct_{j,f}^{payload}=1$) and 0 otherwise.

8.2.6 Product platform component vector

The product platform component vector *PlCt* is the input vector to the mapping matrix machine-components matrix [*MCt*] defined in section 8.2.5. However, in order to determine the product platform component vector *PlCt*, a product-component matrix [*PtCt*] is required in order to facilitate the determination of the product platform component vector *PlCt*. The elements of the product-component matrix [*PtCt*] can be defined as:

$$ptct_{i,f} = \begin{cases} 1, if\ product\ variant\ i\ contains\ component\ f \\ 0, otherwise \end{cases}, \forall i, f \tag{8.19}$$

Where $i=\{1,2,\dots I\}$ is the set of product variants within the product family. Since the product platform is defined as the common components among product variants within a product family, the product platform vector *PlCt* elements can be derived as:

$$plct_f = \begin{cases} 1, if\ ptct_{i,f} = 1, \forall i = 1,2,\dots,I \\ 0, otherwise \end{cases}, \forall f \tag{8.20}$$

8.2.7 Assembly system platform vector

The assembly system platform vector *ASP* is the output vector from the methodology. With the aid of the machine-component mapping matrix equation (8.18) and input vector (8.20), the assembly system platform is calculated as:

$$asp_j = \min\left(1, \sum_{f=1}^{F} mc_{j,f} \times plct_f\right), \forall j \qquad (8.21)$$

The formulation of equation (8.21) insures that "*aspj*" takes a value of 1 if the value "$\Sigma_f mc_{j,f} plct_f$" is greater than 0. Values of "$\Sigma_f mc_{j,f} plct_f$" greater than 0 mean that assembly machine type "j" is a platform assembly machine since it can assemble product platform component. Therefore, the value of "asp_j" is equal to 1 if assembly machine type "j" is a platform machine and 0 otherwise.

8.3 Functional synthesis of machine types and number of each machine type

After obtaining the platform and non-platform machine candidates, it is required to obtain the optimum platform and non-platform assembly machine types among the assembly machine candidates calculated in section 8.2 as well as their number. Outputs from the model in section 8.2 will be used as inputs in this model such as the machine-component mapping matrix as well as the assembly machine candidates chosen by the previous model. The next subsections are concerned with developing the model for functional synthesis of assembly machine types and number of each assembly machine type which is a mixed integer linear programming model.

8.3.1 Input parameters

The input parameters are given as:

$$z_{i,t} = \begin{cases} 1, if\ product\ variant\ \ i\ is\ available\ in\ production\ period\ t \\ 0, otherwise \end{cases} \qquad (8.22)$$

$$\rho_{i,f} = \begin{cases} 1, if\ product\ component\ f\ is\ available\ in\ product\ variant\ i \\ 0, otherwise \end{cases} \qquad (8.23)$$

$$mf_{j,f} = \begin{cases} 1, if\ machine\ j\ can\ assemble\ product\ component\ f \\ 0, otherwise \end{cases} \qquad (8.24)$$

$$purcost_j: Purchase\ cost\ of\ machine\ type\ j \qquad (8.25)$$

$$sellcost_j: Salvage\ cost\ of\ machine\ type\ j \qquad (8.26)$$

$$atime_{f,j}: processing\ time\ of\ product\ component\ f\ on\ machine\ j \qquad (8.27)$$

$$demand_{i,t}: demand\ of\ product\ variant\ i\ in\ production\ period\ t \qquad (8.28)$$

8.3.2 Decision variables

The decision variables are defined as:

$$x_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ a\ platform\ machine\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{8.29}$$

$$y_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ non-platform\ machine\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{8.30}$$

$$a_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ added\ as\ non-platform\ machine\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{8.31}$$

$$r_{j,t}^{m} = \begin{cases} 1, if\ machine\ j\ is\ removed\ from\ non-platform\ machines\ in \\ \quad production\ period\ t \\ 0, otherwise \end{cases} \tag{8.32}$$

$$x_{f,t}^{p} = \begin{cases} 1, if\ product\ component\ f\ is\ product\ platform\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{8.33}$$

$$y_{f.t}^{p} = \begin{cases} 1, if\ product\ component\ f\ is\ not\ product\ platform\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{8.34}$$

$$\varphi_{i,j,f,t} = \begin{cases} 1, if\ product\ component\ f\ in\ product\ variant\ i\ is\ assembled \\ \quad by\ machine\ j\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{8.35}$$

$$\delta_{f,t} = \begin{cases} 1, if\ product\ component\ f\ is\ available\ in\ at\ least\ one\ product \\ \quad variant\ in\ production\ period\ t \\ 0, otherwise \end{cases} \tag{8.36}$$

$$\sigma_{f} = \begin{cases} 1, if\ product\ component\ f\ is\ available\ in\ all\ production\ period\ t \\ 0, otherwise \end{cases} \tag{8.37}$$

$$Nst_{j,t}: Number\ of\ machine\ type\ j\ in\ production\ period\ t \tag{8.38}$$

8.3.3 Objective function

The objective function is given in equation (8.39). The first and second term are the initial investment cost in platform and non-platform assembly machines, respectively in the first production period "*t=1*". The third and fifth terms are the cost of addition of platform and non-platform assembly machines, respectively in production periods "*t>1*". The fourth and sixth terms are the cost of removal of platform and non-platform assembly machines, respectively in production periods "*t>1*". The seventh term is the cost of integration and testing of assembly machines when added or removed from the assembly system. The eighth term is a penalty term which constrains the number of each assembly machine type in each production period. The rest of the parameters are illustrated in chapter 5.

$Minimize$:

$$\begin{aligned}
&\sum_{j=1}^{J} purcost_j Nst_{j,t} x_{j,t=T_0}^{m} + \sum_{j=1}^{J} purcost_j Nst_{j,t} y_{j,t=T_0}^{m} \\
&+ \sum_{t=1}^{T} \sum_{j=1}^{J} max(0, Nst_{j,t+1} - Nst_{j,t}) purcost_j x_{j,t+1}^{m} \\
&+ \sum_{t=1}^{T} \sum_{j=1}^{J} min(0, Nst_{j,t+1} - Nst_{j,t}) sellcost_j x_{j,t+1}^{m} \\
&+ \sum_{t=1}^{T} \sum_{j=1}^{J} max(0, Nst_{j,t+1} - Nst_{j,t}) purcost_j y_{j,t+1}^{m} \\
&+ \sum_{t=1}^{T} \sum_{j=1}^{J} min(0, Nst_{j,t+1} - Nst_{j,t}) sellcost_j y_{j,t+1}^{m} \\
&+ \sum_{t=1}^{T} \frac{A_{0,t}^{m} B^{m}}{I_0^{m} \alpha_t^{m}} \begin{pmatrix} \sum_{b=1}^{J} \sum_{\hat{b}=1}^{J} d^{f_{b,\hat{b}}-1} y_{\hat{b},t}^{m} r_{b,t}^{m} + \sum_{b=1}^{J} \sum_{\hat{b}=1}^{J} d^{f_{b,\hat{b}}-1} y_{\hat{b},t}^{m} a_{b,t}^{m} \\ + \sum_{a=1}^{J} \sum_{b=1}^{J} d^{f_{a,b}-1} x_{b,t}^{m} r_{a,t}^{m} + \sum_{a=1}^{J} \sum_{b=1}^{J} d^{f_{a,b}-1} x_{b,t}^{m} a_{a,t}^{m} \end{pmatrix} \\
&+ 100 \sum_{j=1}^{J} \sum_{t=1}^{T} Nst_{j,t}
\end{aligned} \tag{8.39}$$

The rest of the design variables and parameters in equation (8.42) are defined as:

$$\alpha_t^{m} = \frac{\sum_{j=1}^{J} x_{j,t}^{m}}{\sum_{j=1}^{J} x_{j,t}^{m} + \sum_{j=1}^{J} y_{j,t}^{m}}, \forall t \tag{8.40}$$

$$I_0^{m} = \sum_{j=1}^{J} purcost_j Nst_{j,t=T_0} x_{j,t=T_0}^{m} \tag{8.41}$$

8.3.4 Constraints

Constraint equation (8.42) is concerned with the addition of non-platform assembly machine type "*j*" in production period "*t+1*".

$$a_{j,t+1}^{m} \leq \sum_{i=1}^{I} \sum_{f=1}^{F} \varphi_{i,j,f,t+1} (1 - y_{j,t}^{m})(1 - x_{j,t}^{m}) \leq M a_{j,t+1}^{m}, \forall j, t \tag{8.42}$$

Constraint equation (8.43) is concerned with the removal of non-platform assembly machine type "*j*" in production period "*t+1*".

$$r_{j,t+1}^{m} \leq \sum_{i=1}^{I} \sum_{f=1}^{F} y_{j,t}^{m} (1 - \varphi_{i,j,f,t+1}) \leq M r_{j,t+1}^{m} \ \forall j, t \tag{8.43}$$

Constraint equation (8.44) is concerned with the identification of product platform component "*f*" which is available in all production periods as well as in all product variants in each production period.

$$M\sigma_f - M + 1 \leq \ 1 - T + \sum_{t=1}^{T} x_{f,t}^{p} \leq \ (1-\epsilon)\left(1-\sigma_f\right) + \sigma_f, \forall f \tag{8.44}$$

Constraint equation (8.45) is concerned with assigning product platform components to platform assembly machines.

$$x_{j,t}^{m} \ \leq \sum_{i=1}^{I} \sum_{f=1}^{F} \varphi_{i,j,f,t}\sigma_f \ \leq \ Mx_{j,t}^{m}, \forall j,t \tag{8.45}$$

Constraint equation (8.46) insures that a non-platform assembly machine type "*j*" is either added or removed in production period "*t*".

$$a_{j,t}^{m} + r_{j,t}^{m} \leq 1, \forall j,t \tag{8.46}$$

Constraint equation (8.47) insures that platform assembly machines are available in all production periods.

$$x_{j,t}^{m} = x_{j,t+1}^{m}, \forall j,t \tag{8.47}$$

Constraint equation (8.48) pertains the relationship between non-platform assembly machine type "*j*" in production period "*t+1*" relative to production period "*t*".

$$y_{j,t+1}^{m} = y_{j,t}^{m} + a_{j,t+1}^{m} - r_{j,t+1}^{m}, \forall j,t \tag{8.48}$$

Constraint equation (8.49) is used to define the decision variable "$\delta_{f,t}$" which is equal to 1 if product platform component "*f*" is present in at least one product variant in production period "*t*" and 0 otherwise.

$$\delta_{f,t} \leq \sum_{i=1}^{I} z_{i,t}\rho_{i,f} \leq \ M\delta_{f,t}, \forall f,t \tag{8.49}$$

Constraint equation (8.50) insures that if a product component "*f*" is available in production period "*t*", then it either a platform component or a non-platform component.

$$x_{f,t}^{p} + y_{f,t}^{p} = \delta_{f,t}, \forall f,t \tag{8.50}$$

Constraint equation (8.51) is used to insure the presence of product platform component "*f*" in all production periods.

$$x_{f,t}^{p} = x_{f,t+1}^{p}, \forall \ f,t \tag{8.51}$$

Constraint equations (8.52), (8.53) and (8.54) require that a product component "*f*" in product variant "*i*" is mapped to a unique assembly machine type "*j*" in production period "*t*".

$$\sum_{j=1}^{J} \varphi_{i,j,f,t} = z_{i,t}\rho_{i,f} \text{ , } \forall\, i, f, t \quad (8.52)$$

$$\varphi_{i,j,f,t} = z_{i,t}\rho_{i,f} mf_{j,f} \mu_{i,j,f,t}(x_{j,t}^{m} + y_{j,t}^{m}) \text{ , } \forall\, i, j, f, t \quad (8.53)$$

$$\sum_{j=1}^{J} \mu_{i,j,f,t} = 1 \text{ , } \forall\, i, f, t \quad (8.54)$$

Constraint equation (8.55) is concerned with finding the optimum number of machine types based on the assembly time of component "f" on assembly machine type "j" and the demand of product variant "i" in production period "t".

$$\sum_{f=1}^{F} \sum_{i=1}^{I} demand_{i,t} \times atime_{f,j} \times \varphi_{i,j,f,t} \leq 3600 \times NHD \times \left(x_{j,t}^{m} + y_{j,t}^{m}\right) Nst_{j,t}, \forall\, j, t \quad (8.55)$$

8.4 Synthesis of manufacturing system configuration

After obtaining the optimum types of platform and non-platform assembly machines and numbers of each type, it is required to obtain the assembly system configuration which is defined as determining the number of stages as well as the type and number of each assembly machine in each stage. Outputs from the model in section 8.3 will be used as inputs in this model such as the machine-component mapping matrix as well as the optimum assembly machine types chosen by the model in subsection 8.3. The next subsections are concerned with developing the model for physical synthesis of assembly system configuration which is a mixed integer linear programming model.

8.4.1 Input parameters

The distinguishing input parameter in the model developed in this section is:

$$prec_{i,f,q} = \begin{cases} 1, if\ component\ q\ is\ assembled\ before\ component\ f\ in\ product\ variant\ \ i \\ 0, otherwise \end{cases} \quad (8.56)$$

8.4.2 Decision variables

The distinguishing decision variables in the model developed in this section are:

$$\vartheta_{i,j,f,l,t} = \begin{cases} 1, if\ component\ f\ in\ product\ variant\ i\ in\ \ production \\ \quad period\ t\ is\ \ assigned\ to\ machine\ j\ within\ stage\ l \\ 0, otherwise \end{cases} \quad (8.57)$$

$$st_{j,l,t} = \begin{cases} 1, if\ machine\ j\ is\ chosen\ for\ stage\ l\ in\ production\ period\ t \\ 0, otherwise \end{cases} \quad (8.58)$$

$$nst_{j,l,t}: Number\ of\ machine\ type\ j\ in\ stage\ l\ in\ production\ period\ t \quad (8.59)$$

8.4.3 Objective function

The objective function for the physical synthesis of the manufacturing system configuration. The first to seventh terms are illustrated in a similar manner as in section 8.3.3.

The term "$\sum_a \sum_b st_{a,l1,t} st_{b,l2,t} d^{f_{a,b}-1} x_{b,t}^m r_{a,t}^m$" is considered in order to illustrate the seventh term in equation (8.60). The term "$st_{b,l2,t}$" is a decision variable which equals to 1 if assembly machine type "*b*" is at stage "*l2*" in production period "*t*" and 0 otherwise. The condition "$|l1-l2|=1$" insures that assembly machine type "*a*" is either downstream to assembly machine type "*b*" or upstream to assembly machine type "*b*". The multiplication of the terms "$st_{a,l1,t}$" and "$st_{b,l2,t}$" with the condition "$|l1-l2|=1$" is equal to 1 if assembly machines type "*a*" and "*b*" are in two consecutive stages. An integration and testing cost will be acquired if non-platform assembly machine type "*a*" is removed from the manufacturing system in production period "*t*" (i.e. $r_{a,t}^m=1$) and at the same time, platform assembly machine type "*b*" is available within the manufacturing system in production period "*t*" (i.e. $x_{b,t}^m=1$) and assembly machines type "*a*" and "*b*" are in two consecutive stages (i.e. $st_{a,l1,t} \times st_{b,l2,t}=1$ where $|l1-l2|=1$). Therefore, an integration and testing cost is acquired. The eighth term adds a penalty value whenever a stage is required in period "$t+1$"compared to period "*t*".

The eighth term is a penalty term which minimizes the number of stages in each production period (i.e. $st_{j,l,t+1}$) compared to the preceding production period (i.e. $st_{j,l,t}$) in order to use stages in certain production period similar to the preceding production period. The ninth term adds a penalty value on the number of assembly machines within all stages the in order to insure that the exact number of machines are available within the manufacturing system. The eighth and ninth terms are not part of the investment cost. The tenth term is the constraint equation (8.69) added to the objective function similar to the augmented function. The reason of adding this term is to achieve the optimum solution in reasonable time.

$Minimize$:

$$\sum_{j=1}^{J} purcost_j Nst_{j,t=T_0} x_{j,t=T_0}^{m} + \sum_{j=1}^{J} purcost_j Nst_{j,t=T_0} y_{j,t=T_0}^{m}$$
$$+\sum_{t=1}^{T}\sum_{j=1}^{J} \max(0, Nst_{j,t+1} - Nst_{j,t}) purcost_j x_{j,t+1}^{m}$$
$$+\sum_{t=1}^{T}\sum_{j=1}^{J} \min(0, Nst_{j,t+1} - Nst_{j,t}) sellcost_j x_{j,t}^{m}$$
$$+\sum_{t=1}^{T}\sum_{j=1}^{J} \max(0, Nst_{j,t+1} - Nst_{j,t}) purcost_j y_{j,t+1}^{m}$$
$$+\sum_{t=1}^{T}\sum_{j=1}^{J} \min(0, Nst_{j,t+1} - Nst_{j,t}) sellcost_j y_{j,t}^{m}$$
$$+\sum_{t=1}^{T} \frac{A_{0,t}^{m} B^{m}}{I_0^{m} \alpha_t^{m}} \Bigg(\sum_{b=1}^{J} \sum_{\substack{\hat{b}=1 \\ |l1-l2|=1}}^{J} st_{b,l1,t} st_{\hat{b},l2,t} d^{f_{b,\hat{b}}-1} y_{\hat{b},t}^{m} r_{b,t}^{m} +$$
$$\sum_{b=1}^{J} \sum_{\substack{\hat{b}=1 \\ |l1-l2|=1}}^{J} st_{b,l1,t} st_{\hat{b},l2,t} d^{f_{b,\hat{b}}-1} y_{\hat{b},t}^{m} a_{b,t}^{m} + \quad (8.60)$$
$$\sum_{a=1}^{J} \sum_{\substack{b=1 \\ |l1-l2|=1}}^{J} st_{a,l1,t} st_{b,l2,t} d^{f_{a,b}-1} x_{b,t}^{m} r_{a,t}^{m} +$$
$$\sum_{a=1}^{J} \sum_{\substack{b=1 \\ |l1-l2|=1}}^{J} st_{a,l1,t} st_{b,l2,t} d^{f_{a,b}-1} x_{b,t}^{m} a_{a,t}^{m} \Bigg)$$
$$+1000 \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} \left| st_{j,l,t+1} - st_{j,l,t} \right|$$
$$+100 \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} nst_{j,l,t}$$
$$+100 \Big(\sum_{j=1}^{J} \sum_{\substack{l=1 \\ f \neq q}}^{L} l \times \vartheta_{i,j,f,l,t} \times prec_{i,f,q} - \sum_{j=1}^{J} \sum_{\substack{l=1 \\ f \neq q}}^{L} l \times \vartheta_{i,j,q,l,t} \times prec_{i,f,q} \Big)$$

8.4.4 Constraints

The constraint equations (8.61), (8.62) and (8.63) are similar to constraint equations (8.52), (8.53) and (8.54).

$$\sum_{j=1}^{J} \varphi_{i,j,f,t} = z_{i,t} \rho_{i,f}, \forall\, i, f, t \quad (8.61)$$

$$\varphi_{i,j,f,t} = z_{i,t} \rho_{i,f} mf_{j,f} \mu_{i,j,o,f,t} \left(x_{j,t}^{m} + y_{j,t}^{m} \right), \forall\, i, j, f, t \quad (8.62)$$

$$\sum_{j=1}^{J} \mu_{i,j,f,t} = 1, \forall\, i, f, t \quad (8.63)$$

Constraint equation (8.64) is concerned with finding the optimum number of assembly machine types in each stage based on the assembly time of component "*f*" on assembly machine type "*j*" and the demand of product variant "*i*" in production period "*t*".

$$\sum_{i=1}^{I} demand_{i,t} \times atime_{f,j} \times \vartheta_{i,j,f,l,t} \leq 3600 \times NHD \times \left(x_{j,t}^{m} + y_{j,t}^{m}\right) nst_{j,l,t}, \forall j,t,l \quad (8.64)$$

Constraint equation (8.65) is used to insure that the total number of assembly machine type "*j*" is equal to the number of assembly machine type "*j*" in all stages.

$$\sum_{l=1}^{L} nst_{j,l,t} = Nst_{j,t}, \forall j,t \quad (8.65)$$

$$nst_{j,l,t} \leq n_{max}, \forall j,l,t \quad (8.66)$$

Where the constant "n_{max}" is the total number of identical assembly machines allowed in a single stage. This value is constrained by the facility layout. Constraint equation (8.67) is concerned with assigning product component "*f*" in product variant "*i*" assembled by machine type "*j*" in production period "*t*" to only one stage.

$$\sum_{l=1}^{L} \vartheta_{i,j,f,l,t} = \varphi_{i,j,f,t}, \forall i,j,t \quad (8.67)$$

Constraint equation (8.68) is concerned with defining decision variable "$st_{j,l,t}$".

$$st_{j,l,t} \leq \sum_{i=1}^{I} \sum_{f=1}^{F} \vartheta_{i,j,f,l,t} \leq M \; st_{j,l,t}, \forall j,l,t \quad (8.68)$$

Constraint equation (8.69) is the precedence constraint which ensure the correct sequence of stages according to the precedence relationship between components. This constraint is illustrated as follows; if product component "*q*", which is required for product variant "*i*" and is processed on assembly machine type "*j*" in production period "*t*", precedes product component "*f*", therefore, product component "*q*" must be performed within an earlier (or at least same) stage than product component "*f*".

$$\sum_{j=1}^{J} \sum_{l=1}^{L} l \times \vartheta_{i,j,f,l,t} \times prec_{i,f,q} \leq \sum_{j=1}^{J} \sum_{l=1}^{L} l \times \vartheta_{i,j,q,l,t} \times prec_{i,f,q}, \forall i,t,f,q \quad (8.69)$$

8.5 Case Study: Assembly of cylinder heads taken ABB flexible automation

The case study introduced in this subsection is concerned with cylinder heads assembly company adapted from ABB flexible automation [124, 125]. The assembly line is required to produce double overall head cam type cylinder heads, I-Head type, F-Head type and single overhead cam type configurations. The different cylinder head components as well as configuration is shown in Figure 8.5 and Figure 8.6. The purpose of the case study is to propose a newly synthesized assembly system based on the co-platforming strategy by applying the different phases illustrated in Figure 8.1. The different inputs to the model is shown in Table 8.2 to Table 8.12 as well as Figure 8.7.

According to [124], the cylinder head assembly line is composed of manual workstations, ABB jointed-arm and conventional automated stations. The cylinder head assembly line produces cylinder heads for Audi model A4 and A6. which are double head cam (DOHC). It is required in this chapter to synthesize the assembly system in two production periods based on co-platforming. The first production period is concerned with the assembly of double head cam and I-Head cylinder heads while the second production period is concerned with the assembly of single head cam and F-head cylinder block.

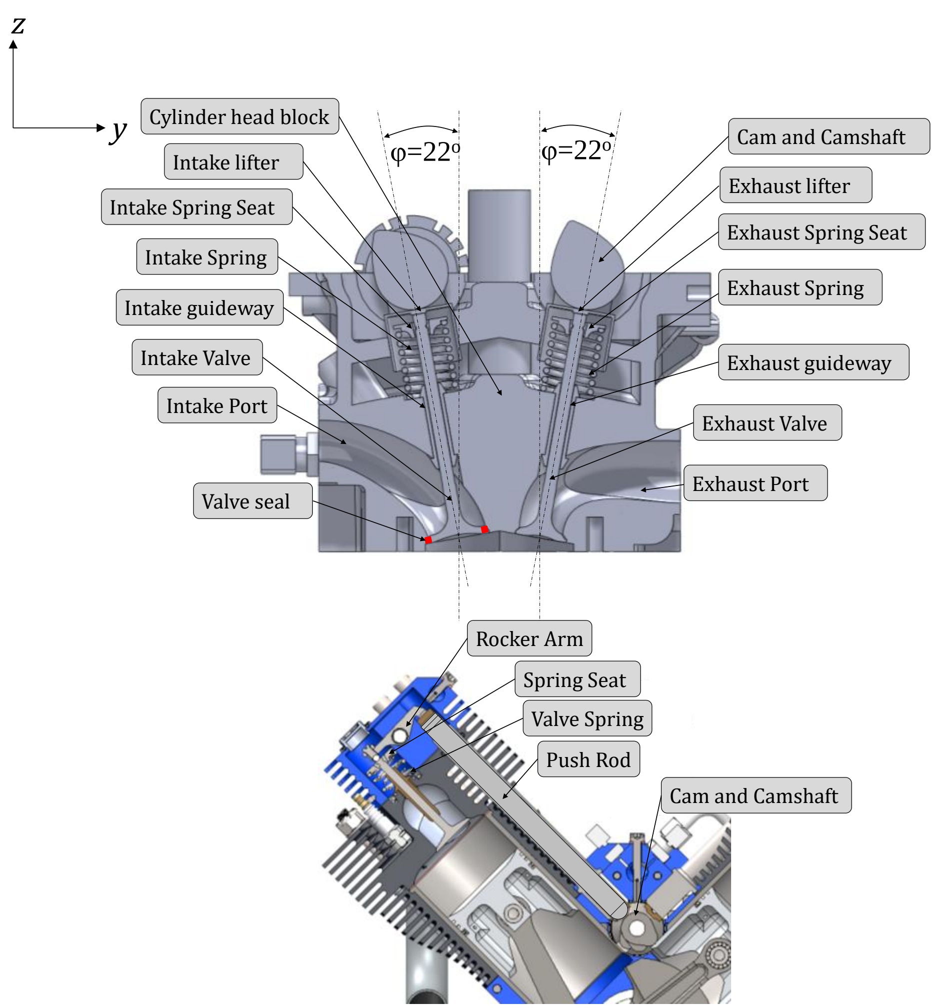


Figure 8.5 Main components of cylinder head: Overhead camshaft type (top), I-Head type (bottom)

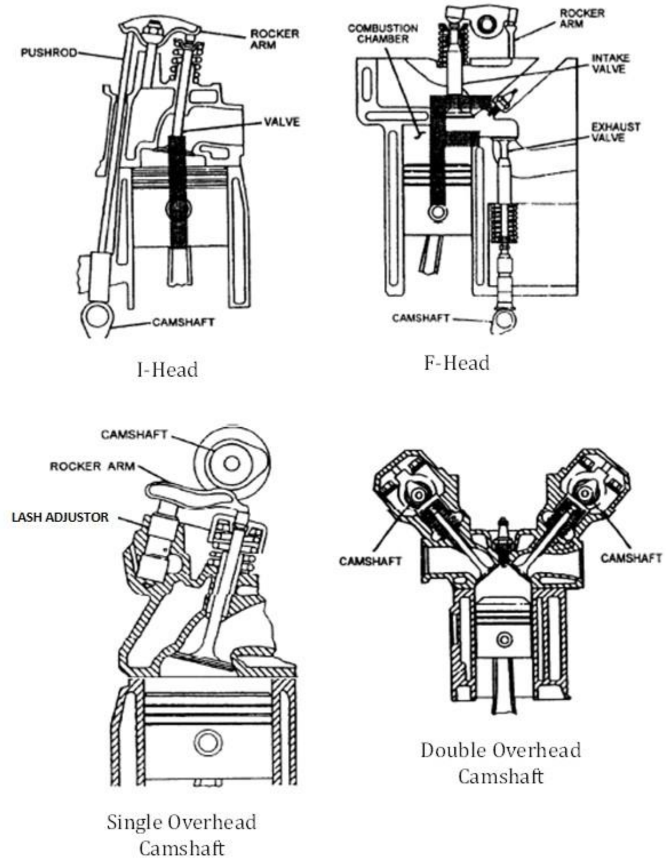


Figure 8.6 Schematic of the different cylinder head configuration (http://www.waybuilder.net/)

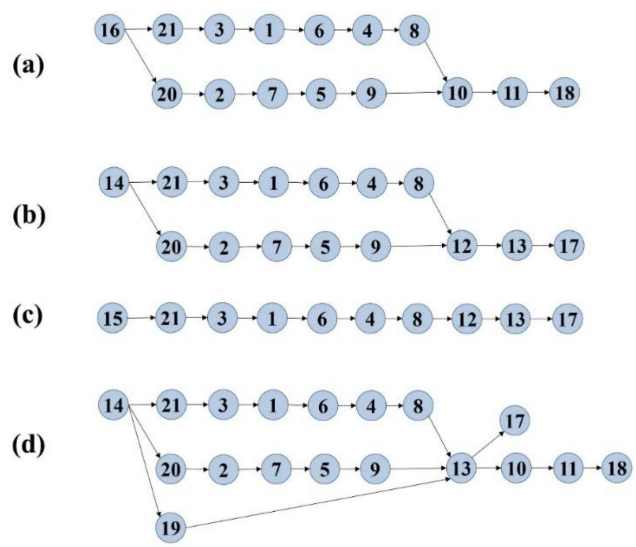


Figure 8.7 Precedence relationship for product variants (a) DOHC (b) I-Head (c) F-Head (d) SOHC

Table 8.2: Design Structure Matrix

	Intake valve	exhaust valve	valve seal	intake spring seat	exhaust spring seat	inlet spring	outlet spring	Intake lifter	Outlet lifter	Camshaft	Brackets	pushrods	rocker arm	body 1	body 2	body 3	Screw for rocker arm	Screw for brackets	Lash adjustor	exhaust guideway	intake guideway	Pallet
Intake valve	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust valve	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
valve seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
intake spring seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust spring seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
inlet spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
outlet spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake lifter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outlet lifter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Camshaft	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Brackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pushrods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rocker arm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
body 1	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1	1	1	1	0
body 2	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0
body 3	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	1	0
Screw for rocker arm	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Screw for brackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lash adjustor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust guideway	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
intake guideway	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pallet	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0

Table 8.3: Fit matrix $\Delta_{f,q} \times 10^{-3}$ (mm)

	Intake valve	exhaust valve	valve seal	intake spring seat	exhaust spring seat	inlet spring	outlet spring	Intake lifter	Outlet lifter	Camshaft	Brackets	pushrods	rocker arm	body 1	body 2	body 3	Screw for rocker arm	Screw for brackets	Lash adjustor	exhaust guideway	intake guideway	Pallet
Intake valve	0	0	0	-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust valve	0	0	0	0	-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
valve seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
intake spring seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust spring seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
inlet spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
outlet spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake lifter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outlet lifter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Camshaft	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0
Brackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pushrods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rocker arm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
body 1	0	0	0	0	0	0	0	0	0	50	0	15	0	0	0	0	-1	-1	-1	-1	-1	0
body 2	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	-1	0
body 3	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	-1	0	-1	-1	0
Screw for rocker arm	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0
Screw for brackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lash adjustor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust guideway	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
intake guideway	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pallet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.4: Machine-available Capability matrix

Equipment name	Repeatability ϵ_0 (mm)	Axis 4	6	X	Y	Force F^{ax} (N)***	Payload (kg)	k_x*** (ib/in)	k_θ*** (in.ib/rad)	k_θ/k_x***	Angular error θ_0 (deg)	length of gripper (mm)	Purchase cost (Salvage cost) $\$\times10^3$
Articulated 1 [44]	0.1	0	1	0	0	8896	5	240	313	1.30417	1.2	68.58	140(1.4)
Articulated 2 [44]	0.1	0	1	0	0	3447	10	169	112	0.66272	1.5	68.58	135(1.35)
Scara 1[44]	0.02	1	0	0	0	1557	5	120	68	0.56667	0.5	68.58	100(1)
Scara 2 [44]	0.3	1	0	0	0	1223	150	197	112	0.56853	0.5	68.58	110(1.1)
Gantry 1 [44]	0.2	0	1	0	0	2669	80	103	94	0.91262	0.05	68.58	150(1.5)
Gantry 2 [44]	0.4	0	1	0	0	1557	1200	70	55	0.78571	0.05	68.58	160(1.6)
KR 120 R2700 EXTRA HA*	0.05	0	1	0	0	2002	120	120	68	0.56667	1.5	68.58	125(1.25)
IRB 6640 / IRB 6640ID**	0.07	0	1	0	0	1223	235	60	40	0.66667	2.1	68.58	130(1.3)
IRB 1600-6/1.2**	0.06	0	1	0	0	3447	30.5	197	112	0.56853	2.3	68.58	145(1.45)

*http://www.kuka-robotics.com/ **http://new.abb.com/ *** http://www.pfa-inc.com/pdfs/Automation.pdf

Table 8.5: Product-components matrix

	Intake valve	exhaust valve	valve seal	intake spring seat	exhaust spring seat	inlet spring	outlet spring	Inlet lifter	Outlet lifter	Camshaft	Brackets	pushrods	rocker arm	body 1	body 2	body 3	Screw for rocker arm	Screw for brackets	Lash adjustor	exhaust guideway	intake guideway	Production period 1(units/day)	Production period 2 (units/day)
Double head cam DOHC	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	1	0	1	1	1000	0
I_Head	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	1	0	0	1	1	500	0
F_Head	1	0	1	1	0	1	0	1	0	0	0	1	1	0	1	0	1	0	0	0	1	0	1500
Single overhead cam OHC_A	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	0	400
Mass of components (kg)	0.5	0.5	0.1	0.1	0.1	0.5	0.5	0.5	0.5	4	1	1	1	15	15	15	0.1	0.1	1	0.2	0.2	-	-

Table 8.6: Component diameter matrix $D_{f,q}$ (mm)

	Intake valve	exhaust valve	valve seal	intake spring seat	exhaust spring seat	inlet spring	outlet spring	Intake lifter	Outlet lifter	Camshaft	Brackets	pushrods	rocker arm	body 1	body 2	body 3	Screw for rocker arm	Screw for brackets	Lash adjustor	exhaust guideway	intake guideway	Pallet
Intake valve	0	0	0	5.97	0	40	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust valve	0	0	0	0	5.95	0	40	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0
valve seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
intake spring seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust spring seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
inlet spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
outlet spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake lifter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outlet lifter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Camshaft	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0
Brackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pushrods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rocker arm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
body 1	0	0	40	0	0	0	0	0	0	30	30	10	0	0	0	0	12	10	22	10	10	0
body 2	0	0	40	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	10	0
body 3	0	0	40	0	0	0	0	0	0	30	30	0	0	0	0	0	0	10	0	10	10	0
Screw for rocker arm	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0
Screw for brackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lash adjustor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust guideway	0	5.953	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
intake guideway	5.973	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pallet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.7: Component length of contact matrix $l_{f,q}$ (mm)

	Intake valve	exhaust valve	valve seal	intake spring seat	exhaust spring seat	inlet spring	outlet spring	Intake lifter	Outlet lifter	Camshaft	Brackets	pushrods	rocker arm	body 1	body 2	body 3	Screw for rocker arm	Screw for brackets	Lash adjustor	exhaust guideway	intake guideway	Pallet
Intake valve	0	0	0	10	0	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust valve	0	0	0	0	10	0	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0
valve seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
intake spring seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust spring seat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
inlet spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
outlet spring	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intake lifter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Outlet lifter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Camshaft	0	0	0	0	0	0	0	0	0	0	750	0	0	0	0	0	0	0	0	0	0	0
Brackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pushrods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rocker arm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
body 1	0	0	5	0	0	0	0	0	0	750	40	250	0	0	0	0	30	30	60	90	90	0
body 2	0	0	5	0	0	0	0	0	0	0	0	250	0	0	0	0	0	0	0	0	90	0
body 3	0	0	5	0	0	0	0	0	0	750	40	0	0	0	0	0	0	30	0	90	90	0
Screw for rocker arm	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0
Screw for brackets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lash adjustor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
exhaust guideway	0	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
intake guideway	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pallet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8.8: Component-Tool Approach Direction for Double head cam cylinder head type matrix

	x+	x-	y+	y-	z+	z-
Intake valve	0	0	0	*sin* 22º	0	*cos* 22º
exhaust valve	0	0	0	*sin* 22º	0	*cos* 22º
valve seal	0	0	0	*sin* 22º	0	*cos* 22º
intake spring seat	0	0	0	*sin* 22º	0	*cos* 22º
exhaust spring seat	0	0	0	*sin* 22º	0	*cos* 22º
inlet spring	0	0	0	*sin* 22º	0	*cos* 22º
outlet spring	0	0	0	*sin* 22º	0	*cos* 22º
Intake lifter	0	0	0	*sin* 22º	0	*cos* 22º
Outlet lifter	0	0	0	*sin* 22º	0	*cos 22º*
Camshaft	0	0	0	0	0	1
Brackets	0	0	0	0	0	1
pushrods	0	0	0	0	0	0
rocker arm	0	0	0	0	0	0
body 1	0	0	0	0	0	0
body 2	0	0	0	0	0	0
body 3	0	0	0	0	0	1
Screw for rocker arm	0	0	0	0	0	0
Screw for brackets	0	0	0	0	0	1
Lash adjustor	0	0	0	0	0	0
exhaust guideway	0	0	0	*sin* 22º	0	*cos* 22º
intake guideway	0	0	0	*sin* 22º	0	*cos 22º*
Pallet	0	0	0	*0*	0	*0*

Table 8.9: Component-Tool Approach Direction for I-Head cylinder head type matrix

	x+	x-	y+	y-	z+	z-
Intake valve	0	0	0	*sin* 22º	0	*cos* 22º
exhaust valve	0	0	0	*sin* 22º	0	*cos* 22º
valve seal	0	0	0	*sin* 22º	0	*cos* 22º
intake spring seat	0	0	0	*sin* 22º	0	*cos* 22º
exhaust spring seat	0	0	0	*sin* 22º	0	*cos* 22º
inlet spring	0	0	0	*sin* 22º	0	*cos* 22º
outlet spring	0	0	0	*sin* 22º	0	*cos* 22º
Intake lifter	0	0	0	*sin* 22º	0	*cos* 22º
Outlet lifter	0	0	0	*sin* 22º	0	*cos* 22º
Camshaft	0	0	0	0	0	0
Brackets	0	0	0	0	0	0
pushrods	0	0	0	*sin* 22º	0	*cos* 22º
rocker arm	0	0	0	0	0	1
body 1	0	0	0	0	0	1
body 2	0	0	0	0	0	0
body 3	0	0	0	0	0	0
Screw for rocker arm	0	0	0	0	0	1
Screw for brackets	0	0	0	0	0	0
Lash adjustor	0	0	0	0	0	0
exhaust guideway	0	0	0	*sin* 22º	0	*cos* 22º
intake guideway	0	0	0	*sin* 22º	0	*cos* 22º
Pallet	0	0	0	*0*	0	*0*

Table 8.10: Component-Tool Approach Direction for F-Head cylinder head type matrix

	x+	x-	y+	y-	z+	z-
Intake valve	0	0	0	*sin* 22º	0	*cos* 22º
exhaust valve	0	0	0	0	0	0
valve seal	0	0	0	*sin* 22º	0	*cos* 22º
intake spring seat	0	0	0	*sin* 22º	0	*cos* 22º
exhaust spring seat	0	0	0	0	0	0
inlet spring	0	0	0	*sin* 22º	0	*cos* 22º
outlet spring	0	0	0	0	0	0
Intake lifter	0	0	0	*sin* 22º	0	*cos* 22º
Outlet lifter	0	0	0	0	0	0
Camshaft	0	0	0	0	0	0
Brackets	0	0	0	0	0	0
pushrods	0	0	0	*sin* 22º	0	*cos* 22º
rocker arm	0	0	0	0	0	1
body 1	0	0	0	0	0	0
body 2	0	0	0	0	0	1
body 3	0	0	0	0	0	0
Screw for rocker arm	0	0	0	0	0	1
Screw for brackets	0	0	0	0	0	0
Lash adjustor	0	0	0	0	0	0
exhaust guideway	0	0	0	0	0	0
intake guideway	0	0	0	*sin* 22º	0	*cos* 22º
Pallet	0	0	0	*0*	0	*0*

Table 8.11: Component-Tool Approach Direction for Single overhead cam cylinder head type matrix

	x+	x-	y+	y-	z+	z-
Intake valve	0	0	0	*sin* 22º	0	*cos* 22º
exhaust valve	0	0	0	*sin* 22º	0	*cos* 22º
valve seal	0	0	0	*sin* 22º	0	*cos* 22º
intake spring seat	0	0	0	*sin* 22º	0	*cos* 22º
exhaust spring seat	0	0	0	*sin* 22º	0	*cos* 22º
inlet spring	0	0	0	*sin* 22º	0	*cos* 22º
outlet spring	0	0	0	*sin* 22º	0	*cos* 22º
Intake lifter	0	0	0	*sin* 22º	0	*cos* 22º
Outlet lifter	0	0	0	*sin* 22º	0	*cos* 22º
Camshaft	0	0	0	0	0	1
Brackets	0	0	0	0	0	1
pushrods	0	0	0	0	0	0
rocker arm	0	0	0	0	0	1
body 1	0	0	0	0	0	1
body 2	0	0	0	0	0	0
body 3	0	0	0	0	0	0
Screw for rocker arm	0	0	0	0	0	1
Screw for brackets	0	0	0	0	0	1
Lash adjustor	0	0	0	0	0	1
exhaust guideway	0	0	0	*sin* 22º	0	*cos* 22º
intake guideway	0	0	0	*sin* 22º	0	*cos* 22º
Pallet	0	0	0	*0*	0	*0*

The precedence relationship for the assembly of cylinder head Figure 8.7 is derived according to Figure 8.6. The precedence for the F-head cylinder head type in Figure 8.7c is to be illustrated. Initially, the assembly starts with cylinder head body (component 15). After that, the intake guideway (component 21) is assembled to the cylinder head body (component 15). Then the valve seal (component 3) to the intake guideway (component 21). the intake valve (component 1) is assembled after the valve seal (component 3) is assembled. Intake spring (component 6) is assembled after the intake valve (component 1) is assembled. The intake spring seat (component 4) is assembled above the intake spring (component 6). After that, the intake lifter (component 8) is assembled to hold the intake spring seat (component 4). Push rod (component 12) is assembled followed by the rocker arm (component 13). Finally, the rocker arm (component 13) is held in position by screws (component 17). The value of "n_{max}" is taken as 2. The rest of the input parameters "B^m", "$A_{0,t}{}^m$", "$f_{j,b}$" and "$d^{fj,b-1}$" are taken from chapter 5.

8.6 Results and discussion

First, the functional synthesis of generic candidate assembly machines model is used. The machine-component mapping matrix is calculated using equation (8.18) and is shown in Table 8.13. The product platform component vector can be calculated from equation (8.20) with the aid of Table 8.5 as:

$$\overrightarrow{PlCt} = [1\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1] \tag{8.70}$$

According to vector (8.70), the product platform components are components 1 (intake valve), 3 (valve seal), 4 (intake spring seat), 6 (inlet spring),8 (inlet lifter) and 21 (intake guideway). Finally, the assembly system platform vector *ASP* is calculated from equation (8.21) with the aid of Table 8.13 as:

$$\overrightarrow{ASP} = [1\ 1\ 0\ 0\ 1\ 1\ 1\ 1\ 1] \tag{8.71}$$

According to the assembly system platform vector (8.71), the assembly system platform machines are the industrial robots articulated 1, articulated 2, gantry 1, gantry 2, KR12R2700, IRB6640 and IRB1600-6/1.2.

The main common characteristics between these assembly machines is the 6 degree of freedom as shown in Table 8.4. However, these assembly machines differ in other characteristics such as repeatability, payload, axial force…etc. Consider the platform assembly machine articulated 1 which can apply a maximum axial force of 8896*N* (highest axial force among the rest of the assembly machines in Table 8.4). For this reason, platform assembly machine articulated 1 can assemble components experiencing shrink fitting which requires relatively high insertion force exist between them such as intake and exhaust spring seat with the intake and exhaust valve as well as intake and exhaust guideways with the cylinder head body. Consider the shrink fit between the intake guideway and body 1. According to equation (8.8) with $E=200GPa$ and $\mu=0.15$ (steel to steel contact), the required insertion force is 4241*N* which is greater than the axial force in all assembly machines in Table 8.4 except for the platform assembly machine articulated 1. For this reason, a value of 1 is only available for the cell in Table 8.13 corresponding to intake guideway and articulated 1.

Gantry 1 and Gantry 2 are 6 degrees of freedom assembly robots. The main distinguishing characteristic of gantry 1 and gantry 2 according to Table 8.4 is the relatively low angular error (0.05^o) compared to the rest of robots. For this reason, gantry 1 and gantry 2 robots can assemble the pushrod as shown in Table 8.13. Robots KR12R2700, IRB6640 and IRB1600-6/1.2 are characterized by 6 degrees of freedom with axial forces of 2002N, 1223N and 3447N, which are less than the axial force of articulated 1. For this reason, Robots KR12R2700, IRB6640 and IRB1600-6/1.2 can assemble components that do not require a large amount of insertion force such as the insertion of the intake valve to intake guideway as shown in Table 8.13.

Articulated robot 2 possess 6 assembly axes and a repeatability of 0.1mm similar to articulated robot 1. However, in this case study, articulated robot 2 can only assemble components characterized by clearance fit due to relatively lower axial force performed by the robot gripper compared to articulated robot 1. Scara robot 1 and 2 possess 4 assembly axis (or degree of freedom) which restrains them from being chosen by the model as platform assembly machines. According to Table 8.8, Table 8.9, Table 8.10 and Table 8.11, all product platform components lie within an inclined angle.

Table 8.12: Assembly time of the different components on the different machines (seconds)

	Intake valve	exhaust valve	valve seal	intake spring seat	exhaust spring seat	inlet spring	outlet spring	Intake lifter	Outlet lifter	Camshaft	Brackets	pushrods	rocker arm	body 1	body 2	body 3	Screw for rocker arm	Screw for brackets	Lash adjustor	exhaust guideway	intake guideway
Articulated 1	43	30	35	35	40	33	40	33	43	0	50	0	28	0	0	0	48	38	25	43	40
Articulated 2	28	50	48	0	0	45	33	38	38	0	43	0	38	0	0	0	45	45	43	0	0
Scara 1	0	0	0	0	0	0	0	0	0	48	43	0	28	0	0	0	35	25	0	0	0
Scara 2	0	0	0	0	0	0	0	0	0	28	25	0	38	25	43	48	0	0	0	0	0
Gantry 1	40	43	30	0	0	48	28	28	40	48	28	38	28	45	50	45	48	35	0	0	0
Gantry 2	50	48	45	0	0	35	30	40	33	35	50	48	30	48	28	50	25	28	0	0	0
KR 120 R2700 EXTRA HA	45	30	38	0	0	43	43	35	40	0	43	0	43	35	25	33	33	30	0	0	0
IRB 6640 / IRB 6640ID	35	30	48	0	0	25	25	45	35	0	25	0	35	45	45	25	0	0	0	0	0
IRB 1600-6/1.2	48	33	40	0	0	25	40	28	25	0	38	0	40	48	50	48	40	38	45	0	0

Table 8.13: Machines-components matrix

	Intake valve	exhaust valve	valve seal	intake spring seat	exhaust spring seat	inlet spring	outlet spring	Intake lifter	Outlet lifter	Camshaft	Brackets	pushrods	rocker arm	body 1	body 2	body 3	Screw for rocker arm	Screw for brackets	Lash adjustor	exhaust guideway	intake guideway
Articulated 1	1	1	1	1	1	1	1	1	1	0	1	0	1	0	0	0	1	1	1	1	1
Articulated 2	1	1	1	0	0	1	1	1	1	0	1	0	1	0	0	0	1	1	1	0	0
Scara 1	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	1	1	0	0	0
Scara 2	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	0	0	0	0	0
Gantry 1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Gantry 2	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
KR 120 R2700 EXTRA HA	1	1	1	0	0	1	1	1	1	0	1	0	1	1	1	1	1	1	0	0	0
IRB 6640 / IRB 6640ID	1	1	1	0	0	1	1	1	1	0	1	0	1	1	1	1	0	0	0	0	0
IRB 1600-6/1.2	1	1	1	0	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	0	0

The functional synthesis of assembly machine types and their number and synthesis of assembly system configuration models proposed in sections 8.3 and 8.4, respectively, are non-linear. In order to guarantee global optimum solution, the non-linear models must be changed to the equivalent linear formulation. The equivalent linear formulation is accomplished through [126].

Second, the functional synthesis of assembly machine types and their numbers model is used. This model is solved using NEOS (https://neos-server.org/) in 238.55 seconds and the optimum solution of the objective function equation (7.25) is 3010000. The optimum types of assembly machines chosen according to the functional synthesis of assembly machines types and their numbers model is shown in Table 8.14.

The optimum platform assembly machines determined by the model are assembly robot type "$j=1$" (articulated 1), assembly robot type "$j=5$" (gantry 1), assembly robot type "$j=7$" (KR120R2700 EXTRA HA) and assembly machine type "$j=8$" (IRB6640/IRB6640ID) which are subsets of the assembly system platform vector (8.71). Non-platform assembly machines do not exist in this case study. This is due to the high assembly capability of the assembly robots, which allows the platform assembly robots to assemble all product components (platform and non-platform product components). For example, the assembly system platform industrial robots articulated 1, articulated 2, gantry 1, gantry 2, KR12R2700, IRB6640 and IRB1600-6/1.2 are 6 degree of freedom robots which provides flexibility to these robots in assembling components within different orientations. Hence, the platform assembly robots possess the assembly capability to assemble non-platform product components (in addition to platform product components) such as exhaust valve, outlet spring, camshaft, pushrods and rocker arm.

From mathematical point of view, the developed model is concerned with minimization of the total investment cost, which includes initial investment cost in assembly robots, cost of addition and removal of assembly robots as well as integration and testing cost. For this case study, when minimizing the objective function equation (8.39), the integration and testing cost as well as the addition of assembly machines in the subsequent production periods are 0 and the total investment cost is only incurred for the initial investment cost in assembly robots.

This complies with the characteristics of platform assembly machines listed in chapter 2 section 2.6 in which platform assembly machines can process or assemble non-platform product features or components if they possess the sufficient capabilities.

Table 8.14: Optimum platform and non-platform machines types and their numbers

j	Machine type	Platform machines ($x_{j,t}^{m}$)		Non-platform machines ($y_{j,t}^{m}$)		Number of machines ($Nst_{j,t}$)	
		$t=1$	$t=2$	$t=1$	$t=2$	$t=1$	$t=2$
1	Articulated 1	1	1	0	0	3	3
2	Articulated 2	0	0	0	0	0	0
3	Scara 1	0	0	0	0	0	0
4	Scara 2	0	0	0	0	0	0
5	Gantry 1	1	1	0	0	1	1
6	Gantry 2	0	0	0	0	0	0
7	KR 120 R2700 EXTRA HA	1	1	0	0	2	2
8	IRB 6640 / IRB 6640ID	1	1	0	0	3	3
9	IRB 1600-6/1.2	0	0	0	0	0	0

Third, the physical synthesis of assembly system configuration model is used. This model is solved using NEOS in 2175 seconds and the optimum solution of the objective function equation (8.60) is -1290640 with a MIPgap of 1.9436%. The results according to the physical synthesis of assembly system configuration is shown in Figure 8.8. The components being assembled in each stage for each product variant is identified in the shaded box.

It is evident that there is a difference in the number of machines when determining the assembly system configuration in Figure 8.8 compared to the results in Table 8.14. This difference occurs as a result of using constraints equations (8.55) and (8.64). After calculating the number of machines in the whole system according to equation (8.55), the final solution is rounded once for the whole number of machines in the assembly system. However, for equation (8.64), the final solution is the summation of the rounded solution for each stage.

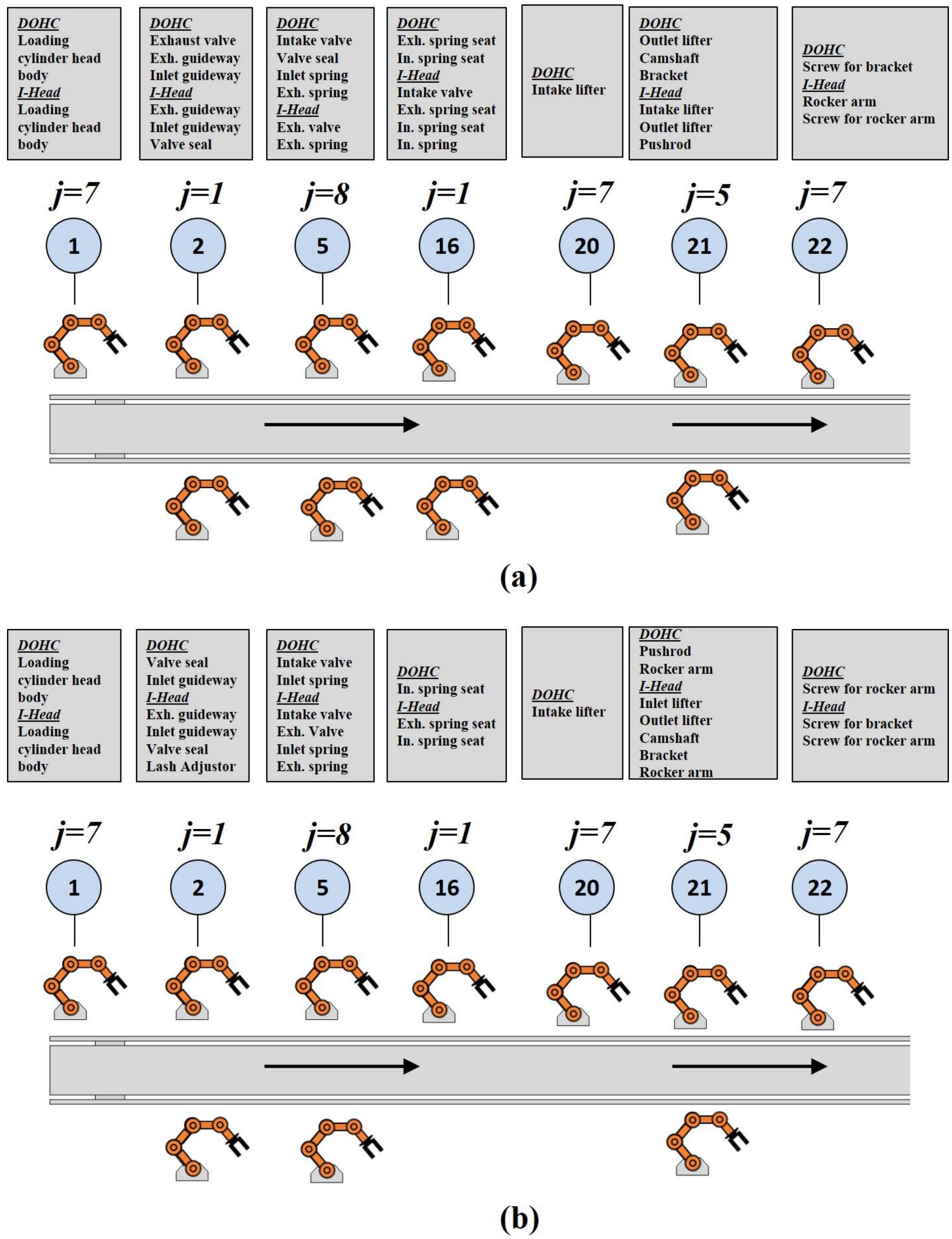


Figure 8.8 Assembly system configuration for (a) production period 1 and (b) production period 2

8.7 Conclusion

This chapter provides an integrated model for the co-platforming methodology for assembly systems. The integrated co-platforming methodology is solved in three phases namely; functional synthesis of assembly machine candidates, functional synthesis of optimum assembly machine types and their number and finally, physical synthesis of assembly configuration. For each phase, various models such as matrix-based formulation and mixed integer linear programming optimization models are used.

The methodology is applied to a case study of engine cylinder head assembly. the outputs from the model in phase 1 are used as input parameters to the mathematical model in phase 2. The optimum assembly machine types and their numbers are chosen based on the objective function, which minimizes the total investment cost (initial investment cost, addition and removal cost as well as integration and testing cost). Next, phase 3 is applied which is concerned with the physical synthesis of the assembly system configuration. The objective function is to minimize the total investment cost). The order of the assembly system stages is chosen based on the precedence relationship between the assembled components and their assembly operations.

The platform assembly machines were chosen with relatively high assembly capabilities (in the form 6 assembly axis robot or 6 degrees of freedom) than the non-platform assembly machines. In addition, platform assembly machines mainly assemble product platform components. However, in this case study, platform assembly machines might also be used to assemble non-platform product features and components when the platform assembly machines possess sufficient assembly capabilities.

The significance of the proposed methodology is two folds. First, the proposed newly synthesized assembly system is used to assemble the different product variants (cylinder heads) within different production periods. Second, when the model is solved within different phases, the complexity of the mathematical model each phase is reduced since inputs to each phase are considered outputs from preceding phase. This reduces the burden of solving each phase on its own.

CHAPTER 9. DISCUSSION AND CONCLUSION

9.1 Overview

This chapter provides the novelty and contribution achieved in this dissertation as well as the industrial significance. The future work as well as the final conclusions will also be presented.

9.2 Novelty and Contribution

A new concept in manufacturing system synthesis is proposed in this dissertation in addition to three mathematical models in order to fill research gaps in manufacturing system synthesis:

- A new notion in the field of concurrent development of products and manufacturing systems; namely ‘‘Co-platforming’’ was introduced. “Co-platforming” is used to synthesize manufacturing systems through mapping platform and non-platform product components and features with platform and non-platform machines, respectively.
- A new matrix based mapping model has been developed in order to synthesize functional candidate manufacturing system machines through mapping platform and non-platform product components and features to candidate platform and non-platform machines, respectively. In addition to synthesizing the manufacturing system, the powerfulness of this method is also evident in its ability to provide on-field support due to the low computational time which can provide sufficiently quick results to decision makers within the facility and hence the method can handle real size problems.
- A new coefficient called the candidate ranking coefficient is proposed in order to assist decision maker within a manufacturing firm to choose among platform machines based on their cost or their machining capabilities.
- A new mixed integer linear programming model is developed in order to synthesize functional selected machine types among the candidates specified in the previous point and number of each machine type. The model has been applied on a case study taken from automotive engine manufacturer. The results from the model indicates that significant cost savings (compared to other manufacturing paradigms such as dedicated system and flexible systems) is achieved by maintaining a common core of manufacturing system components which are kept intact during the different periods,

while accounting for evolvable product requirements through non platform system components.

- A new mixed integer linear programming model is developed in order to synthesize functional selected machine types and numbers taking the system and machine level change into consideration.
- A new mixed integer linear programming model is developed in order to synthesize the physical manufacturing system configuration (manufacturing system layout, number of stages, number of machines in each stage, optimum type of platform and non-platform machines among the candidate of platform and non-platform machines).
- A integrated co-platforming model is proposed for synthesizing the functional and physical level of the manufacturing system. The model is applied for functional synthesis of generic machine candidates, functional synthesis of optimum machine types and their number and finally, the physical synthesis of manufacturing system configuration. This model is solved within different phases which reduces the complexity of mathematical model in each phase of the solution since inputs to each phase are considered outputs from the preceding phase hence giving different levels of solutions depending on the details required by the manufacturing firm.
- The developed models are applied on two industrial case studies. The first case study is concerned with machining of automotive cylinder block engines. The second case study is concerned with assembly of automotive cylinder heads.

9.3 Limitations

The models introduced in this dissertation have limitations on the computational level. For the functional synthesis of generic machine candidates model in chapter 4, the model has been solved using Matlab on process Intel® Xeon® CPU 2.67GHz and RAM 12.0 GB. The elapsed CPU time for case instances 1 and 2 is approximately 0.034 seconds. On the same computer configuration, the elapsed CPU time for 500 types of features, 500 machines, 500 different axis and 500 variants is 317.8 seconds. The elapsed CPU time for 1000 types of features, 1000 machines, 1000 different axis and 1000 variants is 2493.4 seconds.

The models in chapters 5, 6 and 7 have been solved using NEOS server. For the functional synthesis of machine types and the number of each machine model in chapter 5, the largest attempted problem size of 2 production periods, 8 products variants, 18 machining operations, 20 product features and 10 machines has been solved in 361.34 seconds.

For the cost of change of manufacturing system through co-platforming taking into consideration machine and system level model in chapter 6, when solving a problem size of 3 production periods, 8 product variants, 18 machining operations, 9 product features and 12 machines, the computational time is 1807.95 seconds. With similar problem size but increasing the machining operations to 54 instead of 18, the mathematical model is not solved.

For the physical synthesis model in chapter 7, the maximum problem size achieved is 2 production periods, 8 products variants, 18 machining operations, 9 product features and 10 machines at 1068.9 seconds.

It should be mentioned that since the mathematical programming models will be used during system design stage, the solution time is not critical since it is not a real time application.

9.4 Significance

The proposed dissertation is beneficial in synthesizing manufacturing system with low investment costs. This is achieved by maintaining a group of platform machines that do not change with the change in product variants in the different production periods. Therefore, a stable manufacturing system is synthesized which requires less re-tooling, upgrades and purchases of manufacturing system components which supports economic sustainability of the manufacturing system. In addition, the synthesized manufacturing system supports product customization, evolution and changes cost effectively. Frequent changes in product design (in the non-platform product components and features) can be accomplished by easily adding or removing non- platform system components with minor layout changes while the platform system components remain intact.

9.5 Future Work

Several extensions can be included as a part of future work. These extensions can be summarized as:

1- Including other types of manufacturing system components: This dissertation mainly focuses on machine tools within a manufacturing system. Other manufacturing system components can be included such as material handling units and buffers.
2- Performance analysis: It will be required to carry out different scenarios using a simulation package in order to determine performance measures such as system utilization and reliability with different product demand scenarios.
3- Reverse mapping from system to product: In this dissertation, the mapping takes place in one direction from product to system. The possibility of reverse mapping direction from system to product may be explored to be able to synthesize product with the prior knowledge of the system.
4- Operation costs: Operation costs can be included in order to determine the overall cost of the manufacturing process.
5- Operating policies: Batch size and production scheduling can be included in order to determine the effect of the co-platforming strategy on the operating policies.
6- Meta-heuristics: The models in the dissertation can be reformulated and solved using meta-heuristic methods such as genetic algorithm in order to accommodate large size problems. However, sub-optimal solutions are considered the main problem when applying meta-heuristics.

9.6 Conclusion

This dissertation introduces a new notion in the field of synthesis of manufacturing systems; namely “Co-platforming”. Co-platforming is defined as the synthesis of manufacturing system by mapping of product platform components/features to platform machines and non-platform product features/components to non-platform machines. Various methods and tools have been developed such as matrix based mapping and optimization mathematical programming models in order to come up with the results in this dissertation. These methods and tools have been developed in order to synthesize manufacturing systems from functional level (specific machine types and numbers) to physical level (manufacturing system configuration).

The methodology has been applied on industrial case study taken from an automotive cylinder blocks manufacturer. The results from the methodology were similar to the results implemented by the cylinder block manufacturer which aids the validation of the proposed methods and accordingly supports its reliability in being applied to other real case studies.

Important conclusions derived from this dissertation can be summarized as:

- Manufacturing systems can be synthesized concurrently with the product design by, on one side, mapping product platform features and components to platform machines. On the other side, non-product platform features and components to non-platform machines. Platform product and system components remain intact within the different production periods while non-platform product and system components are modified according to the change in product design which arises from changes in customer requirements in products.
- Matrix based formulation is used for the functional synthesis of manufacturing systems and not only for analysis purposes.
- The matrix based formulation for the functional synthesis of manufacturing systems only provides the list candidate machines making it less effective compared to mathematical programming which determines the optimum types and number of machines based on objective function (e.g. investment cost).
- The proposed co-platforming method is effective in synthesizing manufacturing systems in different production periods with minimum layout changes, re-tooling and setup modifications.
- In each production period, the platform machines are maintained without modifications while non-platform machines are added or removed
- Reduction in total investment cost of manufacturing system is achieved when maintaining a group of platform machines compared to systems synthesized without platform system machines.
- The platform machines are chosen with relatively higher machining capabilities than the non-platform machines.
- The platform machines can be in the form of modular machines in which machine level changes can be applied. For example, two axes can be added to a 3-axis CNC modular machine in certain production period in order to change the number of axes to 5. This allows for extending the capability of the 3-axis CNC modular platform machine.
- Platform machines mainly process/assemble product platform features and components.
- Platform machines might also be assigned to process non platform product features and components in case the platform machine possesses the sufficient machining/assembly capabilities required.

REFERENCES

[1] ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schonsleben, P., Tseng, M., Bernard, A., 2013, *Product variety management*, CIRP Annals - Manufacturing Technology, 62/2:629-652.

[2] Ulrich, K., 1995, *Role of product architecture in the manufacturing firm*, Research Policy, 24/3:419-419.

[3] D'Souza, B.S., Simpson, T.W., 2002, *A genetic algorithm based method for product family design optimization*, *ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE2002, September 29, 2002 - October 2, 2002*, Montreal, QC, Canada: Web Portal ASME (American Society of Mechanical Engineers), 681-690.

[4] Jianxin, J., Tseng, M.M., 2000, *Fundamentals of product family architecture*, Integrated Manufacturing Systems, 11/7:469-83.

[5] ElMaraghy, H.A. *Changeable and reconfigurable manufacturing systems*. 2009; Available from: http://dx.doi.org/10.1007/978-1-84882-067-8.

[6] Azab, A., ElMaraghy, H.A., 2007, *Mathematical Modeling for Reconfigurable Process Planning*, CIRP Annals - Manufacturing Technology, 56/1:467-472.

[7] ElMaraghy, H.A., 2007, *Reconfigurable process plans for responsive manufacturing systems*, in *Digital enterprise technology*, Springer, 35-44.

[8] Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., Van Brussel, H., 1999, *Reconfigurable manufacturing systems*, CIRP Annals - Manufacturing Technology, 48/2:527-540.

[9] ElMaraghy, H.A., 2005, *Flexible and reconfigurable manufacturing systems paradigms*, International journal of flexible manufacturing systems, 17/4:261-276.

[10] Gedell, S., Michaelis, M.T., Johannesson, H., 2011, *Integrated Model for Co-development of Products and Production Systems: A Systems Theory Approach*, Concurrent Engineering: Research and Applications, 19/2:139-56.

[11] Bryan, A., Wang, H., Abell, J., 2013, *Concurrent design of product families and reconfigurable assembly systems*, Journal of Mechanical Design, Transactions of the ASME, 135/5:

[12] ElMaraghy, H.A., AlGeddawy, T., 2012, *Co-evolution of products and manufacturing capabilities and application in auto-parts assembly*, Flexible Services and Manufacturing Journal, 24/2:142-70.

[13] AlGeddawy, T., ElMaraghy, H., 2012, *A co-evolution model for prediction and synthesis of new products and manufacturing systems*, Journal of Mechanical Design, 134/5:051008 (12 pp.).

[14] ElMaraghy, W., ElMaraghy, H., 2014, *A New Engineering Design Paradigm–The Quadruple Bottom Line*, Procedia CIRP, 21/18-26.

[15] Tomiyama, T., Gu, P., Jin, Y., Lutters, D., Kind, C., Kimura, F., 2009, *Design methodologies: Industrial and educational applications*, CIRP Annals-Manufacturing Technology, 58/2:543-565.

[16] Hanafy, M., ElMaraghy, H., 2014, *Co-design of Products and Systems Using a Bayesian Network*, Procedia CIRP, 17/284-289.

[17] ElMaraghy, H., Kashkoush, M., 2015, *Assembly system synthesis using association rule discovery*, The International Journal of Advanced Manufacturing Technology, 1-18.

[18] Bryan, A., Hu, S.J., Koren, Y., 2013, *Assembly System Reconfiguration Planning*, Journal of Manufacturing Science and Engineering, 135/4:041005-041005.

[19] Demoly, F., Xiu-tian, Y., Eynard, B., Gomes, S., Kiritsis, D., 2012, *Integrated product relationships management: a model to enable concurrent product design and assembly sequence planning,* Journal of Engineering Design, 23/7:544-61.

[20] Michalek, J.J., Ceryan, O., Papalambros, P.Y., Koren, Y., 2005, *Manufacturing investment and allocation in product line design decision-making*, *DETC2005: ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, September 24, 2005 - September 28, 2005*, Long Beach, CA, United states: American Society of Mechanical Engineers, 189-198.

[21] De Lit, P., L'Eglise, T., Delchambre, A., 2001, *Functional entities: A concept to support product family and assembly system design*, *Proceedings of the 2001 IEEE International Symposium on Assembly and Task Planning (ISATP2001) Assembly and Disassembly in the Twenty-first Century, 28-29 May 2001*, Piscataway, NJ, USA: IEEE, 160-5.

[22] Zhonghui, X., Ming, L., 2005, *Concurrent optimization of product module selection and assembly line configuration: a multi-objective approach,* Transactions of the ASME. Journal of Manufacturing Science and Engineering, 127/4:875-84.

[23] Michaelis, M.T., Johannesson, H., ElMaraghy, H.A., 2015, *Function and process modeling for integrated product and manufacturing system platforms,* Journal of Manufacturing Systems, 36/203-215.

[24] Michaelis, M.T., Johannesson, H., 2011, *Platform approaches in manufacturing - Considering integration with product platforms*, *ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2011, August 28, 2011 - August 31, 2011*, Washington, DC, United states: American Society of Mechanical Engineers, 1115-1124.

[25] Ueda, K., Markus, A., Monostori, L., Kals, H.J.J., Arai, T., 2001, *Emergent synthesis methodologies for manufacturing,* CIRP Annals - Manufacturing Technology, 50/2:535-551.

[26] Belisário, L.S., Pierreval, H., 2013, *A conceptual framework for analyzing adaptable and reconfigurable manufacturing systems*, *Industrial Engineering and Systems Management (IESM), Proceedings of 2013 International Conference on*: IEEE, 1-7.

[27] Bordoloi, S.K., Cooper, W.W., Matsuo, H., 1999, *Flexibility, adaptability, and efficiency in manufacturing systems,* Production and Operations Management, 8/2:133-150.

[28] Keddis, N., Burdalo, J., Kainz, G., Zoitl, A., 2014, *Increasing the adaptability of manufacturing systems by using data-centric communication*, *Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA)*: IEEE, 1-8.

[29] American Society of Mechanical, E., 2004, *Mathematical definition of dimensioning and tolerancing principles : an American national standard; ASME Y14.5.1M-1994. [Date of issuance: January 31, 1995; reaffirmed 1999; reaffirmed 2004]*, New York, American Society of Mechanical Engineers.

[30] Shah, J.J., Rogers, M.T., 1988, *Functional requirements and conceptual design of the feature-based modelling system,* Computer-Aided Engineering Journal, 5/1:9-15.

[31] ElMaraghy, H., 1991, *Intelligent product design and manufacture*, *Artificial Intelligence in Design*: Springer, 147-168.

[32] Shahin, T.M., 2008, *Feature-based design–an overview,* Computer-Aided Design and Applications, 5/5:639-653.

[33] Han, J., 1996, *Survey of feature research,* Department of Computer Science and Institute for Robotics and Intelligent Systems, University of Southern California, Los Angeles, CA, USA,

[34] Shah, J.J., 1991, *Conceptual development of form features and feature modelers,* Research in engineering design, 2/2:93-108.

[35] Bernardi, A., Legleitner, R., Klauck, C., 1993, *PIM—skeletal plan-based CAPP*, Computers in industry, 23/1:87-97.
[36] ElMaraghy, H.A., 1993, *Evolution and future perspectives of CAPP*, CIRP Annals - Manufacturing Technology, 42/2:739-751.
[37] Shah, J.J., 1991, *Assessment of features technology*, Computer-Aided Design, 23/5:331-343.
[38] Shah, J.J., Mäntylä, M., Nau, D.S., 2013, *Advances in feature based manufacturing*, Elsevier.
[39] Salomons, O.W., van Houten, F.J., Kals, H., 1993, *Review of research in feature-based design*, Journal of Manufacturing Systems, 12/2:113-132.
[40] Amaitik, S.M., 2012, *An Integrated CAD/CAPP System based on STEP Features, Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey*,
[41] ISO10303-224. *Industrial automation systems and integration -- Product data representation and exchange -- Part 224: Application protocol: Mechanical product definition for process planning using machining features*. 1999; Available from: http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=36000.
[42] Qian, X., Dutta, D., 2004, *Feature-based design for heterogeneous objects*, Computer-Aided Design, 36/12:1263-1278.
[43] Shah, J.J., Mäntylä, M., 1995, *Parametric and feature-based CAD/CAM: concepts, techniques, and applications*, John Wiley & Sons.
[44] Nof, S.Y., 1999, *Handbook of industrial robotics*, Vol. 1, John Wiley & Sons.
[45] Wang, Z., Xu, H., Chen, G., Sun, R., Lining, S., 2014, *A distance error based industrial robot kinematic calibration method*, Industrial Robot, 41/5:439-46.
[46] Youssef, A.M.A., ElMaraghy, H.A., 2006, *Modelling and optimization of multiple-aspect RMS configurations*, International Journal of Production Research, 44/22:4929-4958.
[47] Koren, Y., 2010, *The global manufacturing revolution: product-process-business integration and reconfigurable systems*, Vol. 80, John Wiley & Sons.
[48] Simpson, T.W. *Advances in product family and product platform design : methods & applications*. 2013; Available from: http://dx.doi.org/10.1007/978-1-4614-7937-6.
[49] Nayak, R.U., Chen, W., Simpson, T.W., 2002, *A variation-based method for product family design*, Engineering Optimization, 34/1:65-81.
[50] Simpson, T.W., 2004, *Product platform design and customization: status and promise*, (AI EDAM) Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 18/1:3-20.
[51] Jose, A., Tollenaere, M., 2005, *Modular and platform methods for product family design: Literature analysis*, Journal of Intelligent Manufacturing, 16/3:371-390.
[52] Li, L., Huang, G.Q., 2009, *Multiobjective evolutionary optimisation for adaptive product family design*, International Journal of Computer Integrated Manufacturing, 22/4:299-314.
[53] Zhihuang, D., Scott, M.J., 2007, *Product platform design through sensitivity analysis and cluster analysis*, Journal of Intelligent Manufacturing, 18/1:97-113.
[54] Beibei, F., Guoning, Q., Xiaomei, H., Tao, Y., 2015, *A network methodology for structure-oriented modular product platform planning*, Journal of Intelligent Manufacturing, 26/3:553-70.
[55] Olivares-Benitez, E., Gonzalez-Velarde, J., 2008, *A metaheuristic approach for selecting a common platform for modular products based on product performance and manufacturing cost*, Journal of Intelligent Manufacturing, 19/5:599-610.
[56] Agard, B., Bassetto, S., 2013, *Modular design of product families for quality and cost*, International Journal of Production Research, 51/6:1648-1667.

[57] Hanafy, M., ElMaraghy, H., 2015, *Developing assembly line layout for delayed product differentiation using phylogenetic networks*, International Journal of Production Research, 53/9:2633-51.

[58] Hernandez, G., Allen, J.K., Mistree, F., 2002, *Design of hierarchic platforms for customizable products*, *ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE2002, September 29, 2002 - October 2, 2002*, Montreal, QC, Canada: Web Portal ASME (American Society of Mechanical Engineers), 567-577.

[59] Du, G., Jiao, R.J., Chen, M., 2014, *Joint optimization of product family configuration and scaling design by Stackelberg game*, European Journal of Operational Research, 232/2:330-341.

[60] Zhang, L.L., 2015, *A literature review on multitype platforming and framework for future research,* International Journal of Production Economics, 168/1-12.

[61] Hanafy, M., ElMaraghy, H., 2013, *A Multi-Period Changeable Modular Product Assembly Model*, *5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production*, Munich, Germany,

[62] AlGeddawy, T., ElMaraghy, H., 2013, *Reactive design methodology for product family platforms, modularity and parts integration,* CIRP Journal of Manufacturing Science and Technology, 6/1:34-43.

[63] Fujita, K., Yoshida, H., 2004, *Product variety optimization simultaneously designing module combination and module attributes,* Concurrent Engineering: Research and Applications, 12/2:105-18.

[64] ElMaraghy, H., AlGeddawy, T., 2012, *New dependency model and biological analogy for integrating product design for variety with market requirements,* Journal of Engineering Design, 23/10-11:719-42.

[65] Zhang, W.Y., Tor, S.Y., Britton, G.A., 2006, *Managing modularity in product family design with functional modeling,* International Journal of Advanced Manufacturing Technology, 30/7-8:579-88.

[66] Yan Ling, C., Nee, A.Y.C., Wen Feng, L., 2009, *Optimal design of hierarchic components platform under hybrid modular architecture,* Concurrent Engineering: Research and Applications, 17/4:267-77.

[67] Jianxin, J., Yiyang, Z., Yi, W., 2007, *A generic genetic algorithm for product family design*, Journal of Intelligent Manufacturing, 18/2:233-47.

[68] Chowdhury, S., Messac, A., Khire, R.A., 2011, *Comprehensive product platform planning (CP3) framework*, Journal of Mechanical Design, Transactions of the ASME, 133/10:

[69] Qu, T., Bin, S., Huang, G.Q., Yang, H., 2011, *Two-stage product platform development for mass customisation,* International Journal of Production Research, 49/8:2197-2219.

[70] Kumar, D., Wei, C., Simpson, T., 2009, *A market-driven approach to product family design*, International Journal of Production Research, 47/1:71-104.

[71] Khajavirad, A., Michalek, J.J., Simpson, T.W., 2009, *An efficient decomposed multiobjective genetic algorithm for solving the joint product platform selection and product family design problem with generalized commonality*, Structural and Multidisciplinary Optimization, 39/2:187-201.

[72] Alizon, F., Khadke, K., Thevenot, H.J., Gershenson, J.K., Marion, T.J., Shooter, S.B., Simpson, T.W., 2007, *Frameworks for product family design and development*, Concurrent Engineering: Research and Applications, 15/2:189-99.

[73] Farrell, R.S., Simpson, T.W., 2008, *A method to improve platform leveraging in a market segmentation grid for an existing product line,* Journal of Mechanical Design, 130/3:031403-1.

[74] Simpson, T.W., Bobuk, A., Slingerland, L.A., Brennan, S., Logan, D., Reichard, K., 2012, *From user requirements to commonality specifications: An integrated approach to product family design,* Research in Engineering Design, 23/2:141-153.

[75] Thevenot, H.J., Simpson, T.W., 2009, *A product dissection-based methodology to benchmark product family design alternatives,* Journal of Mechanical Design, Transactions of the ASME, 131/4:0410021-0410029.

[76] Alizon, F., Shooter, S.B., Simpson, T.W., 2006, *Improving an existing product family based on commonality/diversity, modularity, and cost*, *2006 ASME International Design Engineering Technical Conferences and Computers and Information In Engineering Conference, DETC2006, September 10, 2006 - September 13, 2006*, Philadelphia, PA, United states: American Society of Mechanical Engineers,

[77] Moon, S.K., Simpson, T.W., Kumara, S.R.T., 2009, *An agent-based recommender system for developing customized families of products,* Journal of Intelligent Manufacturing, 20/6:649-659.

[78] Eun Suk, S., de Week, O., Il Yong, K., Chang, D., 2007, *Flexible platform component design under uncertainty,* Journal of Intelligent Manufacturing, 18/1:115-26.

[79] Eun Suk, S., de Week, O.L., Chang, D., 2007, *Flexible product platforms: framework and case study,* Research in Engineering Design, 18/2:67-89.

[80] Ma, Q., Tan, R., Jiang, P., Yao, B., Hui, X., 2011, *Flexible product platform based on design parameters*, *4th IFIP WG 5.4 Working Conference on Building Innovation Pipelines through Computer-Aided Innovation, CAI 2011, June 30, 2011 - July 1, 2011*, France, France: Springer New York, 7-15.

[81] Alblas, A., Zhang, L.L., Wortmann, H., 2012, *Representing function-technology platform based on the unified modelling language,* International Journal of Production Research, 50/12:3236-3256.

[82] Levandowski, C.E., Corin-Stig, D., Bergsjo, D., Forslund, A., Högman, U., Söderberg, R., Johannesson, H., 2012, *An integrated approach to technology platform and product platform development,* Concurrent Engineering, 1063293X12467808.

[83] Alblas, A.A., Wortmann, J.C., 2014, *Function-technology platforms improve efficiency in high-tech equipment manufacturing: a case study in complex products and systems (CoPS),* International Journal of Operations & Production Management, 34/4:447-76.

[84] Zhang, L.L., Xu, Q., Helo, P., 2013, *A knowledge-based system for process family planning,* Journal of Manufacturing Technology Management, 24/2:174-196.

[85] Zhang, L.L., Jiao, R.J., 2013, *A graph rewriting system for process platform planning,* Decision Support Systems, 54/2:1174-1191.

[86] Lianfeng, Z., Rodrigues, B., 2010, *Nested coloured timed Petri nets for production configuration of product families,* International Journal of Production Research, 48/6:1805-33.

[87] Ko, J., Hu, S.J., 2009, *Manufacturing system design considering stochastic product evolution and task recurrence,* Journal of Manufacturing Science and Engineering, Transactions of the ASME, 131/5:0510121-05101212.

[88] AlGeddawy, T., ElMaraghy, H., 2015, *Determining Granularity of Changeable Manufacturing Systems Using Changeable Design Structure Matrix and Cladistics,* Journal of Mechanical Design, 137/4:041702.

[89] Eguia, I., Lozano, S., Racero, J., Guerrero, F., 2011, *A methodological approach for designing and sequencing product families in Reconfigurable Disassembly Systems,* Journal of Industrial Engineering and Management, 4/3:418-435.

[90] AlGeddawy, T., ElMaraghy, H., 2010, *Design of single assembly line for the delayed differentiation of product variants*, Flexible Services and Manufacturing Journal, 22/3-4:163-182.

[91] AlGeddawy, T., ElMaraghy, H., 2011, *Manufacturing systems synthesis using knowledge discovery*, CIRP Annals-Manufacturing Technology, 60/1:437-440.

[92] Ko, J., Jack Hu, S., 2008, *Balancing of manufacturing systems with complex configurations for delayed product differentiation*, International Journal of Production Research, 46/15:4285-4308.

[93] Li, S., Wang, H., Hu, S.J., Lin, Y.-T., Abell, J.A., 2011, *Automatic generation of assembly system configuration with equipment selection for automotive battery manufacturing*, Journal of Manufacturing Systems, 30/4:188-195.

[94] Ko, J., Hu, S.J., 2007, *Manufacturing System Design Considering Generational Product Evolution and Task Recurrence*, *ASME 2007 International Manufacturing Science and Engineering Conference*: American Society of Mechanical Engineers, 815-826.

[95] Shabaka, A.I., ElMaraghy, H.A., 2007, *Generation of machine configurations based on product features*, International Journal of Computer Integrated Manufacturing, 20/4:355-69.

[96] Chen, L., Xi, F.J., Macwan, A., 2005, *Optimal module selection for preliminary design of reconfigurable machine tools*, Journal of Manufacturing Science and Engineering, 127/1:104-115.

[97] Mesa, J., Maury, H., Turizo, J., Bula, A., 2014, *A methodology to define a reconfigurable system architecture for a compact heat exchanger assembly machine*, The International Journal of Advanced Manufacturing Technology, 70/9-12:2199-2210.

[98] Hanafy, M., ElMaraghy, H., 2015, *Integrated products–systems design environment using Bayesian networks*, International Journal of Computer Integrated Manufacturing, 1-16.

[99] Wang, H., Zhu, X., Wang, H., Hu, S.J., Lin, Z., Chen, G., 2011, *Multi-objective optimization of product variety and manufacturing complexity in mixed-model assembly systems*, Journal of Manufacturing Systems, 30/1:16-27.

[100] Roemer, T.A., Ahmadi, R., 2010, *Models for concurrent product and process design*, European Journal of Operational Research, 203/3:601-613.

[101] Suh, N.P., 1990, *The principles of design*, Vol. 990, Oxford University Press New York.

[102] Samy, S.N., ElMaraghy, H.A., 2012, *Complexity mapping of the product and assembly system*, Assembly Automation, 32/2:135-51.

[103] Fung, R.Y.K., Popplewell, K., Xie, J., 1998, *An intelligent hybrid system for customer requirements analysis and product attribute targets determination*, International Journal of Production Research, 36/1:13-34.

[104] Ying-Kui, G., Hong-Zhong, H., 2004, *Fuzzy mapping between physical domain and function domain in design process*, International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 12/1:7-20.

[105] Krishnapillai, R., Zeid, A., 2006, *Mapping product design specification for mass customization*, Journal of Intelligent Manufacturing, 17/1:29-43.

[106] Danilovic, M., Browning, T.R., 2007, *Managing complex product development projects with design structure matrices and domain mapping matrices*, International Journal of Project Management, 25/3:300-314.

[107] Yassine, A., Whitney, D., Daleiden, S., Lavine, J., 2003, *Connectivity maps: Modeling and analysing relationships in product development processes*, Journal of Engineering Design, 14/3:377-394.

[108] Mohapatra, P., Benyoucef, L., Tiwari, M., 2013, *Integration of process planning and scheduling through adaptive setup planning: a multi-objective approach*, International Journal of Production Research, 51/23-24:7190-7208.
[109] Vorburger, T., Raja, J., 1990, *Surface finish metrology tutorial*, National Inst. of Standards and Technology.
[110] Hu, J., Xiong, G., 2005, *Dimensional and geometric tolerance design based on constraints*, The International Journal of Advanced Manufacturing Technology, 26/9-10:1099-1108.
[111] Tangkoonsombati, C., 1994, *Assembly tolerance analysis in geometric dimensioning and tolerancing*,
[112] Noritaka, F., Tanaka, Y., Sugano, T., 2006, *Ultra-Flexible Manufacturing Line with a Finishing Machining Center for Cylinder Blocks*, Mitsubishi Heavy Industries, Ltd., 43/3:
[113] ElMaraghy, H., AlGeddawy, T., Azab, A., 2008, *Modelling evolution in manufacturing: A biological analogy*, CIRP Annals - Manufacturing Technology, 57/1:467-472.
[114] Halderman, J.D., Mitchell, C.D., 2001, *Worktext for Automotive engines : theory and servicing*, Upper Saddle River, N.J., Prenctice Hall.
[115] Zacharias, N., Yassine, A., 2008, *Optimal platform investment for product family design*, Journal of Intelligent Manufacturing, 19/2:131-48.
[116] Bisschop, J., 2006, *AIMMS-Optimization modeling*, Lulu. com.
[117] Czyzyk, J., Mesnier, M.P., More, J.J., 1998, *The NEOS Server*, IEEE Journal on Computational Science and Engineering, 5/3:8.
[118] Dolan, E., 2001, *The NEOS Server 4.0 Adiministrative Guide*, Technical Memorandum ANL/MCS-TM-250, Mathematics and Computer Science Division, Argonne National Laboratory,
[119] Gropp, W., More, J.J., 1997, *Optimization Environments and the NEOS Server.* , Approximation Theory and Optimization, M. D. Buhmann and A. Iserles, eds. Cambridge University press,
[120] Kalpakjian, S., 2014, *Manufacturing engineering and technology*, seven ed, Reading, Mass., Addison-Wesley.
[121] Eppinger, S.D.B.T.R. *Design structure matrix methods and applications*. 2012; Available from: http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=458479.
[122] Varma, V., Lloyd, P., Chesser, J., Jansen, J., Kring, C., 1995, *Automated artillery ammunition fuzing using a passive compliance device*, Oak Ridge, Tenn., Oak Ridge National Laboratory.
[123] Hamrock, B.J., Jacobson, B.O., Schmid, S.R., 1999, *Fundamentals of machine elements*, Boston, WCB/McGraw-Hill.
[124] Simonis, G., 1996, *First robotized assembly line for multivalve cylinder heads in Europe*, ABB Review, 8:28-33.
[125] Kimmelmann, W., Wolbring, F., 1999, *First turnkey delivery of robotized assembly lines for car engines and cylinder heads*, ABB Review, 3:24-31.
[126] FICO, 2009, *MIP Formulations and Linearization: A Quick Reference*, Fair Issac Corporation. p. 1-19.

VITA AUCTORIS

NAME: Mohamed Hussein Mohamed Hassan Abbas

PLACE OF BIRTH: Giza, Egypt

YEAR OF BIRTH: 1985

EDUCATION: B.Sc. in Mechanical Design and Production Engineering, Cairo University, Giza, Egypt, 2007

M.Sc. in Mechanical Design, Cairo University, Giza, Egypt, 2011

PUBLICTIONS: **Journal Papers**

1- ElMaraghy, H., Abbas, M., 2015, *Products-manufacturing systems Co-platforming*, CIRP Annals-Manufacturing Technology, Vol.64/1, pp. 407-410.

2- Abbas, M., ElMaraghy, H., 2016, Design Synthesis of Machining Systems Using Co-platforming, Journal of Manufacturing Systems, Vol.41, pp. 299-313

3- Abbas, M., ElMaraghy, H., Synthesis and Optimization of Manufacturing Systems Configuration Using Co-Platforming, CIRP Journal of Manufacturing Science and Technology, Ref. No.: CIRPJ-D-16-00124. (submitted)

4- Abbas, M., ElMaraghy, H., Functional Synthesis of Manufacturing Systems Using Co-Platforming to Minimize Cost of Machines and System Changes, ASME Journal of Mechanical Design, Ref. No.: MD-16-1616 (submitted)

5- Abbas, M., ElMaraghy, H., Assembly System Synthesis using Co-platforming (to be submitted)

Conference Papers

1- Abbas, M., ElMaraghy, H., 2016, Functional Synthesis of Manufacturing Systems Using Co-platforming, Procedia CIRP, 52/102-107

2- AlGeddawy, T., Abbas, M., ElMaraghy, H., 2014, Design for Mobility–A Customer Value Creation Approach, Procedia CIRP, 16/128-133.

3- Abbas, M.H., Metwalli, S.M., 2011, Elastohydrodynamic ball bearing optimization using genetic algorithm and heuristic gradient projection, ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference: American Society of Mechanical Engineers, 3-12.

4- Abbas, M.H., Youssef, A.M., Metwalli, S.M., 2010, Ball Bearing Fatigue and Wear Life Optimization Using Elastohydrodynamic and Genetic Algorithm, ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference: American Society of Mechanical Engineers, 849-856.