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Aggregate Cost Model for Scalability in Manufacturing Systems

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Aggregate Cost Model for Scalability in Manufacturing Systems

by

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Aggregate Cost Model for Scalability in Manufacturing Systems

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DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is a result of joint research of the author and his supervisor Prof. Waguih ElMaraghy. Chapters 3, 4, 5, and 6 of this thesis were co-authored under the supervision of professor Waguih ElMaraghy. In all chapters, the key ideas, primary contributions, model development, data analysis, interpretation, and writing were performed by the author.

I am aware of the University of Windsor Senate Policy on Authorship. I certify that I have properly acknowledged other researchers' contribution to my thesis and have obtained written permission from Prof. Waguih 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. Previous Publication

This thesis includes four 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
3	Alami, D., & ElMaraghy, W. (2020). Traditional and Activity Based Aggregate Job Costing Model. *Procedia CIRP*, *93*, 610-615.	Conference proceeding (published)
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6	Alami, D. and ElMaraghy, W “A Cost-Benefit Analysis for Industry 4.0 in a Job Shop Environment Using a Mixed Integer Linear Programming Model”, International Journal of Production Economics	Journal (submitted)

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ABSTRACT

Manufacturing continues to face escalated cost challenges on a global scale. To gain a competitive advantage among their rivals, manufacturing firms continuously strive to lower their manufacturing costs than their competitors. This dissertation introduces mathematical optimization model based on an Activity-Based Costing (ABC) method, which considers the relationship between hourly rates and annual hours on each machine/workcentre. Several constraints are considered in the proposed models, such as the cost of reconfiguration~~,~~ capacity, available machining hours, a decision on facility expansion and a cost-benefit analysis on industry 4.0 implementation.

The model outputs are the optimum hourly rates, deciding which jobs to accept or reject, and determining reconfiguration's financial feasibility. Reconfiguration in this dissertation describes system-level reconfiguration (investing in additional equipment/machinery) and/or machine-level reconfiguration (extra module to a piece of existing equipment) as well as factory-level (in terms of expanding additional factory segments to the existing facility). The model will be applied to a real-life case study of a global original equipment manufacturer (OEM) of machinery~~.~~

The mathematical models proposed in this dissertation are developed based on a multinational hydraulic-press manufacturing company. The company owns a local machine shop (one of the sister companies in North America) for building hydraulic presses meant to be delivered to companies producing engineered wood products (such as OSB (oriented Strand Board), PB (Particle Board), and MDF Board (Medium-Density Fibre) …etc.). The sister company in North America occupies a footprint of 5,000 meters squared with a number of capabilities such as machining (turning and machining centres, welding, assembly, material handling…etc.). Several aspects of the model proposed in this dissertation had been implemented in the company such as the bi-directional relationship between total hours and hourly rates which

assisted the company in gaining more jobs and projects. In addition, connectivity between strategic suppliers and company branched has been established (enabler of Industry 4.0).

The proposed model's novelty incorporates the bi-directional relationship between hourly rates and annual hours in each workcentre. It provides a managerial decision-making tool for the investment level required to pursue new business and gaining a competitive advantage over rivals. Furthermore, a cost-benefit analysis is performed on the implementation of Industry 4.0. The primary aspect considered in industry 4.0 is Information Communication Technology (ICT) infrastructure with strategic suppliers to intensify interconnection between the manufacturing firm and the strategic suppliers.

This research's significance is focused on cost analysis and provides managers in manufacturing facilities with the required decision-making tools to decide on orders to accept or decline, as well as investing in additional production equipment, facility expansion, as well as Industry 4.0. In addition, this research will also help manufacturing companies achieve a competitive edge among rivals by reducing hourly rates within their facility. Furthermore, the implementation of the model reduced hourly rates for workcentres by up to 25% as a result of accepting more jobs (and accordingly, machining hours) on the available workcentres, and hence, reducing the hourly rates. This implementation has helped the company gain a competitive advantage among rivals since pricing of products submitted to customer was reduced. Additional benefits and significance are (1) providing manufacturing companies with a method to quantify the decision-making process for right-sizing their manufacturing space, (2) the ability to justify growing a scalable system (machine level, system-level and factory level) using costing (not customer demand), (3) expanding market share and, (4) reducing operational cost and allowing companies a numerical model to justify scaling the manufacturing system.

DEDICATION

To my father, Nabil, for his guidance and encouragement through my life

To my mother, Badira, for her unconditional love and infinite care throughout my life

To my wife, Zahra, for her love and continued support during the long journey

To my parents, Gus and Joanne, for their unconditional patience and encouragements to my family

To my kids, Yousef, Amr and Jineanne, for their patience and love during long nights

To my supervisor, for his direction and assistance during uncertain times

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To Fr. Thomas Rosica for believing in me, and allowing me a chance to start me educational journey

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CHAPTER 1 Introduction

1. Motivation

Manufacturing continues to face escalated cost challenges as the global economy challenge grows. The global manufacturing and supply chain are very quickly, becoming our small back yard. With the continued growth of facilitated global communication tools ranging from easier travel flights to Internet communication tools, instant messaging, video conferencing, and live video streaming, the decision to go to low-cost suppliers became the obvious choice and decision for many companies with increased pressure on maintaining/increasing profitability for shareholders. To gain a competitive advantage among its rivals, manufacturing firms continuously strive to lower their manufacturing costs than their competitors. With shortening the supply chain's distance and spreading the geographical distance on the global manufacturing footprint, some unexpected costs that have not been captured in the past within some industries have started showing up in the process. These costs started deteriorating the profitability of many corporations as well as not capturing the actual job cost. The profits that seemed to look attractive at the early stages of the product realization process no longer seemed achievable.

Towards this goal, manufacturing firms started adopting cost models to capture actual product costs adequately. Initially, traditional costing models were extensively used to determine product costs. The most critical costs in traditional cost models are direct labour and direct material costs. However, with the increase in product offering and processes automation in today’s manufacturing era, overhead allocation accounts for a large portion of the cost. Hence, overhead costs are considered the prime cost. Additionally, our modern manufacturing environment started distinguishing itself by diversifying and adapting to frequent product requirements changes. It also required a more adaptable and scalable manufacturing system to keep up with the frequent global changes in both products’ families and processes.

Additionally, manufacturing firms strive to deliver a portfolio of products to their customers to increase their market shares. Since the product development process includes various inter-related activities, it becomes a more significant challenge for manufacturing firms to trace and allocate the different activities to cost objects to specify the cost of their products and services.

Hence the need existed to re-evaluate costing models, predict, and capture all costs associated with the manufacturing system. Besides, additional factors that would include investing in cutting edge technology, changing the footprint of facilities, and integrating Industry 4.0 should be considered to stay ahead of competitors.

This dissertation is organized as follows; Chapter 2 provides a literature survey in costing methods, manufacturing systems and industry 4.0, Chapter 3 provides a mathematical model that minimizes cost by taking into consideration the bi-directional relationship between annual hours and hourly rates. This model's, and subsequent models', output is the decision for which jobs to accept for the manufacturing firm. Chapter 4 provides a mathematical model taking into consideration the cost of reconfiguration in machine and system level, Chapter 5 provides a mathematical model which considers the decision of facility expansion, Chapter 6 proposes a mathematical model which considers the cost-benefit of applying industry 4.0, Chapter 7 is dedicated for validation and verification of the mathematical model. Finally, Chapter 8 summarizes the conclusions and future work of this dissertation.

1.1. Engineering Problem Statement

Working as an engineer and progressing in manufacturing management for more than 20 years in the manufacturing industry, the author has continually faced a common challenge throughout his career. There were times where a decision needed to be made as to grow, or scale, the manufacturing operations, equipment or manufacturing facility. In addition to the general economic environment exhibited in terms of a growing economy, low-interest rate, and status of the industry (in terms of vehicles sold per year), there were no tools available to assist in the decision-making process for scaling the depart/operations/facility size. Each time the author experienced such a scenario, a few months were spent collecting all the data and formulating a specific business case to help make the crucial decision. While the process was very effective and helped the author get promoted in his career, the process was very inefficient and time-consuming. In the early 2000s, while the economy was growing, the author experienced a few occasions while working for Ford Motor Company/Visteon, the need for growth in a manufacturing environment. On the other hand, after the 2008 slowdown/recession, the need existed again. However, this time, it was needed to scale operations down and match the economic situation needs. A similar business case was developed to right-size the manufacturing facility. A few years later, as the need arose, while working at Neapco, the author ran into a case to grow their Mexican facility from 60,000 to 350,000 sq. ft. Again, many pieces of data were collected from the enterprise and developed an overhead model for the facility and tried to build a business case to make the correct decision for the facility's growth. A few years later, when the author was the President of Dieffenbacher North America, a similar problem existed for growth in the department and the overall facility. As the Author got into owning his own automation/manufacturing business, the same issue arose again for growth. Each one of those problems had two common characteristics. First, they all lacked the structure for data for having the required scientific decision for sizing the facility; second, they all followed the same thought process (with minor modifications).

As a result, the author focused on developing mathematical models that encompasses small to medium manufacturing firms that can be used as a tool for the management team by integrating a lot of existing manufacturing data, already available within any given legacy system in the company, to help aid the decision from an "I feel" decision, to a more "Scientific data-backed" decision. The need for such a decision is becoming more relevant and needed, particularly when talking about integrated smart manufacturing environment.

Reconfigurable Manufacturing Systems, Cellular Manufacturing, Flexible Manufacturing Systems and Job Shops have had a tremendous amount of work completed describing what and how these systems function. However, there was not enough discussion and research to create tools to enable changing the system size to enable the system to adjust to the system's environment. Hence:

"It is required to introduce mathematical models which take into consideration realistic costs to capture actual job/projects costs, calculate and reduce the orders/project costs within a low-volume production facility and aid in the decision of scalability (facility expansion/addition of new equipment/modification of current equipment)."

1.2. Research Scope

Cost accounting is the type of cost incurred after the product is manufactured. Accountants prepare this type of cost. There are several types of cost accounting. Process costing method is employed when a standard product is being made, which involves many distinct processes performed in a defined sequence. Process costing is applied mainly in continuous manufacturing (i.e. oil refinery). It is applied to the manufacturing environment in which similar products are produced. Job costing is concerned with finding the cost of each job or contract. Batch costing is a form of job costing. Instead of costing each component separately, each batch of components is taken together and treated as a job. Hybrid costing is a combination of the above. In this research, job costing is used, as it is the most practiced method of costing in the industry and very easily understood and adaptable to the model created herein.

Besides, there exist three main cost systems: (i) traditional costing system, (ii) Activity-Based Costing (ABC) and (iii) variable based costing (Geiszler, Baker, & Lippitt, 2017; Hughes & Paulson Gjerde, 2003). Monroy et al. (Monroy, Nasiri, & Peláez, 2014) presented the three different accounting systems’ approaches to manufacturing; (i) Activity-Based Costing, (ii)Time-Driven Activity-Based Costing and (iii) Lean Accounting.

As lean manufacturing implies, the identification of non-value-add activities and reducing them (if not eliminating them), lean accounting can also be defined as removing or eliminating waste within the accounting process. There are three supporting key points for applying lean accounting in the lean organization: visual management, value stream management and continuous improvement (Maskell & Kennedy, 2007). In this dissertation, Activity-Based Costing (ABC) method is used. Further details on the ABC method will be discussed in the coming section.

As indicated earlier, job costing will be considered in this research. A job is defined as an order pertaining to specific customer orders. A job can be an automated cell solution to be delivered to Tier 1 supplier or OEMs or products to be delivered directly to customers. Each job contains various activities:

- Engineering cost, which pertains to the number of hours spent on designing the product included in the job (Mechanical design concept, design detailing, Electrical design and controls…etc.)
- Production cost, which pertains to machining components, fabrication, assembly (Mechanical, Electrical and hydraulic)
- Commissioning and debugging
- Raw material and commercial components are used in this research, which is related to the direct material cost for each job.

The manufacturing system’s scope of application in this dissertation includes existing and new manufacturing systems. The nature of the manufacturing system in this dissertation is discrete manufacturing systems. Manufacturing System purpose and function include fabrication (machining) and assembly systems. Manufacturing system types considered are job shop, dedicated manufacturing lines, flexible manufacturing systems, manufacturing cells and reconfigurable manufacturing systems, as shown in Fig. 1.

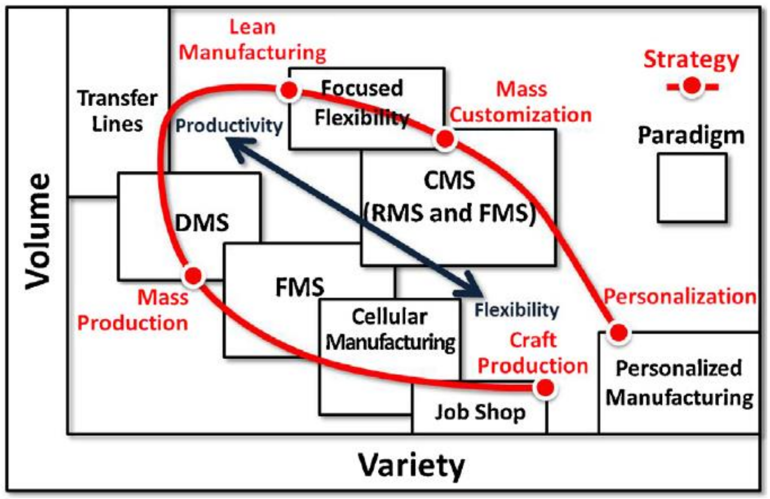

Fig. 1. Production systems types and paradigms (Hoda ElMaraghy et al., 2013)

The considered manufacturing system components include machine tools and assembly machines (e.g. CNC machines, horizontal milling machines, industrial robots, presses…etc.). The changes considered are: System-level change (addition or removal of machines), machine-level change (adding axes, setup change) and factory- level change (adding segments to the factory). Production volume is based on low-to-medium production volume (from 10 to 10,000 units per year) to high production volume (from 10,000 to a million units per year) (Groover, 2019).

The models created in this dissertation can be used to help manufacturing companies' management make decisions. These decisions are usually categorized as strategic, tactical and operational level decisions. The models introduced in this dissertation are designed to be used at any management decision level. They can be applied to any decision level depending on the circumstances around each model, as will be explained in each chapter. The difference among the different decision levels would be based on how the user applies the length of the periods in the model. The common application of all models can assist the management in making decisions at any level, as follows:

- Operational decisions: the user would need to set the period of the model as short-term runs (measured in hours or day). This would require running the model more often. This exercise can help making decisions in operations scheduling, the decision on the job mix and capacity.

- Tactical decisions/medium term (once per year): the user would need to set the period of the model as medium-term runs (measured in week(s) or month(s)). This exercise can be run every six months, or annually. It can help the firm make decisions about accepting sales jobs, capacity planning, and quoting jobs.

- Strategic decisions: the user would need to set the period of the model as long-term runs (measured in quarter(s) to year(s)). This kind of run help management with running what-if scenarios to help the top leadership of the company to make more informed decisions about the future, such facility expansion, strategic moves, etc.

1.3. Definitions

Several definitions are introduced in this section to facilitate the understanding of the different concepts introduced in this research.

1.3.1. Cost Estimation and Accounting

Costing is defined as the process of calculating the cost (or price) required to produce a specific product or a group of products (Aderoba, 1997). It is divided into two types (i) cost estimation and (ii) cost accounting (Kesavan, 2004). *Cost estimation* is determined before the product is manufactured. This cost is delivered to the customer's attention in the form of a quote that is prepared by production planning, technical personnel or engineering. In a different context, Omitaomu (Omitaomu, 2006) defined cost estimation as the process of forecasting the impact of present and future on cash-flow of investment and engineering design. Furthermore, Foussier (Foussier, 2006) defined cost estimation as the forecast of cost and resource usage will be (envisioned by engineers) or should be (according to function fulfilled or the amount the customer is ready to pay for).

On the other hand, *cost accounting* is the type of cost accounted-for after the product is manufactured. Accountants prepare this type of cost. There are several types of cost accounting:

Process costing: This method is employed when a standard product is being made, which involves many distinct processes performed in a definite sequence. Applied mainly in continuous manufacturing (i.e. oil refinery)

Job costing: Job costing is concerned with finding the cost of each job or contract.

Batch costing: Batch costing is a form of job costing. Instead of costing each component separately, each batch of components is taken together and treated as a job.

Hybrid costing: Combination of all of the above.

Nizai et al. (Niazi, Dai, Balabani, & Seneviratne, 2006) classified cost estimation techniques into four main groups: (i) intuitive techniques, (ii) analogical techniques, (iii) parametric techniques and (iv) Analytical techniques as shown in Fig. 2. *Intuitive techniques,* as the name implies, is cost estimation based on judgement and experience. *The Analogical Technique* is a type of product cost estimation based on similar products. In other words, to estimate product cost, another previously produced product is retrieved, which is similar in structure to the product to be estimated. The *Parametric Costing Technique* is based on developing a mathematical model that relates the cost of a product to one or more product parameters such as length, diameter, weight…etc. Analytical costing is based on estimating the product's cost by calculating the total manufacturing cost incurred in each product's production step.

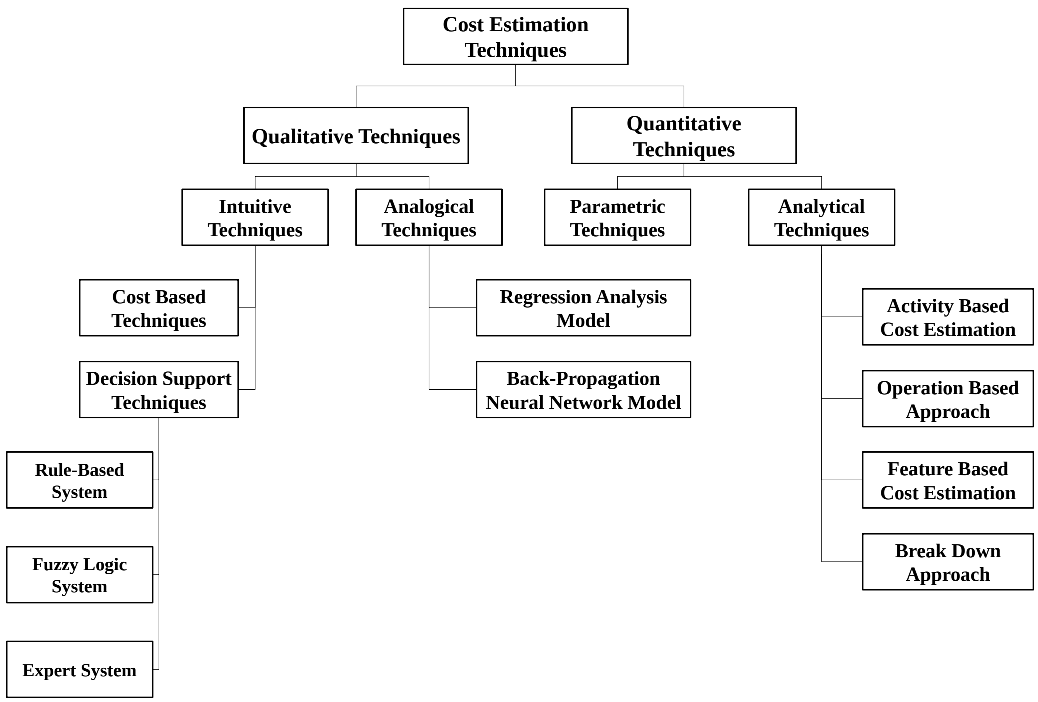

Fig. 2. Detailed categorization of cost estimation techniques adapted from (Hueber, Horejsi, & Schledjewski, 2016)

A less complicated classification for cost estimation techniques has been proposed by Curran et al. (Curran, Raghunathan, & Price, 2004): (i) Analogous Techniques, (ii) parametric techniques and (iii) analytical techniques.

Badiru (Badiru, 2005) proposed a classification of manufacturing cost estimation into three categories depending on the percentage of accuracy from the actual cost (shown in Fig. 3): (i) *Order of magnitude*, (ii) *Preliminary cost estimate* and (iii) *detailed cost estimate*.

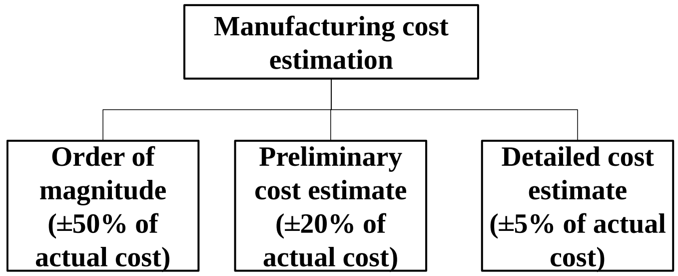

Fig. 3. Manufacturing cost estimation adapted from (Badiru, 2005)

In addition, two different approaches for cost estimate generations were proposed as:

i- *Variant approach*: which is a cost estimate based on the variation from a previously known cost records

ii- *Generative approach*: The cost estimate is determined from scratch without considering any previously known cost records.

Omitaomu (Omitaomu, 2006) classified cost estimating techniques into three categories: (i) Time-series techniques, (ii) subjective techniques and (iii) cost engineering techniques, as shown in Figure 4. *Time-series techniques* are an estimation that is described as a function of time. *Subjective techniques* are estimations based on judgement and experience. *Engineering techniques* are estimations based on mathematical modelling.

According to (Geiszler et al., 2017; Hughes & Paulson Gjerde, 2003), cost systems are categorized into: (i) traditional costing system, (ii) Activity-based costing (ABC), and (iii) variable based costing. *Traditional costing system* uses direct labour, direct material and overhead rates to determine the cost of product. Though simple to use, yet, the traditional costing system does not properly allocate the overhead costs to the different products (average allocation of overhead costs). Jönsson (Jönsson, 2012) categorized cost accounting methods into (i) Activity-Based Costing, (ii) Throughput accounting, (iii) Life cycle costing (defined as the sum of all recurring and non-recurring costs through the complete life of the product and includes design costs, manufacturing costs, operation, installation, upgrade and disposal cost (Sandborn, 2016)), (iv) Kaizen costing and (v) Resource consumption accounting.

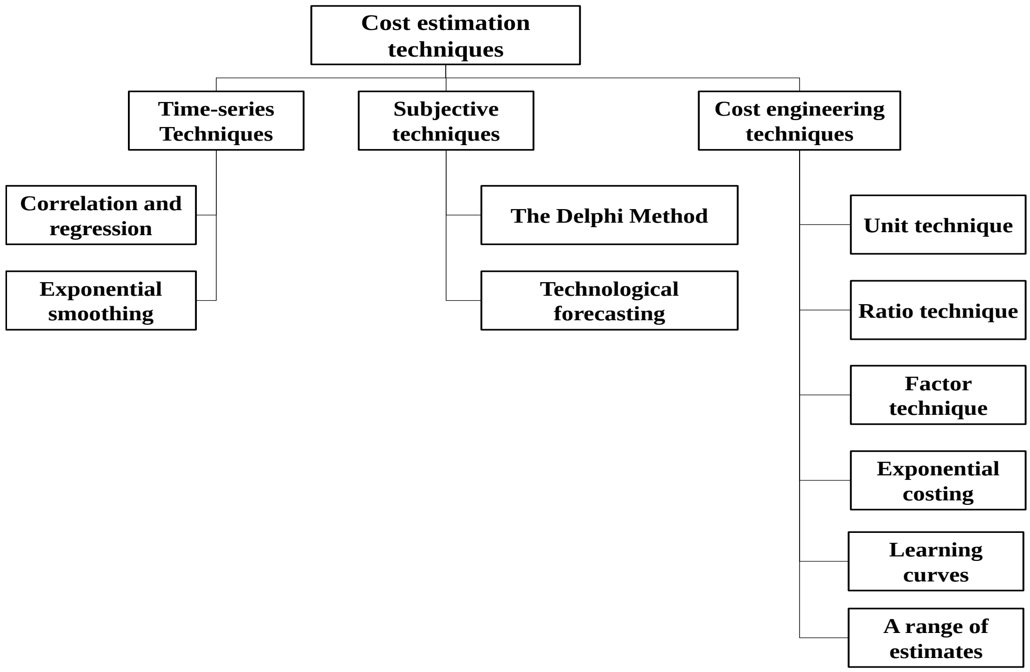

Fig. 4. Cost estimation techniques adapted from (Omitaomu, 2006)

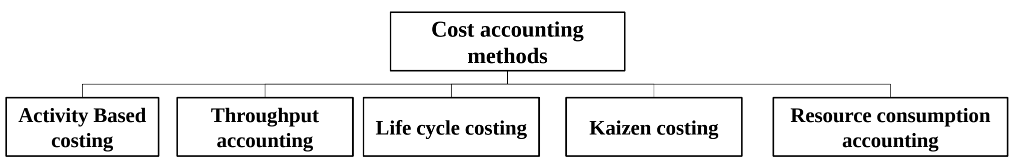

Fig. 5. Cost accounting methods adapted (Jönsson, 2012)

Activity-Based Costing (ABC), initially introduced by (Cooper & Kaplan, 1988a, 1988b), works differently from the traditional costing system. It starts by defining the different activities involved in production (e.g. setup, machining…., etc.), compute the cost for each activity and then allocate each activity to its corresponding product. This type of system works well for companies producing a broad scope of product variants. The ABC method's main drawback is its complexity in identifying the various activities, which is time-consuming and requires high data processing costs. Steps for ABC costing method are shown in Fig. 6.

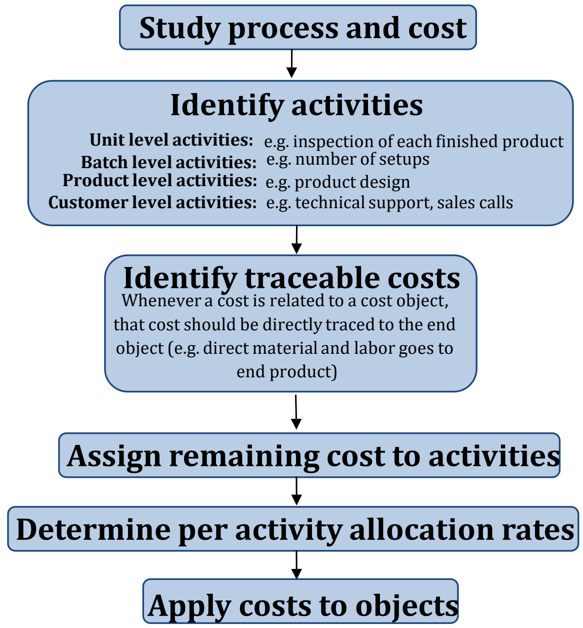

Fig. 6. Steps for ABC costing technique adapted from (Skousen & Walther, 2010)

An example to illustrate that the ABC model is illustrated by (Skousen & Walther, 2010). Company B, which produces Product 1 and Product 2, applies the traditional cost model, as shown in Table 1. Company B selling price for products 1 and 2 is \$60/unit and spends additional sales and administration cost of \$6,000,000, hence a gross profit of:

((900,000+1,100,000) × \$60/unit - \$58,000,000 - \$52,000,000 - \$6,000,000 = \$4,000,000) is acquired.

Company B is willing to switch to ABC model to allocate activities to the products cost accurately, and hence, obtain an accurate estimate.

Table 1 Traditional costing model for Company B

	Product 1	Product 2
Direct material	\$ 30,000,000.00	\$ 44,000,000.00
Direct labour	\$ 7,000,000.00	\$ 2,000,000.00
Factory overhead (300% of direct labour)	\$ 21,000,000.00	\$ 6,000,000.00
Product cost	\$ 58,000,000.00	\$ 52,000,000.00
Units produced	900,000	1,100,000
Cost per unit	\$ 64.44	\$ 47.27

The first step in implementing ABC costing is to breakdown each activity and the cost acquired, as shown in Table 2.

Table 2 Step 1: cost breakdown

Direct material	$ 74,000,000.00
Direct labour	$ 9,000,000.00
Indirect labour	$ 2,000,000.00
Indirect material	$ 1,000,000.00
Factory maintenance	$ 1,500,000.00
Robotics lease	$ 20,000,000.00
Insurance	$ 700,000.00
Other	$ 1,800,000.00
Total production cost	$ 110,000,000.00
SG&A	
Management salaries	$ 800,000.00
Selling expenses	$ 500,000.00
Design & engineering	$ 900,000.00
Ads	$ 3,000,000.00
Office rent	$ 200,000.00
Accounting	$ 600,000.00
Total period cost	$ 6,000,000.00
TOTAL COST	$ 116,000,000.00

The second step is to identify activity pools and map them to activity levels. Activity levels are defined based on Table 3 as unit, batch, customer, product, and market. For this example, the mapping relationship between the activity pools and level is shown in Table 3 where the information in column 3 is based on the given data in (Skousen & Walther, 2010).

Table 3 Step 2: Identify activity levels

Activity pools	Level	Metric
Robotics	Unit	Number of units produced 900,000+1,100,000=2,00,000
Production Setup	Batch	Number of setups 100+1,100=1,200
Tech Support	Customer	Number of tech support calls 1,000+1,100,000=1,101,000
Product Design	Product	Number of products designed (1+1=2)
Ad Campaign	Market	Number of markets (1+1+1=3)

The third step is to map cost drivers and activity pools and assign weights. The weights are assigned subjectively. It is worth noting that direct material and direct labour are not assigned to any activity pool since they are traced directly to end products. The direct material and direct labour are assigned to the cost model at step 6 in Table 6.

Table 4 Step 3 and 4: Identify Traceable costs and Assign remaining costs to activities

	Robotics	Production Setup	Tech Support	Product Design	Ad Campaign	Un-allocated
Direct material	0%	0%	0%	0%	0%	0%
Direct labour	0%	0%	0%	0%	0%	0%
Indirect labour	40%	20%	10%	15%	0%	15%
Indirect material	20%	35%	5%	20%	5%	15%
Factory maintenance	25%	30%	0%	5%	0%	40%
Robotics lease	100%	0%	0%	0%	0%	0%
Insurance	25%	20%	10%	0%	0%	45%
Other	50%	30%	10%	5%	5%	0%
Total production cost						
SG&A						
Management salaries	10%	10%	20%	20%	25%	15%
Selling expenses	0%	0%	15%	15%	60%	10%
Design & engineering	5%	5%	15%	75%	0%	0%
Ads	0%	0%	0%	0%	100%	0%
Office rent	0%	0%	35%	25%	5%	35%
Accounting	5%	5%	10%	5%	10%	65%

With the aid of the cost breakdown in Table 2 and Table 4, each cost driver's cost corresponding to each activity pool is calculated, as shown in Table 5. Comparing the costs of products 1 and 2 from traditional and ABC costing in Table 1 and Table 6, product 1 as per ABC is reduced to $49,406,908.26 compared to $58,000,000 as per traditional costing. While product 2 is $64,598,091.73 as per ABC compared to $52,000,000 as per traditional costing.

In addition to the definitions provided in this chapter, there are a few definitions that will be listed below to facilitate comprehension of this dissertation:

- Direct material costs: costs of all materials that become part of a cost object and easily be traced to cost objects in a feasible way (Datar & Rajan, 2018).
- Direct labour costs: the compensation of labours that can be traced to cost objects (Datar & Rajan, 2018).
- Indirect manufacturing costs: all manufacturing costs that are part of a cost object but cannot be traced easily to individual cost objects (Datar & Rajan, 2018). Indirect costs are composed of indirect material costs and indirect labour costs.
- Cost object: it refers to an entity in which managers and decision-makers want to know how much it costs. These entities can be product, service, project, customer, brand category, activity, department or programme (Datar & Rajan, 2018).
- Overhead costs: marketing, manufacturing (other than direct cost) and administration costs (Drury, 2013).

According to Generally Accepted Accounting Practice (GAAP), all manufacturing costs (direct costs, direct material and overhead) must be allocated to the manufacturing firm unit output (e.g. job, product, project,…etc.) (Datar & Rajan, 2018). GAAP is defined as the set of rules and regulations that firms should follow while reporting financial information to third parties such as investors, banks and government agencies (Datar & Rajan, 2018).

Table 5 Step 4 (Cont’d) & 5: Assign remaining costs to activities and determine per activity allocation rate

	Robotics	Production Setup	Tech Support	Product Design	Ad Campaign	Un- allocated
Direct material	$0	$0	$0	$0	$0	$0
Direct labour	$0	$0	$0	$0	$0	$0
Indirect labour	$800,000	$400,000	$200,000	$300,000	$0	$300,000
Indirect material	$200,000	$350,000	$50,000	$200,000	$50,000	$150,000
Factory nance	$375,000	$450,000	$0	$75,000	$0	$600,000
Robotics lease	$20,000,000	$0	$0	$0	$0	$0
Insurance	$175,000	$140,000	$70,000	$0	$0	$315,000
Other	$900,000	$540,000	$180,000	$90,000	$90,000	$0
Total production cost	$0	$0	$0	$0	$0	$0
SG&A	$0	$0	$0	$0	$0	$0
Management s	$80,000	$80,000	$160,000	$160,000	$200,000	$120,000
Selling expenses	$0	$0	$75,000	$75,000	$300,000	$50,000
Design & ering	$45,000	$45,000	$135,000	$675,000	$0	$0
Ads	$0	$0	$0	$0	$3,000,000	$0
Office rent	$0	$0	$70,000	$50,000	$10,000	$70,000
Accounting	$30,000	$30,000	$60,000	$30,000	$60,000	$390,000
Total cost (A)	$22,605,000	$2,035,000	$1,000,000	$1,655,000	$3,710,000	$1,995,000

Step 4

	Measures				
	Units	Setups	Calls	Design	Market
Product 1	900,000	100		1	
Product 2	1,100,000	1,100		1	
Customers es)			1,000		
Customers duals)			1,100,000		
Markets					3
Total Activity ty (B)	2,000,000	1,200	1,101,000	2	3
Activity cost per re (A/B)	11.30	1,695.83	0.91	827,500.00	1,236,666

Step 5

Table 6 Step 6: Apply costs to cost objects

	Cost/measure	Product 1	Product 2	Total
Direct Material	Traceable	$30,000,000	$44,000,000	$74,000,000
Direct Labour	Traceable	$ 7,000,000	$2,000,000	$9,000,000
Robotics	$11.30	$10,172,250	$12,432,750	$22,605,000
Production Set up	$1,695.83	$169,583.33	$1,865,416.67	$2,035,000
Tech Support	$0.90	$908.27	$999,091.73	$1,000,000
Product Design	$827,500	$827,500	$827,500	$1,655,000
Total (A)		$48,170,242	$62,124,758	$110,295,000
	Asia		$1,236,667	$1,236,667
Ad Campaign	Europe	$ 618,333.33	$618,333.33	$1,236,667
	America	$618,333.33	$618,333.33	$1,236,667
Total (B)		$1,236,666.66	$2,473,333.33	$3,710,000
Total traceable and allocated costs (A+B)		$49,406,908.26	$64,598,091.73	$114,004,999.99
Unallocated costs (C)				$1,995,000
Total cost (A+B+C)				$116,000,000

An important term in this dissertation is the building/general assets overall costs. This term includes the following:

- Building
- Office Improvements
- Computers (IT)
- Engineering Assets
- Furniture
- Small Tools
- Auto and Truck
- Machinery and equipment maintenance
- Lifting Equipment

The total cost for the building/general assets overall costs is allocated to all workcentres/engineering department using general assets allocation costs. The general assets allocation cost for each workcentre/engineering apartment is the ratio between the number of actual hours assigned to each workcentre to the total hours assigned to all workcentres multiplied by the total building/general assets overall costs.

1.3.2. Manufacturing Systems

Dedicated manufacturing lines (DML), or transfer lines (Koren, 2014), are based on affordable fixed automation and produce a company's core products or parts at high volume. Each dedicated line is typically designed to produce a single part (i.e., the line is rigid) at a high production rate achieved by the operation of several tools simultaneously in machining stations (called "gang drilling"). When the product demand is high, the cost per part is relatively low. DMLs are cost-effective as long as demand exceeds supply, and they can operate at their full capacity. Nevertheless, with increasing pressure from global competition and over-capacity built worldwide, there may be situations in which dedicated lines do not operate at full capacity.

Flexible manufacturing systems (FMS) (H. A. ElMaraghy, 2005; Koren, 2014) can produce a variety of products, with changeable volume and mix, on the same system. FMSs consist of expensive, general-purpose computer numerically controlled (CNC) machines and other programmable automation. Because of the CNC machines' single-tool operations, the FMS throughput is lower than that of DML. The cost per part is relatively high due to the general-purpose machine's high cost and low throughput.

Reconfigurable Manufacturing Systems (RMS): Type of system characterized by rapid adjustability of functionality and capacity to meet changing demand (H. A. ElMaraghy, 2005; Mehrabi, Ulsoy, & Koren, 2000). The design of the reconfigurable manufacturing systems is intended for part family, unlike DML and FMS, which mainly focus on single part a general-purpose machine, respectively. A summarized comparison between DML, FMS and RMS is shown in Table 7. Several characteristics and enablers qualify a system as reconfigurable. These characteristics are (Mehrabi et al., 2000):

- Modularity: modular system components to facilitate adjustment of the system capacity and capability (adding/removing system components)

- Integrability: all system components must be easily integrated through appropriate interfaces
- Convertibility: quick changeover when changing between products (mixed model production)
- Diagnosability: quick identification of errors or malfunctions
- Customization: match system capability and capacity to the product demand
- Scalability: The ability to adjust the production capacity of a system through system reconfiguration with minimal cost in minimal time over a large-capacity range at given capacity increments (Putnik et al., 2013; P Spicer, Koren, Shpitalni, & Yip-Hoi, 2002). In this research, Scalability is achieved through:

    a. Machine Level: adding more spindles/axis to machine

    b. System Level: adding machines to a system

    c. Plant Level: Expanding plant or buying a new facility

Table 7: Comparison between dedicated lines, FMS and RMS (H. A. ElMaraghy, 2005; Koren, 2014)

	Dedicated Lines	Flexible Manufacturing Systems	Reconfigurable Manufacturing Systems
Machine Structure	Fixed	Fixed	Adjustable
System focus	Part	Machine and part family	Machine and Part family
Scalability	No	Yes	Yes
Flexibility	No	General	Customized

Focused Flexibility Manufacturing Systems (FFMS) (Tolio, 2008): it is a hybrid type of manufacturing systems in which Flexible Manufacturing Systems (FMS) exist with Dedicated Manufacturing Lines, and hence, flexibility is introduced not only through the individual general purpose machines (e.g. CNC), but from the interaction between the two systems.

Job Shop (Aderoba, 1997): Mainly consists of a group of general-purpose machines (e.g. CNC) together with often dedicated equipment to mainly suit low volume production with a wide variety. Typically, there is no specific type of flow in job shops due to its nature as a make-to-order type of facility, which depending on the customer's orders (daily orders can vary full-size presses to small-sized spare parts). This leads to a complicated scheduling and material handling within the shop.

Cellular Manufacturing Systems (CMS) (Esmaeilian, Behdad, & Wang, 2016): It is based on the grouping of part families that are similar in shape, material and manufacturing process and assign them to a group of machines known as cells. A key enabler of cellular manufacturing is group technology. Group technology is a concept in which relies on grouping parts sharing similar design, material and manufacturing processes into part families. Each of the previous manufacturing systems paradigms can be plotted on a volume to a variety curve, as shown in Fig. 1.

1.3.3. Industry 4.0

There have been four industrial revolutions, as illustrated in Fig. 7. The First industrial revolution started with steam power utilization and converted to mechanical energy to run machines. The Second industrial revolution started with the discovery of electricity. The Third industrial revolution relied mainly on information and programmable logic controller (PLC), which are used to run CNC machines. The Fourth industrial revolution or Industry 4.0 is the current industrial revolution that relies mainly on enabling extensive communication between production system elements to produce autonomous sub-systems capable of communicating with the surroundings, gathering information, and making decisions (Yin, Stecke, & Li, 2018).

Numerous definitions exist for Industry 4.0. According to the German Federal Ministry of Education and Research, Industry 4.0 is defined as (Shrouf, Ordieres, & Miragliotta, 2014) the increase in value-creating networks through the increase of the Cyber-Physical Production Systems (CPPS) , which permits machines and plants to adapt to the nature of the market (change

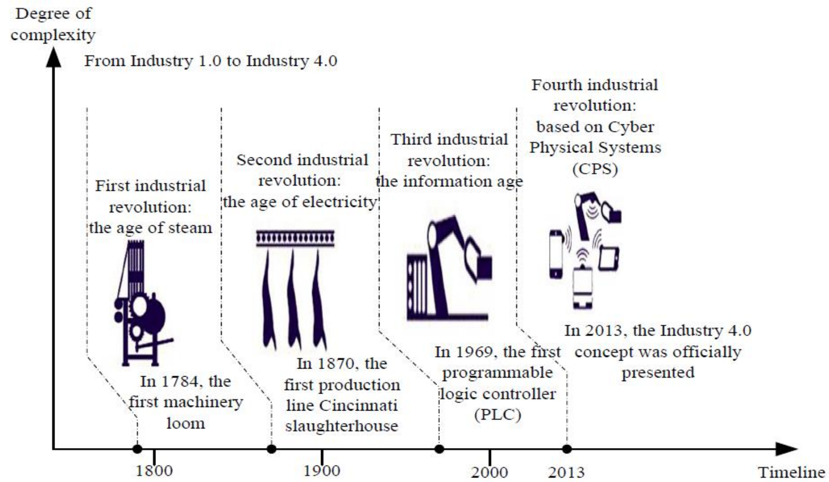

Fig. 7. The four industrial revolutions (Zhou, Liu, & Zhou, 2015)

in orders, demand, etc.) and operating conditions. Another definition provided by (MacDougall, 2014)which defines industry 4.0 as embedded systems and machine to machine communication, Internet of Things (IoT) and Cyber-Physical Systems (CPS), which integrate the physical and the cyber/virtual space. There are several characteristics of Industry 4.0 (Vogel-Heuser & Hess, 2016):

1- Interoperability: connecting and communicating operators, CPS and CPPS among one another
2- Virtualization: maintaining a virtual copy of CPPS
3- Decentralization: CPPS are autonomous (i.e. decide on their own)
4- Real-Time Capability: The ability to extract real-time data for analysis
5- Modularity: the ease of adding or removing system module in response to new requirements

The main enabling components of industry 4.0 is Cyber-Physical Systems (CPS), Internet of Things (IoT) and Cloud Computing (L. D. Xu, Xu, & Li, 2018):

- *Cyber-Physical System (CPS)*: the technologies and systems that are used to manage the interconnected systems between the physical component and the computational resources

(Jazdi, 2014). Besides, another term commonly used in conjunction with CPS is Cyber-Physical Production Systems (CPPS), which is defined as the autonomous subsystems that are connected through the whole organization starting from the manufacturing process up-to management and logistics (Monostori, 2014) and can analyze data and make decisions on its own. Monostori et al. (Monostori et al., 2016) defined CPS as the intersection between the cyber and physical domains.

- *Internet of Things (IoT)*: it is a means of communication in which the things/objects (machines, sensors, operators, etc.). are connected to the internet through wired or wireless network connections (Atzori, Iera, & Morabito, 2010). These emerging technologies will contribute to the manufacturing system's self-awareness in which human operators and machines can make decisions. The main vital elements for enabling IoT are RFIDs and Wireless Sensor Network (WSN) (L. D. Xu et al., 2018).
- *Cloud Computing*: is a distributed system that consists of connected and virtual computers being employed on service levels between service providers and customers (Ustundag & Cevikcan, 2017).

Cloud computing and Internet of Things are considered essential enablers for cloud manufacturing in which manufacturing resources are transferred to the cloud environment (Li, Barenji, & Huang, 2018).

1.4. Research Plan

This dissertation is presented in eight chapters. An IDEF0 model is provided in Fig. 8 in which each activity block signifies Chapters Three to Six. The main theme of this research, as illustrated earlier, is to introduce a new costing model based on the ABC methodology and to optimize the model to obtain the number of jobs to be accepted/rejected in manufacturing firm (job mix) as well as decisions in regards to reconfiguration in machine, system and factory level. Finally, the mathematical model is extended to consider subcontracting to suppliers and investing in infrastructure to connect strategic suppliers with the manufacturing firm to achieve agility.

Based on the IDEF0 model in Fig. 8, the main dissertation chapters can be summarized as follows:

- Chapter 3: The interrelationship between machine rate and annual hours assigned to the machine: The relationship between the machine hourly rate and the total hours in a year is interrelated. On one hand, as the machine hourly rate is reduced, more working hours are assigned in terms of new orders (price gets competitive). On the other hand, as more hours are assigned to the machine, the machine hourly rate is reduced, further.
- Chapter 4 and chapter 5: Integrating the above model with a scalability cost model to aid in decision making on whether to invest in a machine (cost of reconfiguration either in a machine or system level) or expansion of the facility (Factory level).
- Chapter 6: Integrating the above two with a model for industry 4.0 implementation and its cost justification. As stated in the literature review section, this integration is attainable through establishing connectivity with suppliers.

1.5. Thesis Hypothesis

The Hypothesis being tested in this dissertation is:

"Manufacturing firms are capable of achieving competitive advantage through accepting specific jobs from customers through reducing hourly rates and investing in additional equipment, facility expansion and applying industry 4.

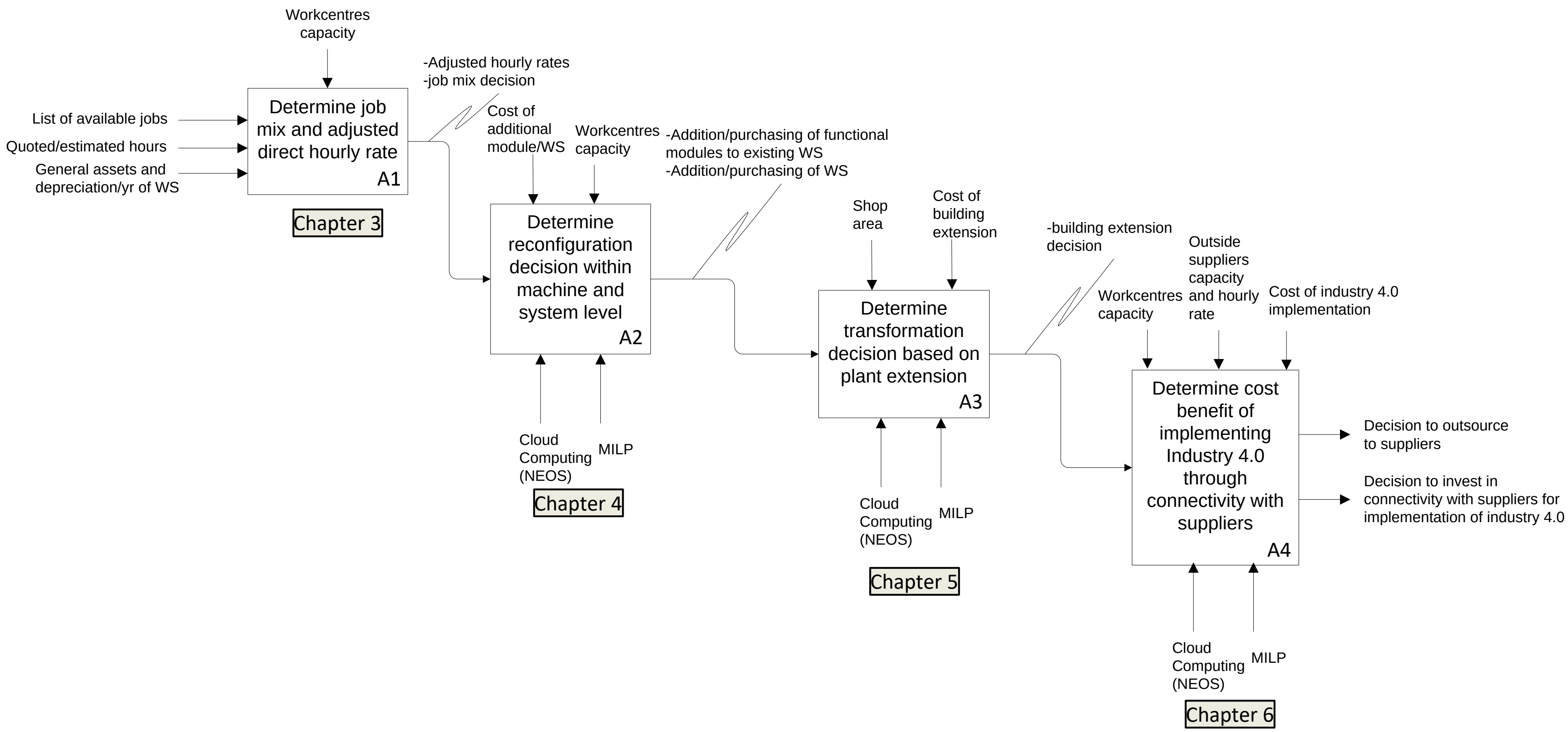

Fig. 8. IDEF0 of the different models in this research

CHAPTER 2 Literature Review

2. Overview

This chapter provides a detailed literature survey on the most relevant topic within this research. The first section is concerned with the literature survey on the topic of costing systems. The second section is concerned with the literature on the topic of manufacturing systems. The third section is concerned with Industry 4.0. The last section identifies the research gaps in the literature and discusses how to fill these gaps.

2.1. Costing Systems

Mohsenijam and Lu (Mohsenijam & Lu, 2016) proposed a regression method to estimate the fabrication labour hours/cost based on each project or division. The model's input variables were design variables related to steel fabrication (e.g. size of weld penetration, type of steel section, type of bolts used…etc.). The output from the model was the required fabrication labour hours. The proposed model only calculated the labour hours/cost based on historical data without any optimization performed. In addition, the bi-directional relationship between the machine rate and the number of hours was not considered.

Xu et al. (Y. Xu et al., 2012) provided a literature survey on cost engineering, including design cost, manufacturing cost, operating cost, disposal cost, life cycle cost and affordability engineering cost. Several gaps were introduced in regards to the cost engineering. For example, in manufacturing cost research, the focus is on using the information provided by CAD data for design feature recognition and design by feature. The authors pointed out the importance of integrating the service cost instead of only manufacturing cost for operating costs. Furthermore, the authors pointed out the importance of storing relevant information for cost analysis in a centralized controlled environment.

Windmark et al. (Windmark, Gabrielson, Andersson, & StŒhl, 2012) introduced an economic model to determine the optimal automation level in a discrete batch manufacturing environment. The model aims to study the part costs within the different automation levels and the demand for the part and the manufactured batch size. Various terms were considered in the model, such as: the cost of the equipment, maintenance cost, tooling costs, number of batches, processing time, etc.

Agyapong-Kodua et al. (Agyapong-Kodua, Asare, & Ceglarek, 2014) propose a dynamic cost model that is applied to the initial digital modelling phase of the production system. The proposed methodology considers product costing based on product features and in conjunction with process, resources and cost accounting data. The authors also concluded the importance of integrating the product features with the process capabilities, resources, and cost to understand the cost implications of resource utilization and the suggested process. Finally, the authors suggested developing correlations between product design, processes, resource utilization, and cost accounting in order to reflect the dynamic utilization of the resources.

Mourtzis et al. (D Mourtzis, Efthymiou, & Papakostas, 2011) introduced a product cost model for early design stages cost estimation. The model considers Case-Based Reasoning methodology along with the Regression Analysis. When implemented on an industrial case study from automation, a mean deviation of 14% from the actual cost was calculated, which helped engineers develop relatively accurate enough costs within the early design stages.

Soufhwee et al. (Rahman, Mohamad, & Rahman, 2019) proposed a model that integrates Time-Dependent Activity-Based Costing with a simulation tool (ARENA) to optimize the assembly process and reduce assembly cost of the capacity of the resources. The authors conducted three scenarios to determine the simulation model's cost changes based on each resource's utilization. The simulation model successfully eliminated unnecessary resources in the production line. Scenario two showed a decrease in cost by 15.51% in which two operators were eliminated.

Savory and Williams (Savory & Williams, 2010) incorporated Activity-Based Costing to discrete event simulation models. They applied their model to a U-shaped manufacturing cell, which produces a particular part family with four variants. The model's output is a detailed Bill of Activities and specific information about the cost drivers and pools. The authors reported that their model could be utilized in cost estimation, cell design and scheduling.

Plank (Plank, 2018) proposed a model (maximizing revenue to cost function, taking resources capacity and product pricing into consideration) to study the performance of cost systems and decisions on product mix as well as product pricing. The author extended the models proposed by Hwang et al. (Hwang, Evans III, & Hegde, 1993), Homburg (Homburg, 2004); Balakrishnan et al. (Balakrishnan, Hansen, & Labro, 2011) and Anand et al. (Anand, Balakrishnan, & Labro, 2013) into dynamic model considering different marketing and environmental scenarios as well as integrating cost-stickiness into decision problems. The author concluded that by using complex models, profit errors are reduced by half (52%). However, the author did not discuss the effect of hourly rates with the number of hours assigned to resources in each production period,

Ning et al. (Ning, Shi, Cai, Xu, & Zhang, 2020) proposed a deep learning method for manufacturing process estimation. Two-dimensional and three-dimensional convolutional neural network (CNN) training images and voxel data methods were proposed for the manufacturing cost estimation. They concluded that 3D CNN provides better results than 2D CNN since 2D CNN cannot capture all features information. Additionally, the authors concluded that as the number of training data increased, the model's accuracy increased.

Kadir et al. (Kadir, Yusof, & Wahab, 2020) presented a classification for cost estimation for additive manufacturing. The classified the classification techniques (which consider production cost) into task-based and level-based (which considers lifecycle costing, design to cost reduction, remanufacturing and value engineering). In addition, additive manufacturing models were classified into Architecture-related additive manufacturing models and software-based additive manufacturing cost models based on the implementation of architecture and software development studies. They concluded that there is no satisfactory model for additive manufacturing modelling, which considers technologies and applications.

Tang et al. (Tang, Wang, & Ding, 2012) proposed an improved cost estimation and product pricing model through input-output (in the form of matrix operations) analysis. The model considers activity-based rates (activity-based machining rates), raw materials and purchased components pricing when utilized in production and the cost of defected items. They concluded that the proposed model was more accurate than the traditional ABC method for costing through error analysis. However, the proposed approach did not consider the bi-directional relationship between the machine rates and the annual number of hours. In addition, the proposed approach is based on matrix operations with no optimization carried.

Needy et al. (Needy, Bidanda, & Gulsen, 2000) developed an ABC model for small manufacturers with a case study adapted from a printing company. It was concluded that cost savings were achieved by applying the ABC system compared to the traditional costing system in which mark-up was reduced from 15%-30% to 10%.

Aderoba (Aderoba, 1997) proposed a product cost estimating model for the job shop environment, which considers cost rates for machines, labour and utility cost elements (water, electricity, compressed air…etc.). The costing system used for their model is the activity-based costing system in which cost is calculated based on the facility's activities.

Qian and Ben Arieh (Qian & Ben-Arieh, 2008) presented a cost estimated model by combining the ABC system and parametric costing within the rotational parts' design and development stage. The approach provided was in the form of a framework without any optimization model that considers the bi-directional relationship between machine rate and the machine's annual hours

Ozbayrak et al. (Özbayrak, Akgün, & Türker, 2004) proposed a mathematical and simulation model and activity-based (ABC) system to estimate the cost of product and manufacturing within an automated assembly system. The proposed method was developed to determine the effect of production planning and control strategies, specifically push and pull, on the manufacturing costs. Activities such as setup time and processing time were considered. In addition, various rates were considered, such as machining/assembly cost rate, machine rate and material cost were considered.

Roy et al. (Roy, Souchoroukov, & Shehab, 2011) provided a detailed illustration of the type of data and information required to carry out detailed manufacturing cost estimation in the automotive industry. The data and information were categorized into internal (such as Bill of Material, Engineering design, drawings, specifications, purchasing department) and external (information related to the vendor supplies). A breakdown of direct material, labour, overheads cost and machine rates were included. The approach provided was in the form of a framework without any optimization model that considers the bi-directional relationship between machine rate and the machine's annual hours.

Kolati et al. (Koltai, Lozano, Guerrero, & Onieva, 2000) introduced the concept of flexible costing in a manufacturing system, which is a method for reallocating the overhead cost based on production plan results and simulated performance of the process. The proposed method utilizes the ABC system together with a mathematical programming model.

Lin et al. (Lin, Lee, & Bohez, 2012) provided a model for integrating manufacturing and production system performance cost. The integration between manufacturing and costing was achieved by linking the Activity-Based Costing (ABC) and Design for Manufacturing (DFM). Though labour and machine rate costs were considered, the relationship between the machine rate cost and yearly hours was not considered.

Fazelollahtabar and Mahdavi-Amiri (Fazlollahtabar & Mahdavi-Amiri, 2013) proposed a cost estimating model based on fuzzy rules and dynamic. Factors considered in cost estimation were used as a machine, operator/labour and product specification. Though labour and machine rate costs were considered, the relationship between the machine rate cost and yearly hours was not considered.

Ramadan et al. (Ramadan, Al-Maimani, & Noche, 2017) proposed a real-time manufacturing cost estimation method using RFID. It was concluded that the proposed real-time manufacturing tracking system is beneficial in identifying causes for a redundant cost, which can be an enabler for lean manufacturing. This paper will be investigated further as well as other related papers since it is believed that it integrates and bridges the gap between the costing estimation model required and the justification of industry 4.0 costs within a manufacturing company.

Kareem et al. (Kareem, Oke, Lawal, & Lawal, 2011) developed an ABC system method for lathe machining, considering maintenance. When calculating the cost, the proposed method showed an insignificant difference compared to the traditional costing method (<5%). Material costs were not considered as well as the bi-directional relationship between machine rates and total annual hours.

Hanafy and ElMaraghy (Hanafy & ElMaraghy, 2017) proposed a mathematical model for customizing products through assembly and disassembly of components to and from a product platform to produce different product variants. The model considered the assembly and disassembly labour rates. The mathematical model determined the number of assembly stations required to assemble and disassemble components from mass-assembled product platforms to derive new product variants. However, the proposed approach did not consider the bi-directional relationship between the machine rates and the annual number of hours.

Abbas and ElMaraghy (Abbas & ElMaraghy, 2018) introduced a mathematical model for a synthesis of manufacturing systems using co-platforming through the minimization of a cost objective function. The model considers the changes occurring in the machine and system level. However, the machining rate cost and annual hours relationship was not considered.

Youssef and ElMaraghy (Youssef & ElMaraghy, 2006) proposed a model that optimizes the capital cost of Reconfigurable Manufacturing Systems (RMS) configurations with the aid of Genetic Algorithm by including the arrangement of machines, equipment selection and operations-machines assignment. 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 besides the cost. However, the machining rate cost was considered.

Moghaddam et al. (Moghaddam, Houshmand, & Fatahi Valilai, 2018) applied a two-phased mathematical model to address the problem of RMS configuration design with a fluctuating demand of a single product within the product life cycle for a single product flow line. The objective function was to minimize the reconfiguration costs. The first phase utilized an Integer Linear Programming (ILP) model to determine the machine level's reconfiguration cost satisfying the demand. The second phase utilizes a Mixed Integer Linear Programming (MILP) model to select the optimal configuration. The authors mainly concentrate on scalability enabler.

Yi et al. (Yi, Wang, & Zhao, 2018) proposed a method for evaluation and optimization of reconfiguration schemes using Multi-Attribute Decision making VIKOR to evaluate reconfiguration schemes and quantitative evaluation to come up with the best solution. The three evaluation criteria used are module chain similarity, module interface complexity and reconfiguration cost.

Koren et al. (Koren, Gu, & Guo, 2018a) implemented an analysis study for the different manufacturing systems configurations suiting high volume manufacturing *(serial & parallel lines (SLP) and reconfigurable manufacturing systems*) to determine the performance of each system based on investment cost, throughput, responsiveness to change and product quality. They concluded that RMS has higher scalability than SLP lines. Hence it has a higher responsiveness when there is a change in demand; however, RMS has a higher investment cost than SLP. RMS has a higher throughput than SLP lines, while a large investment in tooling costs characterizes pure parallel lines.

Prasad and Jayswal (Prasad & Jayswal, 2019) proposed a method for assessment of *RMS* based on *Average Local Clustering (ALC) and Analytical Hierarchical Process (AHP).* They concluded that machines are to be grouped based on the reconfiguration efforts. They also concluded that RMS most suits a lean manufacturing environment.

Andersen et al. (Andersen, ElMaraghy, ElMaraghy, Brunoe, & Nielsen, 2018) proposed a participatory system design methodology for Changeable Manufacturing Systems (CMS), taking into consideration manufacturing systems paradigm as well physical and logical enablers in an attempt to transfer towards CMS based on the knowledge of products, production and technology.

Spicer and Carlo. (Patrick Spicer & Carlo, 2007) introduced a mathematical model to calculate and optimize the cost of reconfiguration using dynamic programming. Labour cost and salvage cost of machines were included in their objective function.

Choi et al. (J.-W. Choi, Kelly, Raju, & Reidsema, 2005) developed a knowledge-based system using CATIA V5 to estimate the manufacturing cost of composite parts, which reported beneficiary during the conceptual design stage. However, the machining rate cost and annual hours relationship was not considered.

Rezaie et al. (Rezaie, Ostadi, & Torabi, 2008) proposed a method that utilizes traditional costing (TC) and the ABC system for parts costing within a flexible manufacturing system. The method commenced by defining activities involved and resources to produce the part and then assigns a cost to each activity and resource. The method was applied to a case study from the forging industry. It was concluded that ABC provides more accurate results than TC.

Chougule and Ravi (Chougule & Ravi, 2006) proposed a costing model for casted parts driven by solid modelling though capturing features and their attributes. The proposed model considered direct material cost, indirect material cost, labour cost, energy cost, tooling cost and overhead cost.

Myrelid and Olhager (Myrelid & Olhager, 2019) proposed a hybrid cost approach for a mixed process environment (job shop, flow shops and assembly lines) to establish a cost allocation for the manufacturer's products. *Traditional, lean and throughput* accounting approaches were used and applied on three different products with varying complexity. *Mathematical formulae* were formulated for each approach. They concluded that the lean accounting cost model is allocated to assembly lines, throughput accounting cost models to flow shops, and traditional accounting costs to a job-shop environment. However, their approach did not provide an optimal solution to the problem under study and did not consider the relationship between hourly rate and annual hours worked.

Ikumapayi et al. (Ikumapayi, Akinlabi, Onu, Akinlabi, & Agarana, 2019) proposed mathematical formulation for manufacturing cost estimation in batch production, job shop and mass production environments given different automation levels (i.e. manual operations, semi and fully automated). Though the model took into consideration various cost elements for automation implementation (i.e. maintenance cost, programming cost, training cost, etc.), yet the models provided did not discuss the relationship between the annual hours and hourly rates.

Supakulwattana and Chattinnawat (Supakulwattana & Chattinnawat, 2018) proposed an *ant bee colony algorithm* and Material Flow Cost Accounting (MFCA_ a costing technique used to trace material and calculate all activities in monetary terms) in a serial production environment to calculate the suboptimal inspection sampling size and batch size in a multi-stage process. They used four different types of costs; material cost, system cost, energy cost and waste treatment cost. The objective function was to maximize the favourable product cost to the total cost based on the *ABC costing technique*. However, the proposed approach did not consider the relationship between hourly rate and annual hours worked.

Boyd and Cox (Boyd & Cox Iii, 2002) performed a comparison study between four types of cost accounting approached; *traditional cost accounting, activity-based costing, direct costing, and throughput accounting*. They utilized *statistical analysis* for each approach and compared it to the *linear programming model*. The decision variables considered in their study are pricing of each product, product mix decision, buy vs. make a decision, facility expansion and equipment purchasing. They concluded that the throughput accounting approach provided a better profit margin based on the pre-mentioned decision variables. It provided the same solution to the linear programming model (optimal solution).

Lea and Fredendall (Lea & Fredendall, 2002) developed *an integrated information system* to determine the effect of three management accounting systems (*traditional costing, ABC and Throughput accounting costing*), two product mix decision algorithms (LP and Theory of constraint heuristics), two product structures (single and multilevel BOM) and planning horizon (short and long term) on the performance of a highly automated industry with high overhead. Their extensive study concluded that no single shop setting (management accounting system type, product structure, mix decision algorithm, and planning horizon) could maximize all performance measures (profit, bottleneck, WIP and customer service level). Details about shop settings and performance can be viewed in section 5 in (Lea & Fredendall, 2002)

Elsukova (Elsukova, 2015) illustrated the lean and throughput cost accounting approach and proposed a framework for integrating both approaches. The author concluded that the lean and throughput cost accounting approaches supplement one another as the throughput cost accounting determines the improvement required for the flow of material (restricted by bottlenecks). Lean cost accounting is mandatory to improve productivity and reduce waste.

Kee and Schmidt (Kee & Schmidt, 2000) proposed a general *mathematical integer linear programming model* in which the *theory of constraints (TOC)* and *Activity-Based Costing (ABC)* are considered a particular case of the model to provide a managerial decision tool on the mix of products to be used. They concluded that the general proposed model excels the TOC and ABC (which are suitable when firm management has either full or no control of labour and overhead resources) with varying degrees of control on labour and overhead resources. Additionally, they concluded that the ABC model maximizes profit when firm management has full control of labour and overhead resources. However, the model considers the hourly rate as constant and does not consider the planning time horizon.

Sajadfar and Ma (Sajadfar & Ma, 2015) proposed a framework for cost estimation for welded features using data mining and linear regression to develop a feature cost estimation. The benefit of their model is determining product cost based on known confidence measures the reduced time required to come up with the estimates. Besides, the model is effective in providing accurate estimates based on historical data. However, the model does not consider the variation occurring indirect costs resulting from a change in annual worked hours.

Franchetti and Kress (Franchetti & Kress, 2017) proposed a mathematical formulation to study the cost structure and breakeven points of Additive Manufacturing versus traditional methods by studying the cost requirements of additive manufacturing versus injection molding and relating it to lot sizes. The cost structures considered in the analysis were: costs of raw material, capital cost, setup time, energy consumption, scrape percentage, depreciation and labour cost. Based on their case study, injection is cost-effective when producing more than 200 units or larger lot sizes runs. However, the model does not consider the variation occurring indirect costs resulting from a change in annual worked hours.

Jiang et al. (Jiang, Walczyk, McIntyre, & Chan, 2016) proposed a manufacturing cost model, which considers *labour, material and overhead costs* for *mycelium-based bio-composite sandwich structures*. They initially started implementing an *excel sheet to calculate the equivalent annual cost*. The equivalent annual cost is defined as: "*the annual cost of owning, operating, and maintaining an asset over its entire life. EAC is often used by firms for capital budgeting decisions, as it allows a company to compare the cost-effectiveness of various assets that have unequal lifespans*. (Investopia, 2019)" The overhead cost was allocated to direct costs, such as in traditional accounting costs. They implemented *a simulation model* afterwards to build the manufacturing line taking actual data from a commercial firm to establish a benchmark and applied tab search to determine the best configuration. The proposed model is significant and effective since it addresses existing manufacturing resources, maximize efficiency and minimize cost. The model took into account the planning period. However, the model does not consider the variation occurring indirect costs resulting from a change in annual worked hours.

Myrelid and Olhager (Myrelid & Olhager, 2015) provided a *comparative study using mathematical formulae* for three different types of cost accounting techniques; *lean accounting, throughput accounting and traditional costing* through *pairwise comparison*. The case study concluded that neither lean accounting nor throughput accounting provides the full costing data necessary for product costing. In addition, they concluded that the application of the accounting technique depends on the manufacturing firm environment in which lean accounting is suitable for *flowlines. In contrast,* throughput accounting is suitable for shops with significant bottleneck resources. They suggested integrating the lean and throughput accounting system for accurate results at the end of their study.

Souren et al. (Souren*, Ahn, & Schmitz, 2005) proposed a comparative study between the Theory Of Constraint (TOC) and existing product mix tools. They concluded that using TOC does not provide a better solution than Linear Programming models; however, TOC is easier to use.

Tu and Song (Tu & Song, 2016) proposed a framework for analyzing and predicting manufacturing costs through data mining techniques. They used process model-enhanced cost (provide a detailed cost of each activity) and cost prediction (provide work in progress) based on production volume and time prediction using work-in-progress of manufacturing processes.

Orji and Wei (Orji & Wei, 2016b) proposed a *process-based cost (Process-based* costing is used when a manufacturing firm is mass-producing similar products*)* model and system dynamics to develop a cost methodology calculation in a *green manufacturing environment*. They utilized the labour cost, material cost, energy-saving cost activity, equipment cost and carbon emissions cost as significant cost drivers for the green manufacturing environment. They concluded that the total product lifecycle cost of a specific product within a green-manufacturing environment is less than the cost of the same product produced within a conventional manufacturing environment.

Saniuk et al. (Saniuk, Saniuk, & Witkowski, 2011) applied the *ABC accounting technique* to estimate production orders' production orders in *metalworking processes*. The rationale behind their research is the rising trend of implementing automation in metalworking shops, which increases the indirect cost. Hence, the traditional costing technique does not provide accurate cost estimates. They concluded, based on their case study, that the usage of ABC provides more accurate results than traditional costing methods when applied to individual production orders

Bellah et al. (Bellah, Li, Zelbst, & Gu, 2014) proposed an *information system utilizing RFID technology* that automatically calculates job cost information for *fixed position projects* automatically and accurately by equipping workers with RFID tags and reading stations to collect data. They applied their model on two case studies; one in a fabrication firm and the other within a classroom during a LEGO test session.

Shakeel et al. (Shakeel, Khan, & Khan, 2016) proposed a new *forecasting model (integrating weighted average and exponential smoothing)* to forecast indirect consumables cost in a *job shop* environment. They compared the results of the proposed model with averaging, weighted average and exponential smoothing forecasting models. They concluded that the proposed forecasting model provided more accurate results than the common forecasting models.

Landscheidt and Kans (Landscheidt & Kans, 2016) proposed a mathematical model called the total cost of ownership (TCO) of industrial robots. The components or cost drivers taken into consideration for the TCO calculation are the cost of acquiring the robotic system, cost of operation, and disposal. After developing the model, the authors tested the model on two case studies on two different companies. The significance of the model, as reported by authors, is to provide management in companies with decision-making on acquiring industrial robots based on the complete life cycle of the product.

Duran and Afonso (Duran & Afonso, 2019) proposed an Activity-Based Costing and Life Cycle Costing (LCC) model as a decision-making tool for managing non-repairable spare parts. The Weibull failure rate distribution was considered to represent the failure rate of the spare parts. The proposed model's significance is to evaluate inventory policies to develop suitable long-term inventory policies and parameters (e.g. stock level, service levels and costs) for non-repairable spare parts.

Orji and Wei (Orji & Wei, 2016a) developed a costing calculation model in green manufacturing using process-based costing and system dynamics. It was reported that in green manufacturing, the main significant cost contributors are the carbon emission costs and equipment costs. Besides, it was reported that the total lifecycle cost of products in green manufacturing is less than the total lifecycle cost of products in the traditional industry.

Mourtzis et al. (Dimitris Mourtzis, Fotia, Boli, & Vlachou, 2019) proposed a model for a digitalized manufacturing system based on information theory to demonstrate how traditional manufacturing systems can transform to industry 4.0 manufacturing system. The proposed method considers several metrics, such as complexity and capacity of communication among the different systems. Though the model discusses the communication among the different system's entities, their study did not provide a cost-benefit on the implementation of communication among systems entities.

Salmi et al. (Salmi, David, Blanco, & Summers, 2016) provided a review on cost estimation of systems design and automation decisions during the early design phase. The cost estimation was categorized based on approach type (quantitative, qualitative), granularity (top-bottom or bottom-up) and phase of applicability (early phase and late phase estimation). The authors pointed out that each model would possess its strength and weakness. However, the authors also pointed out the need for a generic model that considers the type of assembly system (manual, automated, hybrid) and product information such as product design and product features. Another requirement pointed by the authors is the necessity of resource cost rates to calculate the cost of the different operations, as well as overhead and indirect costs.

Santana et al. (Santana, Afonso, Zanin, & Wernke, 2017) proposed a mathematical model incorporating Activity-Based Costing and Time Based Activity-Based Costing for capacity management optimization. The trade-off between capacity maximization and operational efficiency has been analyzed. The authors suggested that capacity should be optimized rather than maximized since maximizing capacity can lead to operational inefficiency. The proposed model did not consider the bi-directional relationship between hourly rates of resources and hours assigned through jobs to each resource.

Tsai et al. (Tsai, Chu, & Lee, 2019) proposed a Green Activity-Based Costing (ABC) model applied within the aluminum alloy wheel industry. The model traces direct and indirect product costs to cost objects as well as allocates carbon tax to cost objects. The authors proposed three different scenarios: ABC model with material fluctuation, ABC with material discount and ABC with material discount and carbon tax. The authors' used LINGO to optimize the proposed models. The authors claim that the effect of labour hours usage in each model is of insignificant difference. In addition, when taking carbon taxation into account, the profit was reduced. The hourly rates were taken as fixed values specified by the authors, and the bi-directional effect between the labour rate and hours assigned to machines was not considered.

Tsai and Lai (Tsai & Lai, 2018) proposed a mathematical programming model combining green manufacturing technologies (i.e.), Activity-Based Costing (ABC) and the theory of constraint to provide optimal production plans based on optimal profitable product mix decision. The model's labour rates have been considered an input parameter to the model, and the bi-directional effect between the labour rate and hours assigned to machines was not considered.

Jurek et al. (Jurek et al., 2012) proposed an Activity-Based Costing (ABC) model for energy analysis within the automotive manufacturer. The cost objects considered were different department’s processes within a paint shop for an automotive manufacturer such as pre-treatment, sealing line, paint booth and post-paint operations. The authors proposed that with the aid of a smart grid, it would be possible to reduce energy consumption.

Kuzgunkaya and ElMaraghy (O Kuzgunkaya & ElMaraghy, 2007) proposed a fuzzy multi-objective model for RMS investment justification considering in-house, outsourcing decisions, machine acquisition, operating costs and cost for reconfiguration. The developed model was applied on two cases: one for RMS and the other for FMS. Several conclusions were derived. First, RMS are more profitable for short reconfiguration periods. Second, for the same configuration, FMS perform better in terms of responsiveness. However, the proposed model did not take into consideration important aspects of operating costs such as the bi-directional effect between hours assigned to workcentres and hourly rates as well as the cost of infrastructure required for suppliers' connectivity.

Youssef and ElMaraghy (Youssef & ElMaraghy, 2006) 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.

2.2. Manufacturing systems

The future of manufacturing requires fast responsiveness to market demands and changes. As a result, RMS is expected to be the manufacturing system paradigm which will accompany the Industry 4.0. Koren et al. (Koren, Gu, & Guo, 2018b; Koren et al., 1999) and ElMaraghy (H. A. ElMaraghy, 2005) proposed key characteristics and enablers that distinguishes RMS which affects the ease and cost of reconfigurability:

- Scalability: ability to alter production capacity by quickly adding/removing system components
- Modularity: functional operations are integrated into the form of modules

- Integrability: ease of integrating system modules through hardware and software interfaces
- Customization: the system is built around the part family being produced with the flexibility explicitly provided for the part family being produced
- Convertibility: quick change-over between variants within a product family and adaptability for future products requirements
- Diagnosability: on-line ability to monitor product quality and quickly identify quality problems

On the applicability, readiness and feasibility of applying the enablers as mentioned earlier and characteristics, Andersen et al. (Andersen, Larsen, Brunoe, Nielsen, & Ketelsen, 2018) proposed a study involving a questionnaire to determine the readiness of a manufacturing firm to implement each enabler of reconfiguration which depends on the size of company, demand, level of automation and business model (i.e. made to order, make to stock, etc.).

Andersen et al. (Andersen, Brunoe, Nielsen, & Rösiö, 2017) presented recent contributions in an attempt to synthesize a generic method for RMS design. Eguia et al. (Eguia, Molina, Lozano, & Racero, 2017) proposed an Integer Linear Programming (ILP) and Mixed Integer Linear Programming (MILP) models to address the problem of cell design and multi-period loading problem in a cellular reconfigurable manufacturing system.

As an extension, Bortolini et al. (Bortolini, Galizia, Mora, & Pilati, 2019) proposed a Linear Integer Programming model for cellular reconfigurable design manufacturing systems taking into consideration multi-period and multi-product as well as the effort to install a new module to the available machines.

Kahloul et al. (Kahloul, Bourekkache, & Djouani, 2016) proposed a Petri net approach to model, simulate and analyze RMS. Huang et al. (Huang, Wang, & Yan, 2019) combined the concept of delayed product differentiation with a reconfigurable manufacturing system which is called Delayed Reconfigurable Manufacturing System (D-RMS). As reported by the authors, the significance of the D-RMS is to reduce production loss during reconfiguration time.

In terms of complexity, ElMaraghy et al. (W. ElMaraghy, ElMaraghy, Tomiyama, & Monostori, 2012) defined complexity as two fundamental types; static and dynamic. Static (structural) complexity is time independent but depends on the structure of the system. Dynamic complexity is time dependant.

Huang et al. (Huang, Wang, Shang, & Yan, 2018) proposed a dynamic complexity-based RMS reconfiguration point decision method. Moghaddam (Moghaddam, Houshmand, Saitou, & Fatahi Valilai, 2019) proposed an Integer Linear Programming (ILP) model and Mixed Integer Linear Programming (MILP) model for the configuration design of scalable RMS which produces a part family.

Kuzgunkaya and ElMaraghy (Onur Kuzgunkaya & ElMaraghy, 2006) proposed a new metric for assessing the structural complexity of manufacturing systems. The authors utilized the information entropy for developing the complexity metric based on classification coding proposed by (H. A. ElMaraghy, Kuzgunkaya, & Urbanic, 2005). The main benefit of the model is to assess decision makers in companies in choosing the least complex manufacturing system among alternative configurations.

Samy et al. (Samy, AlGeddawy, & ElMaraghy, 2015) proposed a model for balancing structural and layout complexity of manufacturing systems. The authors utilized cladistics and granularity analysis in to assess the structural and layout complexity of the manufacturing system. Based on their analysis, a trade off between structural complexity and layout complexity was observed and reported. For example, as structural complexity increases, equipment becomes more integrated with sophisticated structure and accordingly, layout complexity is reduced and vice versa.

Haddou Benderbal et al. (Haddou Benderbal, Dahane, & Benyoucef, 2017) proposed a multi-objective Non-dominated Sorted Genetic Algorithm (NSGA) for machine selection in RMS design under unavailability constraints. In addition, the authors proposed a flexibility index to measure the response of RMS towards machines unavailability.

Koren et al. (Koren, Wang, & Gu, 2017) proposed a mathematical model to maximize RMS throughput after reconfiguration and minimize the total number of machines. The authors proposed that scalability planning and design of a new manufacturing system must be done concurrently. Gu et al. (Gu, Jin, Ni, & Koren, 2015) proposed three measures to measure resilience and assist in the design of multi-stage RMS. The measures are (a) Production loss, (b) Throughput settling time and (c) total underproduction time. Numerical analysis was conducted to investigate the effect of system configuration, built-in capability and buffer capacity on the manufacturing system resilience. They concluded that:

- Manufacturing system built-in redundancy and flexibility improve system resilience performance during a long period of disturbance
- During the absence of redundancy and flexibility, parallel configuration outperforms serial configuration
- Buffers reduce the effect of short periods of disruption

In the problem of product family formation in RMS, Huang and Yan (Huang & Yan, 2019) proposed a part family grouping method using a similarity coefficient, considering process time and capacity demand.

Kashkoush and ElMaraghy (Kashkoush & ElMaraghy, 2014) average linkage hierarchical clustering together with phylogenetic and biology to develop a product family formation model in Reconfigurable Assembly Systems (RAS). Abdi et al. (Abdi, Labib, Edalat, & Abdi, 2018b) proposed an Analytical Network Process (ANP) to develop a product family formation model and RMS selection model. For more publications in the topic of part/product formation in RMS, the reader can refer to (Ashraf & Hasan, 2015; Eguia, Lozano, Racero, & Guerrero, 2011; Goyal, Jain, & Jain, 2013; Pattanaik & Kumar, 2011).

In manufacturing systems coding, ElMaraghy (H. A. ElMaraghy, 2006) proposed a complexity coding system for manufacturing systems classification which captures the features of equipment and the relationship between them. The coding system consists of fields representing manufacturing systems capabilities, buffers and material handling as well as fields capturing physical and logical aspects of the manufacturing system.

ElMaraghy et al. (H ElMaraghy, Samy, & Espinoza, 2010) proposed a classification coding system for assembly systems, consisting of 16 fields capturing the features of equipment, buffers and material handling units. The main benefit of the coding system is using it to capture complexity of assembly systems in an attempt to compare among various alternatives of assembly systems in terms of complexity.

Sorensen et al. (Sorensen, ElMaraghy, Brunoe, & Nielsen, 2020) proposed a classification coding scheme for identification of potential production systems platforms within a production system. The classification code consists of 25 digits to capture the physical and logical characteristics of production system.

The manufacturing systems complexity coding system capture the structural and layout complexity of the manufacturing/assembly systems, yet the coding systems above doesn’t provide any insight about the cost of the manufacturing system.

In production control and planning in RMS, Azab and Naderi (Azab & Naderi, 2015) proposed an optimization model to address RMS production scheduling. Hees and Reinhart (Hees & Reinhart, 2015) proposed a framework for production planning in reconfigurable manufacturing systems using data models, configuration management and sequential method for resource planning.

Hees et al. (Hees, Bayerl, et al., 2017) proposed a Mixed Integer Linear Programming model to determine feasible configurations and realize capacity scalability and functionality changes in production planning processes. For more information on the topic of production planning and control in RMS, the reader can refer to (Y.-C. Choi & Xirouchakis, 2015; Gyulai, Kádár, & Monostori, 2017; Hees, Schutte, & Reinhart, 2017).

For the future and evolution of manufacturing systems paradigms, Abdi et al. (Abdi, Labib, Edalat, & Abdi, 2018a), Yin et al. (Yin et al., 2018) and Hu (Hu, 2013) reviewed the evolution of manufacturing systems paradigms through the industrial revolution as well as enablers and drivers. Accordingly, several directions for future research on manufacturing system paradigm:

- Data collection and evaluation techniques in the presence of IoT
- Production system adaption to new technology and customer demands
- Models to create, manage, operate and maintain manufacturing systems in Industry 4.0
- Manufacturing systems require adaption towards adaptive processes
- Integration of manufacturing systems within the supply chain
- Cost structure rethinking in to cope with digital technology and smart factories
- Regulations in regards to health and safety for the personalized products
- On the fly manufacturability assessment of the personalized products

Towards this end, several researchers proposed new system architectures and paradigms to realize the aforementioned challenges. Gu and Koren (Gu & Koren, 2018) proposed a Reconfigurable Manufacturing System (RMS) architecture for cost-effective mass individualization. The main difference between RMS for mass individualization and RMS for high production volume (Koren et al., 2018a) is the return conveyor, which increases routing flexibility and cycle time variations due to the presence of either identical or different machines in each stage.

Extensive research has been conducted to develop suitable types of production systems and technologies to handle customers' individual needs. However, with the introduction of Industry 4.0, the integration between production facilities (e.g., distributed manufacturing systems), suppliers, and service systems is necessary to build value-added networks (Salkin, Oner, Ustundag, & Cevikcan, 2018). Hence, the coming subsections will be discussing enablers for Industry 4.0, such as Agile Manufacturing Systems, Distributed Manufacturing Systems, Cyber-Physical Systems and Cloud Manufacturing.

2.3. Industry 4.0

Schlechtendahl et al. (Schlechtendahl, Keinert, Kretschmer, Lechler, & Verl, 2015) presented a holistic approach to applying industry 4.0 within production systems that are not Industry 4.0. The proposed approach consists of 3steps, namely: *"discovery of and connection to production systems, data provision of production systems, connection between production systems"*(Schlechtendahl et al., 2015). The proposed approach only considered connectivity and interface aspects within production systems without considering any cost implications.

Lee et al. (Lee, Bagheri, & Kao, 2015) introduced a five unified level architecture for cyber-physical systems (CPS) implementation in industry 4.0. The five levels are (i) Smart connection level (condition monitoring), (ii) Data-to-information conversion level (self-aware), (iii) Cyber level (self-compare), (iv) Cognition level (prioritize and optimize decisions) and (v) configuration level (actions to avoid). Cost was not considered in their study.

In order to implement industry 4.0, several readiness indices and models are available in literature to assess readiness of SMEs to implement industry 4.0 {Mittal, 2018 #381}. The Singapore Smart Industry Readiness Index {Board, 2019 #382} is one of the indices that assists SMEs on determining how SMEs can benefit from implementing industry 4.0 as well as when to start the implementation. The index consists of 3 building blocks (Technology, Process and Organization), 8 pillars (e.g. Automation, Connectiveness, Intelligence…etc.) and 16 dimensions (e.g. Process-Vertical Integration, Process horizontal integration, process-integrated product lifecycle…etc.). Schuh et al. {Schuh, 2017 #384} proposed the acatech industrie 4.0 Maturity Index to provide companies with guides to introduce and implement the digital transformation process. The guide consists of six-stage maturity model to assists companies in implementing and benefiting from Industry 4.0. This index relies on four key structures: resources, information systems, organisational structure and culture.

Schumacher et al. (Schumacher, Erol, & Sihn, 2016) proposed an empirical model to assess the readiness and maturity of industry 4.0 within manufacturing companies. The proposed maturity model is based on nine dimensions: strategy, leadership, customers, products, operations, cultures, people, governance and technology. The benefits of the proposed model are that it takes into consideration various aspects within the organizational level.

AbdulRahman {AbdulRahman, 2019 #380} proposed an industry 4.0 four step implementation strategy to assess SMEs technological maturity level using Analytical Hierarchical Process (AHP). A case study from a local automation company has been used. The benefits of the research are providing a tool for SMEs to transform to Industry 4.0 implementation.

Saldivar et al. (Saldivar et al., 2015) provided a study on the CPS integration for the purposes of Industry 4.0, as well as the future trend for smart manufacturing and product design. It was concluded that integrating CPS, cloud computing, virtual design, and real-time analysis is important to use industry 4.0 in terms of increasing productivity and innovation as the CPS components are self-aware.

Monostori et al. {Monostori, 2016 #206} wrote a comprehensive review paper on cyber physical systems. The authors reported the challenges that existing in implementation of cyber physical systems lies in standardization to integrate CPS solutions, security, computational dynamical systems theory which can handle time in programming languages.

Monostori {Monostori, 2014 #379} discussed the roots for enabling Cyber Physical Production Systems (CPPS) such as intelligent manufacturing systems, biological manufacturing systems, reconfigurable manufacturing systems, holonic manufacturing systems, digital factories and production networks. In addition, the authors pointed out several R&D challenges related to CPPS such as cooperative production systems, robust scheduling and human-machine symbiosis.

Mosterman and Zander (Mosterman & Zander, 2016) illustrated the joint function of the embedded software in communication between Cyber-Physical Systems (CPS), Internet of Things (IoT) and machine to machine interface. Examples of CPS challenges were also presented, such as infrastructure needs. A case study based on a pick and place machine was conducted.

2.4. Discussions

According to the literature review, a few gaps have been identified:

- The interrelationship between machine rate and annual hours assigned to the machine: The relationship between the machine hour rate and the total hours in a year are conflicting. On the one hand, as the machine hourly rate is reduced, more working hours are assigned in terms of new orders (price gets competitive). On the other hand, as more hours are assigned to the machine, the machine hour rate is reduced.
- An aggregate Activity-Based costing model that considers the reconfiguration cost at a machine-level, system-level, and factory level, is needed.
- Cost-benefit of implementation of Industry 4.0 in job shop environment taking into consideration connectivity with suppliers

A summary of the literature survey is shown in Table 8 in which the rows lists authors and columns list the main topics.

Table 8: Summary of Costing Methods literature survey

Author	Method	Labour cost	Machining cost	Product cost	Bi-directional cost	Type of layout or system	Type of solution
Mohsenijam and Lu 2016	Regression and error analysis	x				Job shop	Sub-optimal
Ikumapayi1 el al. 2019	Mathematical formulation	x	x	x		General	N/A
Tang et al. 2012	Matrix-based approach (input-output analysis)	x	x	x		General	Sub-optimal
Hanafy and ElMaraghy 2017	Mathematical modeling	x	x	x		Flow lines/assembly	Optimal
Aderoba 1997	Activity-based costing	x	x	x		Job shop	Sub-optimal
Ozbayrak et al 2004	ABC/ simulation	x	x	x		General	Sub-optimal
Kolati et al. 2010	ABC/ mathematical programming	x	x	x		Flexible manufacturing system	Optimal
Roy et al. 2011	Framework	x	x	x		Flowlines (automotive)	N/A
Kareem et al. 2011	ABC/ mathematical model	x	x			Single machine	Sub-optimal
Youssef and ElMaraghy 2006	Meta-heuristics					Flow lines	Sub-optimal
Abbas and ElMaraghy 2018	Mixed Integer Linear Programming					Flow lines	Optimal
Spicer and Carlo 2006	Dynamic programming	x				General	Optimal
Lin et al. 2012	DFM/ABC	x	x	x		General	Sub-optimal
Ramadan et al. 2016	VSM/Mathematical model	x	x	x		General	Sub-optimal
Qian and Ben Arieh 2008	ABC/Mathematical model/parametric costing		x	x		N/A	Sub-optimal
Choi et al. 2005	Knowledge-based system/CATIA	x	x	x		N/A	Sub-optimal
Rezaie et al. 2007	TC/ABC	x	x	x		Flexible manufacturing system	Sub-optimal
Chougule and Ravi 2006	Mathematical model/solid modelling	x	x	x		N/A	Sub-optimal
Velardi 2005	COSYSMO/ Parametric costing					N/A	Sub-optimal

Researching the gap in both academia as well as the industry in an attempt to cover the need to estimate real and meaningful cost modelling, it was interesting to analyze the papers published, when searched in Scopus, and timeline when they were published, using the search Key-words: “Job-Shop”, “Flexible manufacturing systems”, and “Reconfigurable manufacturing systems”, along with “Industry 4.0” and “Activity-Based Costing”.

Considering all the topics searched, there were 11 clusters in the bibliography data. However, only one cluster included a costing topic. VOSViewer broke the 932 published papers relating to these topics into 11 clusters and 375 common keywords that were used 5 or more times. This network is shown in Fig. 9.

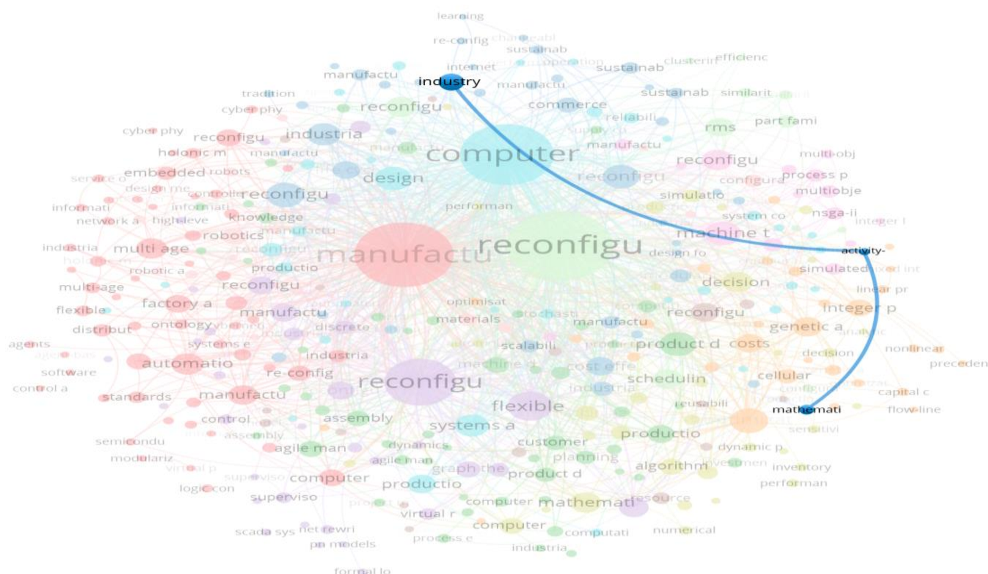

Fig. 9. Mapping by papers on research in keywords Industry, Activity-Based Costing and Mathematical modelling

Additionally, considering the timeline and the intensity of research in these specific areas, it is worth considering that some of the topics, specifically “Costing” topics considered started as early as 1968. However, the majority of research has intensified and has been exponentially growing since early 2000. This is primarily due to two major factors: Reconfigurable manufacturing systems, and adding the fact that Industry 4.0 implementation intensified in the past 10 years as shown in Fig. 10.

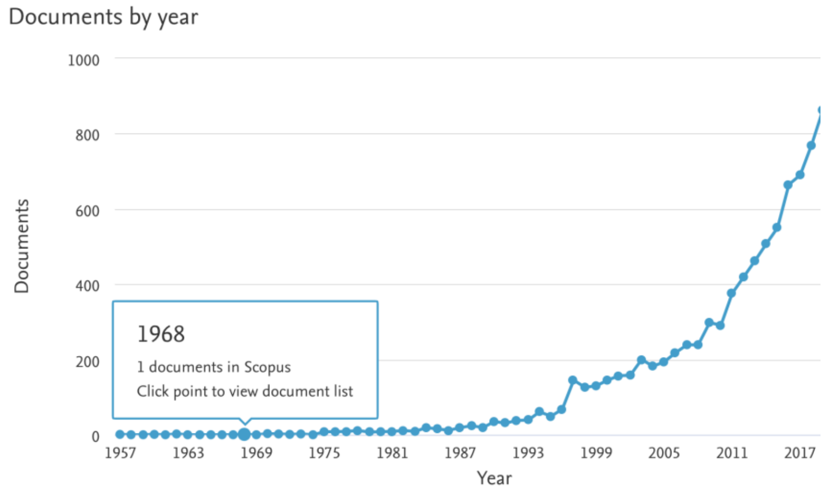

Fig. 10. History of documents based on the search criteria applied.

Finally, considering costing, more specifically ABC costing, these topics were only used across 4 papers in one tiny track on 1 out of the 11 clusters formed. It has been said, "A picture is worth 1,000 words." In this particular case, Figure 1 shows how little research has been completed in the area of costing (ABC), mathematical modelling and Industry 4.0. These streams of research are highlighted compared to the vast world of research completed as shown in Fig. 9.

CHAPTER 3 Traditional and Activity Based Aggregate Job Costing Model Using Mixed Integer Linear Programming

3. Introduction

Manufacturing continues to face escalated cost challenges as the global economy grows. To gain a competitive advantage among its rivals, manufacturing firms are continually striving to lower their manufacturing costs than their competitors. Towards this goal, manufacturing firms are adopting cost models to capture the actual product cost properly adequately. A traditional costing model was extensively used to determine product cost. The prime cost in the traditional model is the direct labour and direct material. However, with the increase in product offering and processes automation in today's manufacturing era, overhead allocation accounts for a large portion of the product cost. Hence, overhead costs are considered the prime cost (Myers & Le Moyne, 2009). As a result, manufacturing firms needed to investigate the proper method for allocating overhead costs closely.

Towards these efforts, the ABC method has been developed and used by manufacturing firms. The main difference between traditional costing and the ABC method is the pooling cost method. Traditional costing method pools cost to departments then to cost objects (e.g. products), while the ABC method pools cost to activity centers than cost objects (Edmonds, Edmonds, Tsay, & Olds, 2000). These activity centers are divided into unit level, batch level, product level and customer level activities.

This section will introduce a Mixed Integer Linear Programming (MILP) model for ABC and traditional costing methods. The section will also introduce a method for calculating the hourly rates based on the total hours assigned to workcentres/departments and how accepting more jobs will reduce the hourly rates and, hence, gain competitive advantage.

This section is organized as follows; Section 1 provides an overview of the ABC method, Section 2 establishes the mathematical model, Section 3 is the discussion of the results, and finally, Section 4 is the conclusion.

3.1. Overview

Activity-Based Costing (ABC), initially introduced by (Cooper & Kaplan, 1988a, 1988b), works differently from the traditional costing system. The main benefit of ABC costing is the allocation of a product's unit cost based on the capacity used for that product. It starts by defining the different activities involved in production (e.g. setup, machining, assembly, etc.), compute the cost for each activity and then allocate each activity to its corresponding product. This type of system works well for companies producing a broad scope of product variants. Last, the variable based costing includes only in its structure the variable costs such as material cost and labour cost with "fixed costs are treated as a lump sum that must be covered by the products' contribution margins" (Hughes & Paulson Gjerde, 2003). The steps for ABC costing are shown in Fig. 6.

For the ABC method, the hourly rate in a specific period for a particular Workcentre or engineering activity is calculated through:

$$Hourly\ rate\ for\ certain\ machine/activity\_ABC = \frac{Blended}{cost} + \frac{General\ assets_{ABC} + Depreciation/yr}{total\ hours\ by\ machine/activity} \quad (1)$$

The traditional costing system uses direct labour, direct material, and overhead to determine the product's cost. Though simple to use, yet, the traditional costing systems allocate the overhead costs to the different products properly (average allocation of overhead costs). The main distinguishing feature of the traditional costing system is the allocation of overhead costs. In this mathematical model, the overhead cost is allocated to the direct labour cost (based on ABC method). The relationship between the machine hour rate and the total hours in a year are conflicting.

On the one hand, as the hourly machine rate is reduced, more working hours are assigned in terms of new orders. On the other hand, as more hours are assigned to the machine, the hourly machine rate is reduced. The relationship between the annual hours and hourly rates can be shown in Fig. 11.

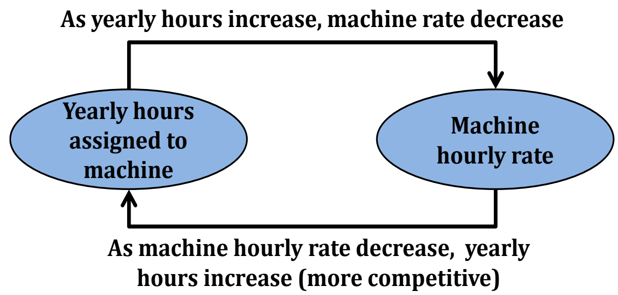

Fig. 11.Relationship between annual hours and hourly rates

Equation (1) is applied for machining workcentres as well as departmental activities such as engineering. However, the deprecation cost in both equations is the critical difference. The deprecation cost of machines is applied through 10 years. However, in engineering departments, the depreciation is negligible compared to process machines prices.

3.2. Mathematical Formulation

The list of input parameters, decision variables, sets, constants, objective function, and constraints is detailed. The list of input parameters is:

$h_{i,j}$: Quoted/budget hours required for engineering department j to complete job i (2)

$g_{i,o}$: Quoted/budget hours required for workcentre o to complete job i (3)

$k_{i,o}$: Quoted/budget hours required for setup workcentre o to complete job i (4)

$Q_{i,t}$: Production demand/quantity of job i in production period t (5)

$d_{i,t}$: Raw material/commercial items cost for job i in production period t (6)

$R_{i,t}$: Selling price of job i in production period t (7)

$C_{o,t}^{WC}$: Available capacity for workcentre o in production period t (8)

$C_{j,t}^{ENG}$: Available capacity for engineering department *j* in production period *t* (9)

$c_o^{DEP\_WC}$: Depreciation cost of workcentre *o* (10)

$c_j^{DEP\_ENG}$: Depreciation cost of equipment in engineering department *j* (11)

$c_o^{GA\_WC}$: General assets allocation cost to existing workcentre *o* (12)

$c_j^{GA\_ENG}$: General assets allocation cost to department *j* (13)

The list of decision variables is:

$$x_{i,t} = \begin{cases} 1, & \text{if job } i \text{ is chosen in production period } t \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

$y_{j,t}$: Hourly rate for engineering department *j* in production period *t* (15)

$z_{o,t}$: Hourly rate for workcentre *o* in production period *t* (16)

The objective function is concerned with maximizing profit. In other words, it is required to minimize the difference between total cost and total selling price. Several assumptions are considered while formulating the objective function. For the purposes of focusing on minimizing cost, it is assumed that selling price is market driven, and considered as a constant. In an attempt to keep the focus on cost minimization, and focusing on the Engineering problem on-hand, an assumption of making the selling price as constant is made. If the model were to be structured as a cost minimization (without including selling price in the objective function), then the minimal and optimal solution would have been zero (do nothing). Hence, selling price was incorporated as a part of the objective function. Materials are purchased towards a specific job, and hence, no carrying or holding cost is considered. The objective function is written as:

$Min\ Z$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} d_{i,t}Q_{i,t}x_{i,t} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} h_{i,j}x_{i,t}y_{j,t}$$

$$+\sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} Q_{i,t}g_{i,o}x_{i,t}z_{o,t} + \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} \frac{\left(k_{i,o}x_{i,t}z_{o,t}\right)}{Q_{i,t}+\varepsilon} \tag{17}$$

$$-\sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t}Q_{i,t}x_{i,t}$$

Manufacturing cost includes activities such as machining, fabrication, assembly, testing and rework (Sandborn, 2016). However, the mathematical model only considers Mechanical and Electrical engineering as well as manufacturing in the form of direct labour cost. Indirect costs, overhead costs, utility rental, installation at customer's site, testing and commissioning costs were not considered. This is not a drawback of the mathematical model since such costs can be considered as additional departments/workcentres.

In Equation (17), the first term is the raw material/commercial items cost. The second term is the total engineering cost. In ABC method terms, the second term is the product level. The third term is the total production cost. In ABC method terms, the third term is the unit level. The fourth term is the total setup cost. In ABC method terms, the fourth term is the batch level. Finally, the fifth term is the selling cost. The symbol ε is a small number (e.g. 0.00005) to prevent an infinite value for the fourth term if $Q_{i,t}$ is zero.

The constraints for the proposed model are:

$$y_{j,t} = a_0 + \frac{a_j^{ENG} + d_j^{ENG}}{\sum_{i=1}^{I} h_{i,j}x_{i,t_0}}, \forall j = 1,2..J, t = 1,2..T, t_0 = t-1 \tag{18}$$

$$z_{o,t} = b_0 + \frac{a_o^{WC} + d_o^{WC}}{\sum_{i=1}^{I} g_{i,o}Q_{i,t_0}x_{i,t_0}}, \forall o = 1,2..O, t = 1,2..T, t_0 = t-1 \tag{19}$$

$$\sum_{i=1}^{I} (g_{i,o} Q_{i,t} x_{i,t} + k_{i,o} x_{i,t}) \leq C_{t,o}^{WC}, \forall o = 1,2..O, t = 1,2..T \tag{20}$$

$$\sum_{i=1}^{I} h_{i,j} x_{i,t} \leq C_{j,t}^{ENG}, \forall j = 1,2..J, t = 1,2..T \tag{21}$$

$$\sum_{i=1}^{I} x_{i,t} \geq 1, \forall t = 1,2..T \tag{22}$$

Equation (18) and Equation (19) are concerned with calculating the hourly rates for engineering and manufacturing, which are the direct implementation of Equations (1). The terms ”a_0“ and ”b_0“ is the blended cost for the engineering and production department, respectively. Equation (20) ensures that the available capacity of workcentre *o* in production period *t* does not exceed the total required machining hours. Equation (21) ensures that the available capacity of engineering department *j* in production period *t* does not exceed the total required engineering hours. Equation (22) forces the model to choose at least one job in each production period. Besides the formulation above, there are several non-linear terms such as $y_{j,t}x_{i,t}$ in Equation (18) in which $y_{j,t}$ is continuous, and $x_{i,t}$ is binary. Such a term requires linearization before solving the model. The reader may refer to (FICO, 2009) for further readings on linearization techniques. We did not explicitly add that the variables are nonnegative as they are assumed to be nonnegative by the solver GUROBI.

3.3. Case Study

This case study considers a real-life example of a global Original Equipment Manufacturer of Machinery. Different variants of machinery are manufactured across the globe in different manufacturing plants. This data is extracted from one plant for such equipment to determine the proper manufacturing size for the plant. However, the same data can be applied to all manufacturing locations. The difference between different locations might lie in each facility's size and the fixed overhead each facility might carry. The case study inputs are given in Table 9,

Table 10, Table 11, Table 12, and Table 13. Besides, some information is not shown in this dissertation due to data protection mandated by the company's finance department for maintaining a competitive edge, such as machine depreciation.

Table 9.Capacities of engineering department ($C_{j,t}^{ENG}$) in production periods in hours

		Engineering dept.	
		Mech	Elec
Production period	1	5000	5000
	2	5000	5000
	3	5000	5000
	4	5000	5000
	5	5000	5000
	6	5000	5000
	7	5000	5000
	8	5000	5000
	9	5000	5000
	10	5000	5000
	11	5000	5000
	12	5000	5000

Table 10. General assets allocation for ABC costing model

	Workcentre ID	c_o^{WC}
Workcentre	1010	$ 20,141.36
	1020	$ 59,057.32
	1030	$ 59,057.32
	1040	$ 14,061.27
	1050	$ 15,186.17
	1060	$ 14,061.27
	1070	$ 8,436.76
	1080	$ 7,030.63
	1090	$ 15,186.17
	1100	$ 20,141.36
	1110	$ 59,057.32
	1120	$ 59,057.32
	1130	$ 59,057.32
	1140	$ 59,057.32
	1150	$ 59,057.32
	1160	$ 20,141.36
	1170	$ 20,141.36
	1180	$ 20,141.36
	Engineering Dept. ID	c_j^{ENG}
Engineering	Dept. 1	$ 7,030.63
	Dept. 2	$ 7,030.63

3.4. Results and Discussions

The mathematical model is written in AMPL (http://ampl.com/) and solved by Gurobi MILP in NEOS (Czyzyk, Mesnier, & Moré, 1998; Dolan, 2001; Gropp & Moré, 1997). An IDEF0 for the model is shown in Fig. 12. The mathematical model's output is shown in Table 14, Fig. 13, Fig. 14, Fig. 37, Fig. 38 and Fig. 39. The optimum objective function for Equation (17) is -$208,960,000 for the ABC method.

Table 11. Direct material cost and selling price for each order

		Total direct material cost $d_{i,t}$	Job/order selling price $r_{i,t}$
Jobs/orders	1	$ 36,866	$ 2,695,320
	2	$ 97,531	$ 2,508,450
	3	$ 21,615	$ 3,909,368
	4	$ 99,247	$ 2,747,559
	5	$ 96,111	$ 2,607,061
	6	$ 35,654	$ 943,705
	7	$ 32,793	$ 3,923,011
	8	$ 69,500	$ 1,434,330
	9	$ 99,464	$ 1,291,080
	10	$ 31,337	$ 3,111,690

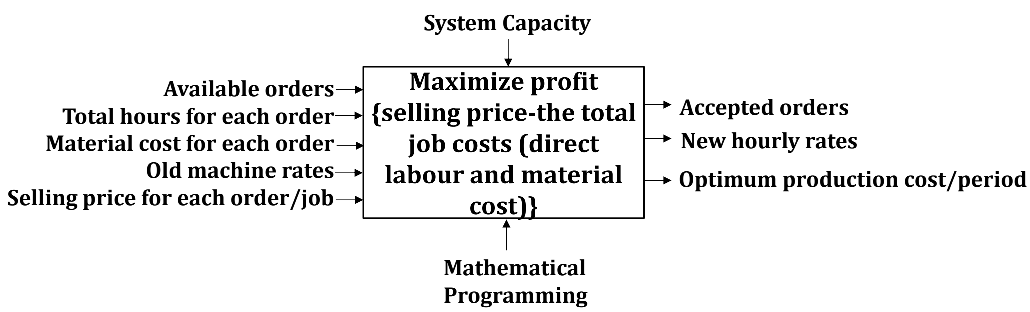

Fig. 12. IDEF0 for the optimum solution of ABC cost model for a job shop environment using mixed integer linear considering the interrelationship between annual hours and direct labour hours model

Table 14 shows the optimum jobs/orders selected for each production period. The mathematical model tends to select most of the jobs/orders if engineering and manufacturing departments' capacities are satisfied to reduce the hourly rate as per Equation (18) and Equation (19). Fig. 13 and Fig. 14 show the optimum hourly rates for the 18 different workcentres for the

ABC method. The variation between each period depends on the hours utilized by each workcentre in the previous period.

The results of this chapter are similar to the real-life implementation of this particular problem. The only difference is job number 8 in production periods 1 and 2. The proposed model rejected these jobs in production periods 1 and 2. However, these jobs were accepted afterwards. Job 8 belongs to a returning customer, and hence, refusing it is not an option for the company as that might lead the customer to go to a different company for future projects and jobs. This job can be indirectly enforced to the mathematical in the form of constraint (i.e. $x_{8,1}$=1 and $x_{8,2}$=1).

Table 12.Capacities of workcentres ($C_{o,t}^{WC}$) in production periods in hours

		Workcentre																	
		1010	1020	1030	1040	1050	1060	1070	1080	1090	1100	1110	1120	1130	1140	1150	1160	1170	1180
Production period	1	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	2	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	3	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	4	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	5	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	6	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	7	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	8	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	9	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	10	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	11	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800
	12	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800

Table 13. Workcentre job/order processing time (setup time) in hours ($k_{i,o}$)

		Workcentres																	
		WS-1010	WS-1020	WS-1030	WS-1040	WS-1050	WS-1060	WS-1070	WS-1080	WS-1090	WS-1100	WS-1110	WS-1120	WS-1130	WS-1140	WS-1150	WS-1160	WS-1170	WS-1180
Job	1	82.048 (2)	1755 (1)	785 (2)	795 (2)	40 (2)	600 (2)	0 (0)	1055 (1)	760 (2)	1240 (1)	670 (1)	760 (1)	0 (0)	0 (0)	80 (1)	267.5 (1)	300 (2)	50 (1)
	2	657.5 (2)	1040 (2)	592.5 (2)	1267 (1)	1900 (1)	3365 (2)	895 (2)	0 (0)	600 (1)	0 (0)	760.5 (2)	520 (2)	520 (2)	650 (2)	756 (2)	677.5 (1)	412.5 (2)	0 (0)
	3	60 (2)	100 (2)	150 (1)	0 (0)	0 (0)	70 (1)	30 (1)	0 (0)	0 (0)	100 (2)	150 (1)	0 (0)	0 (0)	0 (0)	50 (2)	0 (0)	100 (1)	200 (2)
	4	145 (1)	890 (1)	137.5 (1)	200 (2)	105 (1)	0 (0)	0 (0)	0 (0)	1850 (1)	200 (1)	150 (1)	0 (0)	450 (1)	320 (2)	300 (1)	105 (1)	250 (2)	40 (2)
	5	115 (2)	297.5 (2)	250 (2)	100 (1)	100 (1)	0 (0)	0 (0)	0 (0)	1500 (1)	200 (1)	192.5 (2)	0 (0)	450 (2)	220 (2)	300 (2)	100 (2)	200 (2)	110 (2)
	6	30 (1)	935 (2)	1520 (2)	140 (1)	505 (1)	1670 (1)	472.5 (1)	0 (0)	720 (2)	90 (1)	1107.5 (2)	100 (1)	0 (0)	460 (1)	82.5 (1)	80 (2)	200 (2)	880 (1)
	7	0 (0)	0 (0)	5539 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	8	147.5 (1)	330 (2)	55 (2)	680 (2)	7.5 (2)	5 (1)	0 (0)	50 (1)	400 (2)	185 (2)	80 (1)	5 (1)	0 (0)	50 (1)	142.5 (1)	70 (1)	5 (1)	50 (1)
	9	195 (2)	340 (2)	50 (2)	40 (2)	7.5 (1)	25 (2)	0 (0)	80 (1)	400 (2)	230 (2)	202.5 (1)	5 (1)	0 (0)	50 (2)	167.5 (1)	75 (1)	45 (2)	10 (1)
	10	135 (2)	370 (1)	15 (2)	110 (2)	7.5 (2)	25 (2)	0 (0)	90 (2)	400 (1)	250 (1)	100 (2)	5 (1)	0 (0)	50 (1)	167.5 (1)	70 (1)	45 (2)	20 (2)

Table 14. Optimum jobs/orders-production period matrix $x_{i,t}$

		Jobs/ orders									
		1	2	3	4	5	6	7	8	9	10
Production periods	1	1	1	1	1	1	1	1	0	1	1
	2	1	1	0	1	1	1	1	0	1	1
	3	1	1	1	0	1	0	1	1	1	1
	4	1	1	1	1	0	0	1	1	1	1
	5	1	1	0	1	1	1	1	1	0	1
	6	1	1	1	1	1	1	1	0	1	1
	7	1	1	1	0	1	1	0	1	1	1
	8	1	1	1	1	1	1	1	0	1	1
	9	1	1	1	1	0	0	1	1	1	1
	10	1	1	1	1	1	1	1	0	1	1
	11	1	1	1	1	1	0	1	1	0	1
	12	1	1	1	1	1	1	1	0	1	1

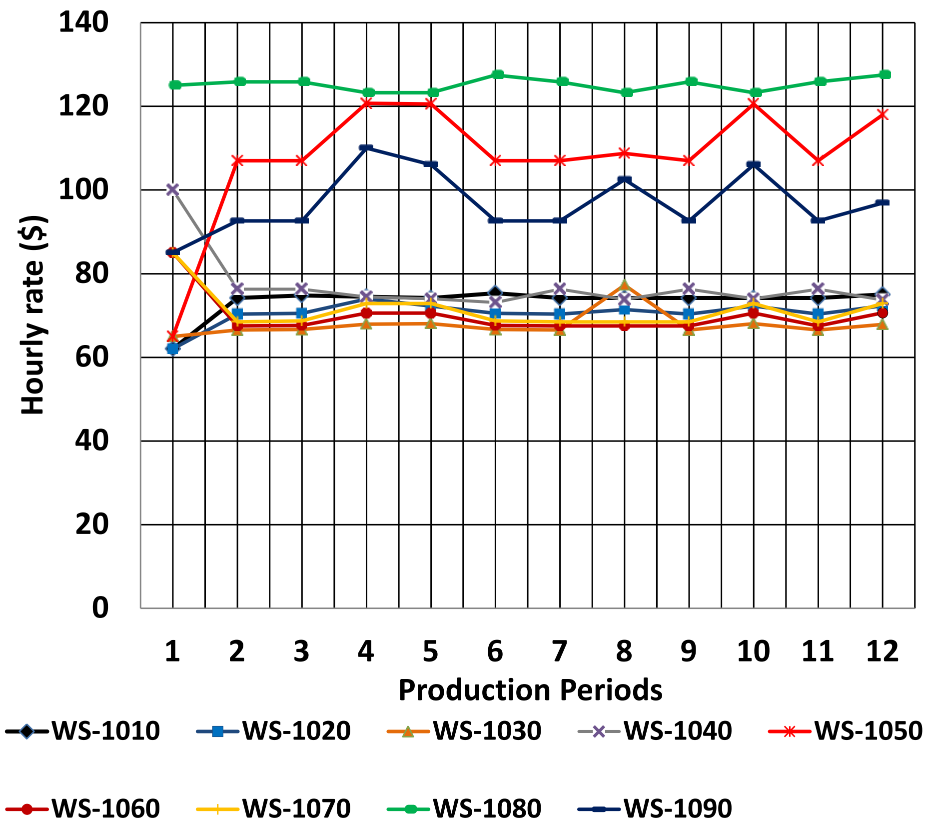

Fig. 13. ABC method optimum hourly rate ($) for workcentres WS-1010 to WS-1090

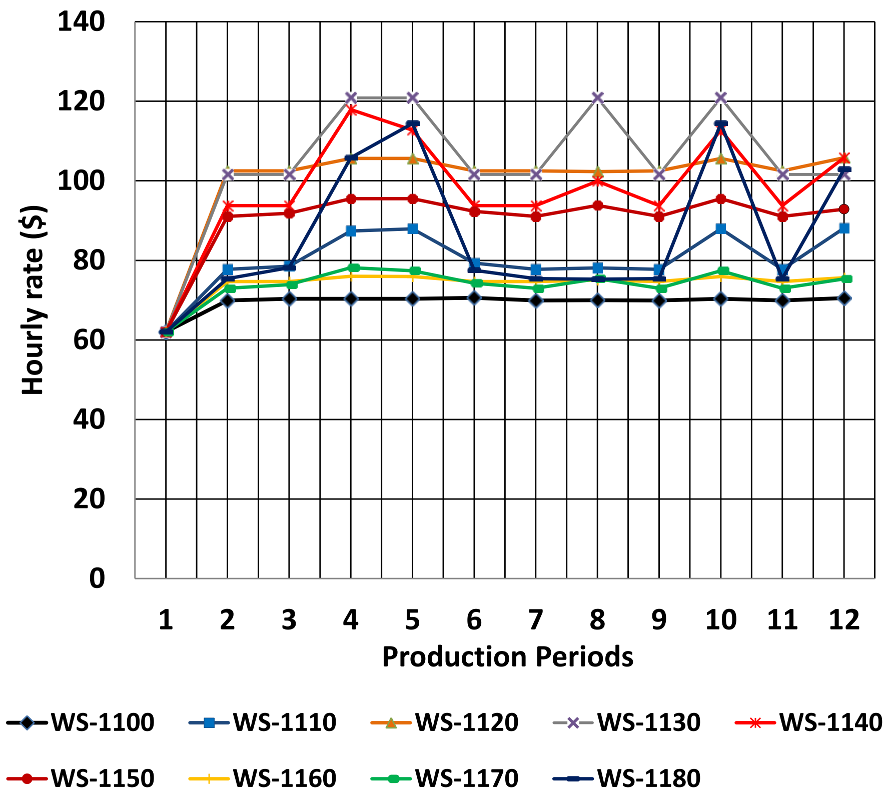

Fig. 14. ABC method optimum hourly rate ($) for workcentres WS-1110 to WS-1180

3.5. Conclusion

This proposed mathematical model addresses the problem of production cost by providing methods and techniques that consider practical industrial aspects. A mathematical programming model was developed in order to minimize the total cost of production, taking into consideration adjustments in machining hourly rates. Besides, the model was solved using the traditional cost method. The proposed ABC model provided a better competitive advantage in terms of hourly rates, allowing manufacturing firms to get a better competitive advantage from its rivals. Furthermore, the implementation of the model reduced hourly rates for workcentres (in the Industrial Case Study) by up to 25% as a result of accepting more jobs (and accordingly, machining hours) on the available workcentres, and hence, reducing the hourly rates. This implementation has helped the company gain a competitive advantage among rivals since pricing of products submitted to customer was reduced.

The significance of the model proposed in Chapter 3 is that it provides managers in manufacturing facilities with a crucial decision-making tool to help them decide which orders to accept per period to minimize labour cost. In addition, this research will help manufacturing companies achieve a competitive edge against their rivals by reducing hourly labour rates.

CHAPTER 4 Activity-Based Aggregate Job Costing Model for Reconfigurable Manufacturing Systems

4. Introduction

Manufacturing continues to face escalated cost challenges as the global economy grows. In order to gain competitive advantage among its rivals, manufacturing firms are in a constant strive to lower their manufacturing costs compared to their competitors. This chapter introduces a mathematical optimization model based on Activity Based Costing (ABC) method for Reconfigurable Manufacturing Systems (RMS) taking into consideration the bi- directional relationship between hourly rates and annual hours on each machine/workcentre. The output from the model will be the optimum hourly rates, decision on which jobs to accept or reject and decision on the financial feasibility of reconfiguration. Reconfiguration in this chapter describes both system-level reconfiguration (investing in additional machining equipment) and/or, machine-level reconfiguration (extra module to an existing equipment). The model will be applied on a real life case study of a global Original Equipment Manufacturer of Machinery. The novelty of the proposed model is the incorporation of the bi-directional relationship between hourly rates and annual hours on each machine and provides a managerial decision making tool in terms of investment level required to pursue new business and gaining competitive advantage over rivals.

4.1. Mathematical Model Formulation

This section lists and illustrates the mathematical model implemented in this chapter. The IDEF0 model is shown in Fig. 15. The detailed description of the model, inputs and outputs will be illustrated in the following subsections. The proposed model is non-linear. To obtain the linear form and convert it to a Mixed Integer Linear Programming (MILP) model, the reader can refer to Linearization methods and techniques in (FICO, 2009).

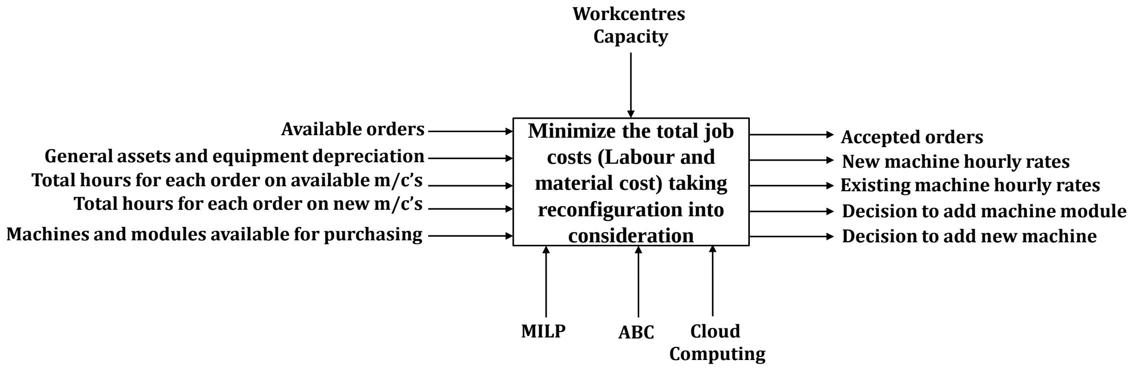

Fig. 15. IDEF0 model for the Activity-Based Aggregate Job Costing Model for Reconfigurable Manufacturing Systems model

The list of input parameters, decision variables, sets, constants, objective function, and constraints is complicating the model, a significant assumption that Selling Price is constant. This is done in order to focus the model on maximizing profit by minimizing costs, similar to the model proposed earlier in Chapter 3. The list of input parameters is:

$$e_{i,o} = \begin{cases} 1, & \text{if workcentre } o \text{ can operate on job } i \\ 0, & \text{otherwise} \end{cases} \tag{23}$$

$g_{m,i,o}$: Quoted/budget hours required for workcentre o to complete job i when module m is added (24)

$g_{i,o}$: Quoted/budget hours required for workcentre o to complete job i (25)

$g_{i,p}^{WC\_NEW}$: Quoted/budget hours required for new workcentre p to complete job i (26)

$h_{i,j}$: Quoted/budget hours required for engineering dept. j to complete job i (27)

$k_{i,o}$: Quoted/budget hours required to setup workcentre o for job i (28)

$k_{i,p}^{WC\_NEW}$: Quoted/budget hours required to setup workcentre p for job i (29)

$Q_{i,t}$: Production demand/quantity of job i in production period t (30)

$d_{i,t}$: Raw material/commercial items cost for job i in production period t (31)

$R_{i,t}$: Selling price of job i in production period t (32)

$C_{o,t}^{WC}$: Available capacity for workcentre o in production period t (33)

$C_{p,t}^{WC\_NEW}$: Available capacity for workcentre p in production period t (34)

$C_{j,t}^{ENG}$: Available capacity for engineering department *j* in production period *t* (35)

$c_{o}^{DEP\_WC}$: Depreciation cost of existing workcentre *o* (36)

$c_{p}^{DEP\_WC\_NEW}$: Depreciation cost of new workcentre *p* (37)

$c_{j}^{DEP\_ENG}$: Depreciation cost of equipment in engineering department *j* (38)

$c_{o,t}^{GA\_WC}$: General assets allocation cost to existing workcentre *o* in period *t* (39)

$c_{p,t}^{GA\_WC\_NEW}$: General assets allocation cost to new workcentre *p* in period *t* (40)

$c_{j,t}^{GA\_ENG}$: General assets allocation cost to engineering department *j* in period *t* (41)

c_{m}^{MOD}: purchase cost of functional module *m* (42)

$c_{p}^{WC\_NEW}$: purchase cost of new workcentre *p* (43)

The list of decision variables are:

$y_{j,t}$: Hourly rate for engineering department *j* in production period *t* (44)

$z_{o,t}$: Hourly rate for workcentre *o* in production period *t* (45)

$z_{p,t}^{WC\_NEW}$: Hourly rate for new workcentre *p* in production period *t* (46)

$$u_{o,mt}^{MOD} = \begin{cases} 1, & \text{if module } m \text{ is bought for workcentre } o \text{ in production period } t \\ 0, & \text{otherwise} \end{cases} \quad (47)$$

$$u_{p,t}^{WC\_NEW} = \begin{cases} 1, & \text{if new workcentre } p \text{ is bought in production period } t \\ 0, & \text{otherwise} \end{cases} \quad (48)$$

$$v_{o,m,t} = \begin{cases} 1, & \text{if module } m \text{ is required in workcentre } o \text{ in production period } t \\ 0, & \text{otherwise} \end{cases} \quad (49)$$

$$w_{p\ t} = \begin{cases} 1, & \text{if workcentre } o \text{ is required in production period } t \\ 0, & \text{otherwise} \end{cases} \quad (50)$$

$$x_{i\ t} = \begin{cases} 1, & \text{if job } i \text{ is chosen in production period } t \\ 0, & \text{otherwise} \end{cases} \quad (51)$$

The objective function is concerned with maximizing the profit in which it is required to minimize the difference between total cost and total selling price. For this purpose, the same assumption from Chapter 3, of keeping selling price as constant, is made within this model. The objective function is written, as shown in (52).

Min Z

$$
\begin{aligned}
&\sum_{i=1}^{I}\sum_{t=1}^{T} d_{i,t}Q_{i,t}x_{i,t} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} h_{i,j}y_{j,t}x_{i,t} \\
&+ \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} Q_{i,t}g_{i,o}z_{o,t}x_{i,t} + \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} \frac{\left(k_{i,o}z_{o,t}x_{i,t}\right)}{Q_{i,t}+\varepsilon} \\
&+ \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=1}^{T} Q_{i,t}g_{i,p}^{WC\_NEW} z_{p,t}^{WC\_NEW} x_{i,t} \\
&\qquad + \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} \frac{\left(k_{i,p}^{WC\_NEW} z_{p,t}^{WC\_NEW} x_{i,t}\right)}{Q_{i,t}+\varepsilon} \\
&+ \sum_{o=1}^{O}\sum_{m=1}^{M}\sum_{t=1}^{T} c_m^{MOD} u_{o,mt}^{MOD} + \sum_{p=1}^{P}\sum_{t=1}^{T} c_p^{WC\_NEW}\, u_{p,t}^{WC\_NEW} \\
&- \sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t}Q_{i,t}x_{i,t}
\end{aligned} \tag{52}
$$

The mathematical model only considers the Mechanical and Electrical Engineering departments and manufacturing direct labour costs. Factory overhead and indirect costs are allocated to the direct hourly rates. In Equation (52), the first term is the raw material/commercial items cost. The second term is the total engineering cost. In ABC method terms, the second term is the product level. The third term and fifth terms are the total production cost for the existing and new workcentres, respectively. In ABC method terms, the third and fifth terms is the unit level. The fourth and sixth terms are the total setup cost for the existing and new workcentres. In ABC method terms, the fourth and sixth term are the batch level. The seventh and eighth terms are the buying costs of functional modules and adding new workcentres, respectively. Finally, the ninth term is the selling price. In the fourth term, the symbol ε is a small number (e.g. 0.0005) to prevent an infinite value for the fourth term, if $Q_{i,t}$ is equal to zero. The constraints for the proposed model are:

$$y_{j,t} = a_0 + \frac{c_{j,t}^{GA\_ENG} + c_j^{DEP\_ENG}}{\sum_{i=1}^{I} h_{i,j} x_{i,t_0}}, \forall j = 1,2..J, t = 1,2..T, t_0 = t-1 \tag{53}$$

$$z_{p,t}^{NEW} = b_0^{NEW} + \frac{c_{p,t}^{GA\_WC\_NEW} + c_p^{DEP\_WC\_NEW}}{\sum_{i=1}^{I} Q_{i,t_0} g_{i,p}^{NEW} x_{i,t_0}}, \forall\, p = 1,2..P, t = 1,2..T, t_0 = t-1 \tag{54}$$

$$z_{o,t} = b_0 + \frac{c_{o,t}^{GA_{WC}} + c_o^{DEP_{WC}}}{\sum_{i=1}^{I} Q_{i,t_0}(g_{i,o} + \sum_{m=1}^{M} f_{m,i,o} v_{o,m,t_0}) x_{i,t_0}}, \quad \forall o = 1,2..O, t = 1,2..T, t_0 = t-1 \tag{55}$$

$$\sum_{i=1}^{I} (g_{i,p}^{WC\_NEW} Q_{i,t} + k_{i,p}^{WC\_NEW}) x_{i,t} \le C_{p,t}^{WC\_NEW}, \forall\, p = 1,2..P, t = 1,2..T \tag{56}$$

$$\sum_{i=1}^{I} \left(g_{i,o} Q_{i,t} + \sum_{m=1}^{M} g_{m,i,o} v_{o,m,t}\, Q_{i,t} + k_{i,o} \right) x_{i,t} \le C_{t,o}^{WC}, \forall o = 1,2..O, t = 1,2..T \tag{57}$$

$$\sum_{i=1}^{I} h_{i,j} x_{i,t} \le C_{j,t}^{ENG}, \forall\, j = 1,2..J, t = 1,2..T \tag{58}$$

$$v_{o,m,t} \le \sum_{i=1}^{I} g_{m,i,o}(1 - e_{i,o}) x_{i,t} \le v_{o,m,t} BigM, \forall\, o = 1,2..O, t = 1,2..T, m = 1,2..M \tag{59}$$

$$u_{o,m,t}^{MOD} BigM - BigM + 1 \le v_{o,m,t} - v_{o,m,t_0} \le (1-\varepsilon)(1 - u_{o,m,t}^{MOD}) + u_{o,m,t}^{MOD}, \quad \forall\, o = 1,2..O, m = 1,2..M, t = 1,2..T, t0 = t-1 \tag{60}$$

$$u_{p,t}^{WC\_NEW} BigM - BigM + 1 \le w_{p,t} - w_{p,t_0} \le (1-\varepsilon)(1 - u_{p,t}^{WC\_NEW}) + u_{p,t}^{WC\_NEW}, \quad \forall p = 1,2..P, t = 1,2..T, t0 = t-1 \tag{61}$$

$$\sum_{i=1}^{I} x_{i,t} \ge 1, \forall t = 1,2..T \tag{62}$$

Equation (53) is an equality constraint. It represents the bi-directional between the hourly rates for department *j* in production period *t* and the hours assigned to department *j* in the previous production period t_0. Similarly, Equation (54) represents the bi-directional relationship between hourly rates for new workcentre *p* in production period *t* and the hours assigned to new workcentre *p* in the previous production period t_0. Equation (55) represents the bi-directional relationship between hourly rates for workcentre *o* in production period *t* and the hours assigned to workcentre o in the previous production period t_0. Equation (56) represents the capacity of the new workcentre p in production period t in hours. Equation (57) represents the capacity of the existing workcentre o in production period t. The left-hand side of Equation (57) is composed of three terms. The first term ($g_{i,o}Q_{i,t}x_{i,t}$) represents the total hours required for job i on existing workcentre o. The second term ($\sum_{m=1,2,..M} g_{m,i,o}\ Q_{i,t}x_{i,t}\ v_{o,m,t}$) denotes the hours from job i added to workcentre o when adding additional functional module m in production period t. The third term ($k_{i,o}x_{i,t}$) is the setup hours required by job i on workcentre o. Equation (58) is the available capacity in department j during production period t. Equation (59) represents the condition in which a functional module m is required by workcentre o in production period t. If functional module m when added to workcentre o can machine job i (i.e. $g_{m,i,o}>0$), but workcentre o without the additional functional module m cannot machine job i (i.e.$1-e_{i,o}=1$. Therefore, functional module m is required by workcentre o (i.e. $v_{m,o,t}=1$). Equation (60) represents the condition in which the purchasing of additional functional module m in production period t for workcentre o takes place ($u^{mod}_{o,m,t}$). If in two consecutive periods t and $t+1$, functional module m is required by workcentre o (i.e. $v_{o,m,t+1}=1$ and $v_{o,m,t}=1$), then there is no purchasing of the additional functional module taking place in production period $t+1$ (i.e. $u^{mod}_{o,m,t+1}=0$). However, if functional module m is not required by workcentre o in production period t (i.e. $v_{o,m,t}=0$), but functional module m is required by workcentre o in production period $t+1$ (i.e. $v_{o,m,t+1}=1$), therefore, purchasing a new module is required in production period $t+1$ (i.e. $u^{mod}_{o,m,t+1}=1$).d Equation (61) represents the condition in which a new workcentre p is to be purchased in production period t. This constraint can be illustrated similarly to the constraint in Equation (59). Finally, Equation (62) represents the condition in which at least one job is selected in each production period. It is evident that several non-linear terms exist in the constraints equations. For example, the second term on the left hand side of Equation (57) ($\sum_{m=1,2,..M} g_{m,i,o}\ v_{o,m,t}\ Q_{i,t}\ x_{i,t}$) is composed of two binary variables multiplied together ($v_{o,m,t}$ and $x_{i,t}$) which requires obtaining such variables in their linear form to use. The reader may refer to (FICO, 2009) for further readings on linearization techniques.

4.2. Industrial Case Study

The case study being considered is adapted from a local machine shop and is part of a multinational machinery builder company situated in Europe. The company shop area is around six thousand square meters, with various departments such as welding, fabrication, machining and assembly. The inputs to the model are shown in Table 15 to Table 21. Each workcentre's name is described as a symbol WS as the workcentres' actual name is not allowed to be disclosed. As per Equation (1), the hourly rate for a particular workcentre at a specific production period is calculated based on the workcentre's assigned hours in the previous period. Hence, the hourly rate for machines and departments for production period one is considered constant and the values are shown in Table 15 and Table 16. The blended costs for existing workcentres, new workcentres and engineering department b_0, b_0^{NEW} and a_0, respectively, are taken as \$60/hr. The number of production periods considered is six production periods in which each period is considered a quarter of a year. The general assets allocated to workcentres and activities are shown in Table 15 and Table 16. Though the general-assets allocated to workcentre/activities must be calculated following ABC methodology, it is taken directly from the company's records as constant to avoid further linearization of terms in the model.

4.3. Results and Discussions

The objective function is concerned with maximizing the profit in which it is required to minimize the difference between total cost and total selling price. Several assumptions are considered while formulating the objective function. The Mixed Integer Linear Programming (MILP) model is written using AMPL (http://ampl.com/) and solved using Gurobi in NEOS (Czyzyk et al., 1998; Dolan, 2001; Gropp & Moré, 1997). The optimum value of the objective function is -9268163.268. The results from the model are presented in Fig. 16 to Fig. 20 and

Table **22**. Fig. 16 shows the hourly rates for the engineering departments during the six production periods. The first period is taken as the blended cost, as illustrated in Equation (1). The hourly rate increases to the maximum at period 5 for the two departments. Since each hourly rate is calculated based on the total hours in the previous period, the hourly rates for period five are calculated based on the hours from period 4. From Table 17 and Table 22, the total engineering hours for departments 1 and 2 are 1640 and 1500 hours, compared to 1970 and 1940 hours for periods 1, 2, 3 and 5 for departments 1 and 2, respectively. Therefore, to reduce the hourly rate further, the manufacturing firm must accept more customers' jobs to reduce the hourly rates for future periods, within certain limits.

Table 15. General assets allocated cost to each workcentre and depreciation cost/yr for each workcentre in ($)

index	Hourly rate at t=1	Workcentre	General assets allocated Cost ($c_{o,t}^{GA\_WC}$) ($)	Depreciation/yr ($c_o^{DEP\_WC}$) ($)
o=1	$62	WS-01	$20,141.36	$-
o=2	$62	WS-02	$59,057.32	$-
o=3	$65	WS-03	$59,057.32	$-
o=4	$100	WS-04	$14,061.27	$29,180.00
o=5	$65	WS-05	$15,186.17	$110,020.00
o=6	$85	WS-06	$14,061.27	$29,180.00
o=7	$85	WS-07	$8,436.76	$3,440.00
o=8	$125	WS-08	$7,030.63	$73,630.00
o=9	$85	WS-09	$15,186.17	$187,950.00
o=10	$62	WS-10	$20,141.36	$2,710.00
o=11	$62	WS-11	$59,057.32	$-
o=12	$62	WS-12	$59,057.32	$-
o=13	$62	WS-13	$59,057.32	$-
o=14	$62	WS-14	$59,057.32	$-
o=15	$62	WS-15	$59,057.32	$-
o=16	$62	WS-16	$20,141.36	$-
o=17	$62	WS-17	$20,141.36	$-
o=18	$62	WS-18	$20,141.36	$-

Table 16 General assets allocated cost to each new workcentre and depreciation cost/yr for each workcentre in ($)

Workcentre Index	Hourly rate at t=1	Workcentre	General assets allocated Cost ($c_{p,t}^{GA\_NEW\_WC}$) ($)	Depreciation/yr ($c_p^{DEP\_NEW\_WC}$) ($)
p=1	$62	WS-01	$20,141.36	$29,180
p=2	$62	WS-02	$59,057.32	$29,180
p=3	$65	WS-03	$59,057.32	$3,000

Table 17. hours required by engineering departments 1 and 2 to complete job i

		Job									
		1	2	3	4	5	6	7	8	9	10
Engineering	1	610	690	770	920	560	520	170	760	510	110
Dept.	2	500	300	810	180	320	280	840	960	390	820

Table 18. Available jobs required machining hours on each new workcentre, selling price in $ and raw material cost in $

Job index	Selling price ($R_{i,t}$) in ($)	Raw material cost ($d_{i,t}$) in ($)	Quoted hours for new machines available for purchasing ($g_{i,o}^{NEW}$) ($)		
			p=1	p=2	p=3
1	$1,347,660.00	$36,866	400	1,755	785
2	$1,254,225.00	$97,531	657.5	1,040	592.5
3	$1,954,684.00	$21,615	400	100	500
4	$1,373,779.50	$99,247	400	890	500
5	$1,303,530.50	$96,111	400	297.5	250
6	$471,852.50	$35,654	600	935	1520
7	$1,961,505.50	$32,793	400	200	5539
8	$717,165.00	$69,500	147.5	330	55
9	$645,540.00	$99,464	195	340	50
10	$1,555,845.00	$31,337	135	370	15

Table 19. Available capacity for existing workcentres and engineering departments in production periods 1 up to 6 in hours

	Existing workcentres capacity ($C_{o,t}^{WC}$) in hours							Engineering Departments Capacity ($C_{j,t}^{ENG}$) in hours	
	1,3,12 13,14 15,16	2	4,6 9,10	5	7	8	11,17 18	1	2
t=1 to t=6	9,600	7,680	4,800	2,880	2,160	3,840	1,920	2,000	2,000

Table 20. Available capacity for new workcentres available for purchasing in production periods 1 up to 6 in hours

Production periods	New workcentres available for purchasing capacity ($C_{p,t}^{NEW\_WC}$) in hours		
	p=1	p=2	p=3
t=1 to t=6	9600	7680	9600

Table 21.Machining hours required by each available job when functional module m=1 is added to existing workcentres

Job index	Available workcentres ($g_{m,o}$) hours o=4	o=5	o=6	o=7	o=8	o=9
i=1	795	40	600	0	0	760
i=2	1267	1900	3365	895	0	600
i=3	0	0	70	300	0	0
i=4	200	105	0	0	0	1850
i=5	100	100	0	0	0	1500
i=6	140	505	1670	472.5	0	720
i=7	0	0	0	0	0	0
i=8	680	750	50	100	150	400
i=9	40	750	250	0	180	400
i=10	110	750	250	200	190	400

Table 22. Jobs accepted in each production period

		Jobs i=1	i=2	i=3	i=4	i=5	i=6	i=7	i=8	i=9	i=10
Periods	t=1	1	1	0	0	1	0	0	0	0	1
	t=2	1	1	0	0	1	0	0	0	0	1
	t=3	1	1	0	0	1	0	0	0	0	1
	t=4	1	0	0	1	0	0	0	0	0	1
	t=5	1	1	0	0	1	0	0	0	0	1
	t=6	0	0	1	0	1	0	0	0	0	1

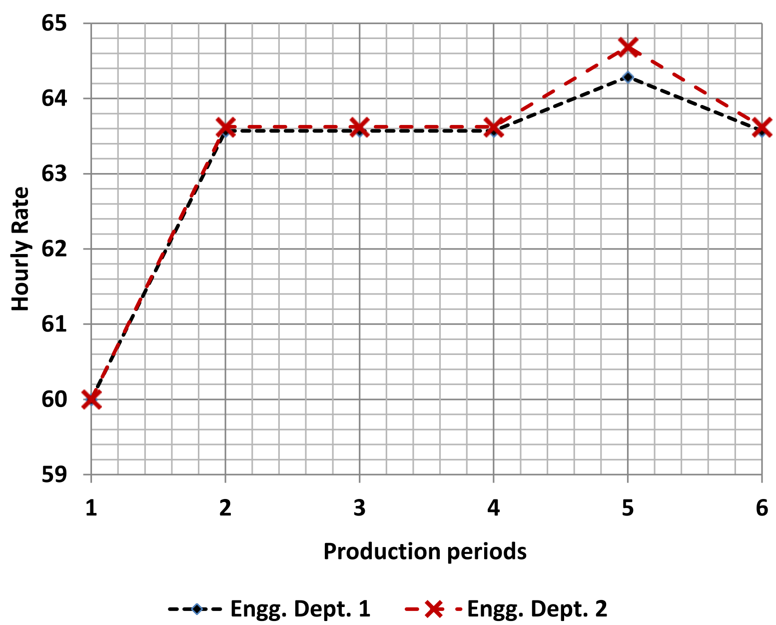

Fig. 16. Hourly rates for engineering departments 1 and 2 during the 6 production periods

Fig. 17 and Fig. 18 show the hourly rates for workcentres WS-01 to WS-09 and WS-10 to WS-18, respectively. From Table 22 and Table 23, the total machining hours in production period 4 sums up to 11,249.55 hours compared to 18,178.55 hours for production periods 1, 2, 3 and 5. Therefore, the hourly rates for production period 5 peaks to the maximum value as per Equation (1). For hourly rates of WS-04 and WS-07 in Fig. 17, the hourly rates are decreased in production period 2 since the total machining hours in production period 1 is at its maximum of 181,718.55 hours.

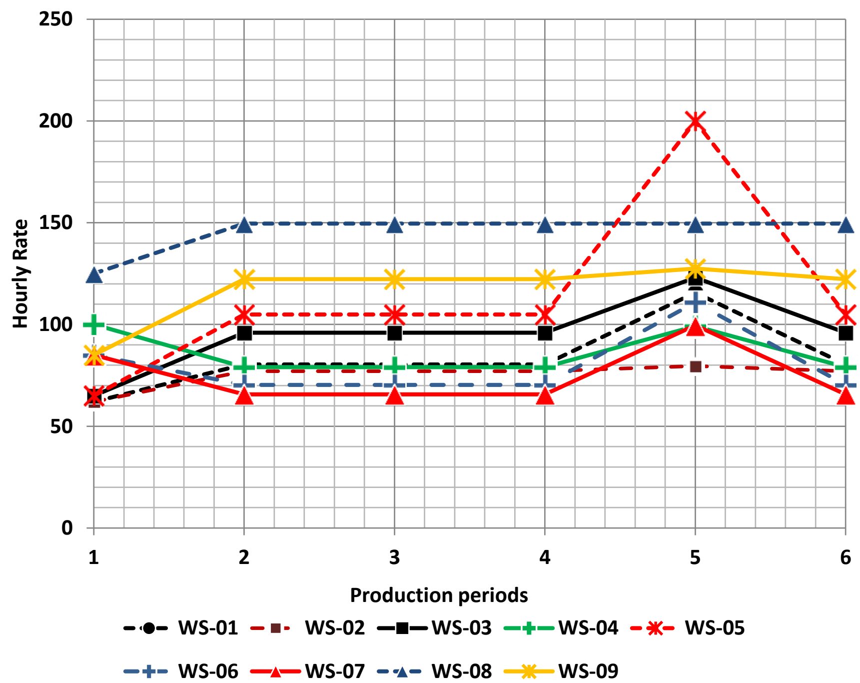

Fig. 17. Hourly rates for existing workcentres WS-01 to WS-09 in the 6 production periods

Table 23. Machining and setup hours (between brackets) required for job i on existing workcentre o

		Workcentre																	
		WS-1010	WS-1020	WS-1030	WS-1040	WS-1050	WS-1060	WS-1070	WS-1080	WS-1090	WS-1100	WS-1110	WS-1120	WS-1130	WS-1140	WS-1150	WS-1160	WS-1170	WS-1180
Job	1	82.048 (2)	1755 (1)	785 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1240 (1)	670 (1)	760 (1)	0 (0)	0 (0)	80 (1)	267.5 (1)	300 (2)	50 (1)
	2	657.5 (2)	1040 (2)	592.5 (2)	0 (0)	0 (0)	0 (0)	895 (2)	0 (0)	0 (0)	0 (0)	760.5 (2)	520 (2)	520 (2)	650 (2)	756 (2)	677.5 (1)	412.5 (2)	0 (0)
	3	60 (2)	100 (2)	150 (1)	0 (0)	0 (0)	0 (0)	300 (1)	100 (1)	0 (0)	100 (2)	150 (1)	0 (0)	0 (0)	0 (0)	50 (2)	0 (0)	100 (1)	200 (2)
	4	145 (1)	890 (1)	137.5 (1)	0 (0)	0 (0)	0 (0)	100 (2)	0 (0)	0 (0)	200 (1)	150 (1)	0 (0)	450 (1)	320 (2)	300 (1)	105 (1)	250 (2)	40 (2)
	5	115 (2)	297.5 (2)	250 (2)	0 (0)	0 (0)	0 (0)	100 (1)	0 (0)	0 (0)	200 (1)	192.5 (2)	0 (0)	450 (2)	220 (2)	300 (2)	100 (2)	200 (2)	110 (2)
	6	30 (1)	935 (2)	1520 (2)	0 (0)	0 (0)	0 (0)	472.5 (1)	0 (0)	0 (0)	90 (1)	1107.5 (2)	100 (1)	0 (0)	460 (0)	82.5 (1)	80 (2)	200 (2)	880 (1)
	7	0 (0)	0 (0)	5539 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	8	147.5 (1)	330 (2)	55 (2)	0 (0)	0 (0)	0 (0)	0 (0)	500 (1)	0 (0)	185 (2)	80 (1)	105 (1)	0 (0)	50 (1)	142.5 (1)	70 (1)	5 (1)	50 (1)
	9	195 (2)	340 (2)	50 (2)	0 (0)	0 (0)	0 (0)	100 (1)	800 (1)	0 (0)	230 (2)	202.5 (1)	150 (1)	0 (0)	50 (2)	167.5 (1)	75 (1)	45 (2)	10 (1)
	10	135 (2)	370 (1)	15 (2)	0 (0)	0 (0)	0 (0)	0 (0)	900 (2)	0 (0)	250 (1)	100 (2)	50 (1)	0 (0)	50 (1)	167.5 (1)	70 (1)	45 (2)	20 (2)

The reason for this decision is to increase the available machining capacity within the facility, and hence, more jobs can be accepted. The model also suggests adding functional module 1 to the existing workcentres WS-04, WS-05, WS-06, WS-07 and WS-09. The reason for this decision is to extend the functionality of the existing workcentres to accept jobs containing new features that cannot be machined by the existing system's capability. To this extent, the more jobs being accepted, the more reduction in job cost will be encountered as a result of reducing the hourly machining rates. It is worth noting that reducing hourly rates and, hence, job cost will put the manufacturing company at an advantage due to the cost leadership business strategy and, accordingly, a higher probability of getting more customers' orders.

This mathematical model results are similar to the actual implementation of this case study during the first two production periods (i.e. t=1 and t=2). Additionally, the manufacturing firm introduced three workcentres and an additional machining axis for an existing workcentre in the actual implementation. This also lines well with the mathematical model in which workcentres WS-01, WS-02 and WS-03 are purchased and functional module 1 is added to existing workcentres WS-04, WS-05, WS-06, WS-07 and WS-09 as shown in Fig. 20. However, the manufacturing firm did not implement the following production p period's scenarios from t=3 to t=6 shown in this mathematical model. The reason for not implementing the subsequent scenarios is due to various decisions made by the mother company situated in Europe. The mother company required some of the jobs being manufactured in Canada to stop and be executed in Europe, per customer request. Fig. 18 and Fig. 19 present the results of the hourly machining rates vary with the different production periods. The machining hourly rates peaks at production period five due to the reduced assigned total machining hours in production period four, which is equal to 5250 hours compared to 6697.5 hours for production periods 1, 2, 3 and 5 and 8,929 hours for production period 6. Fig. 20 presents the reconfiguration level decision on the machine and system level. In production period 1, the mathematical model suggests purchasing three new workcentres.

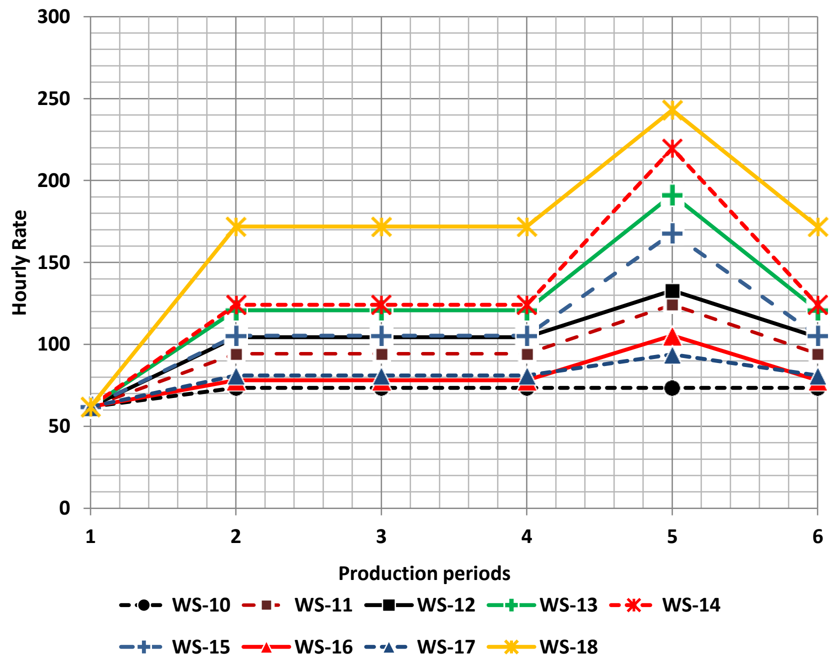

Fig. 18. Hourly rates for existing workcentres WS-10 to WS-18 in the six production periods

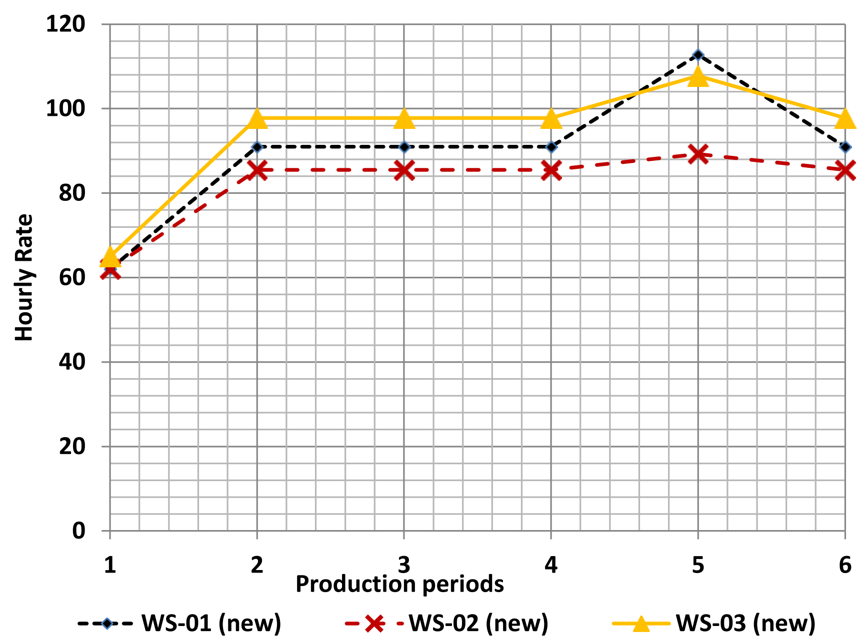

Fig. 19. Hourly rates for the new workcentres in the 6 production periods

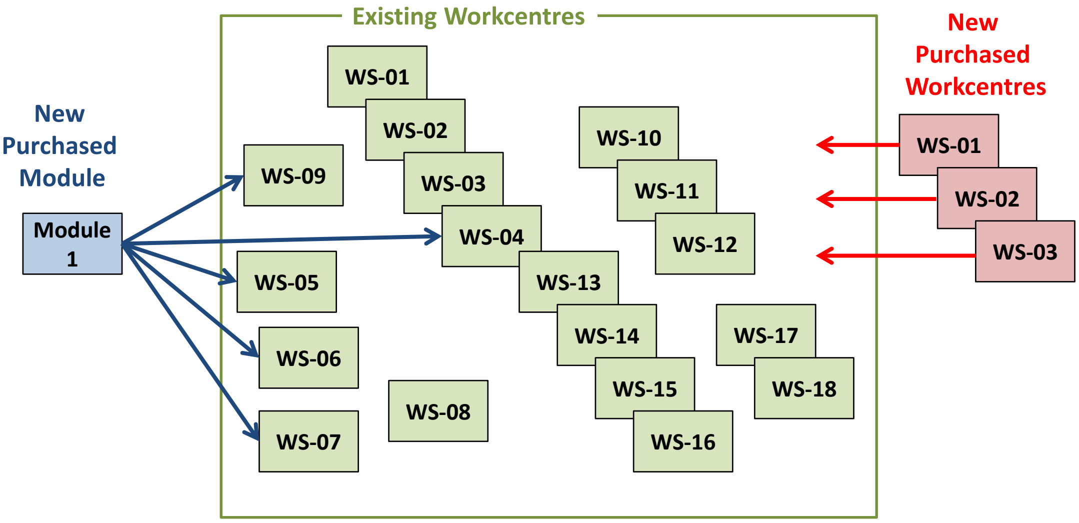

Fig. 20. New purchased modules and workcentres

4.4. Conclusion

This chapter introduces a novel mathematical model to minimize the total cost incurred in a reconfigurable manufacturing environment across production periods. In this case, the cost objects refer to the jobs being processed within the manufacturer's shop floor. The objective function developed is to minimize the total manufacturing cost and increase profit through a proposed ABC model. The mathematical model considers the bi-directional relationship between the number of hours assigned to workcentres/departments and the hourly rates. The main outputs from the mathematical model are:

- the newly calculated hourly rates for the different workcentres/departments,
- the jobs mix decision,
- the decision to add/remove functional modules to existing machinery and finally,
- the decision to purchase new workcentres.

The proposed mathematical model is applied to a case study taken from a local heavy machinery builder machine shop. Furthermore, the implementation of the model reduced hourly rates (in the Industrial Case Study) for workcentres by around to 23% as a result of accepting more jobs (and accordingly, machining hours) on the available workcentres, and hence, reducing the hourly rates. This implementation has helped the company gain a competitive advantage among rivals since pricing of products submitted to customer was reduced.

The significance of the reconfigurability cost model is not restricted to cost analysis, but also provides managers in manufacturing facilities with the required decision-making tools to decide on orders to accept or refuse and invest in additional production equipment. In addition, the work completed in dissertation will help manufacturing companies achieve a competitive edge among rivals by reducing hourly rates in their facility. Additional benefits and significance are (1) providing manufacturing companies a method to quantify the decision-making process for right-sizing their manufacturing space, (2) ability to justify growing a scalable system using costing (not customer demand), (3) expanding market share and, (4) reducing operational cost and allowing companies a numerical model to justify scaling the manufacturing the system.

CHAPTER 5 Activity Based Aggregate Job Costing Model for Reconfigurable Manufacturing Systems and Facility Expansion

5. Introduction

The purpose of this chapter is to study the effect of adding an extension to the shop floor on the total acquired cost. In the previous chapters, the term changeability reflected the machine level and system level reconfiguration in an attempt to determine an optimum solution for the Activity-Based Costing (ABC) model. This chapter will take into consideration an additional level in changeability called transformability which is defined as adding extension to the available shop floor (Wiendahl et al., 2007). The next section will provide further insights on the proposed problem and the accompanying mathematical model with the proposed inputs and expected outputs.

5.1. Overview

This section provides an overview for the proposed mathematical model that deals with facility expansion decision. An IDEF0 model for the facility-expansion model is shown in Fig. 21. The inputs to the model are:

- The list of available orders in which the manufacturing firm will choose whether to proceed with or not
- The general assets and the equipment depreciation which is required to calculate the hourly machining rate
- The total machining hours for each order/job
- Workcentre/functional module reconfigurable cost. This cost takes into consideration the addition of extra workcentres or adding functional modules (e.g. add extra axes to

machines to extend functionality) which is considered as change within the system level and machine level, respectively.

- Alternatives for facility expansion. Each alternative is characterized by a certain footprint and the cost for expansion.

The outputs from the model are:

- Accepted orders by the manufacturing firms
- New calculated hourly rates for machining within the manufacturing firm
- Facility expansion decision
- Workcentre and functional modules reconfiguration decision

There are several constraints within the mathematical model. The most important constraints are the area of the existing shop floor and available machining capacity.

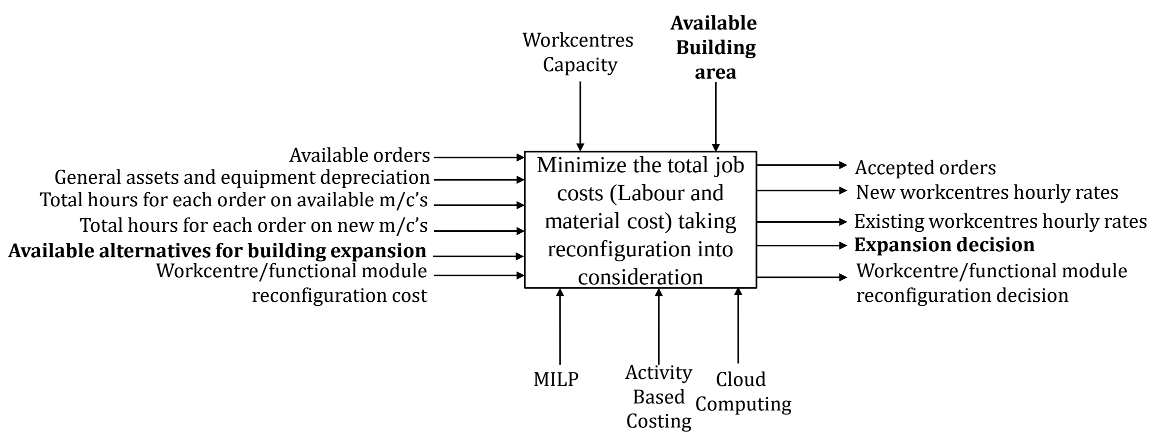

Fig. 21. IDEF0 model for the proposed mathematical model

Fig. 22 shows a brief illustration of how the proposed mathematical model will be utilized to decide on the facility expansion decision. The initial area of the shop floor is shown on the left. It is clear that there are six existing workcentres and two empty positions (dashed rectangles).

Three scenarios are shown on the right side of Fig. 22:

- The first figure shows a scenario in which no additional equipment is required. Hence, no facility expansion is required
- The second figure shows the second scenario in which two new workcentres are required in a specific period. However, there are two empty positions available to add the new workcentres. Hence, no facility expansion is required.

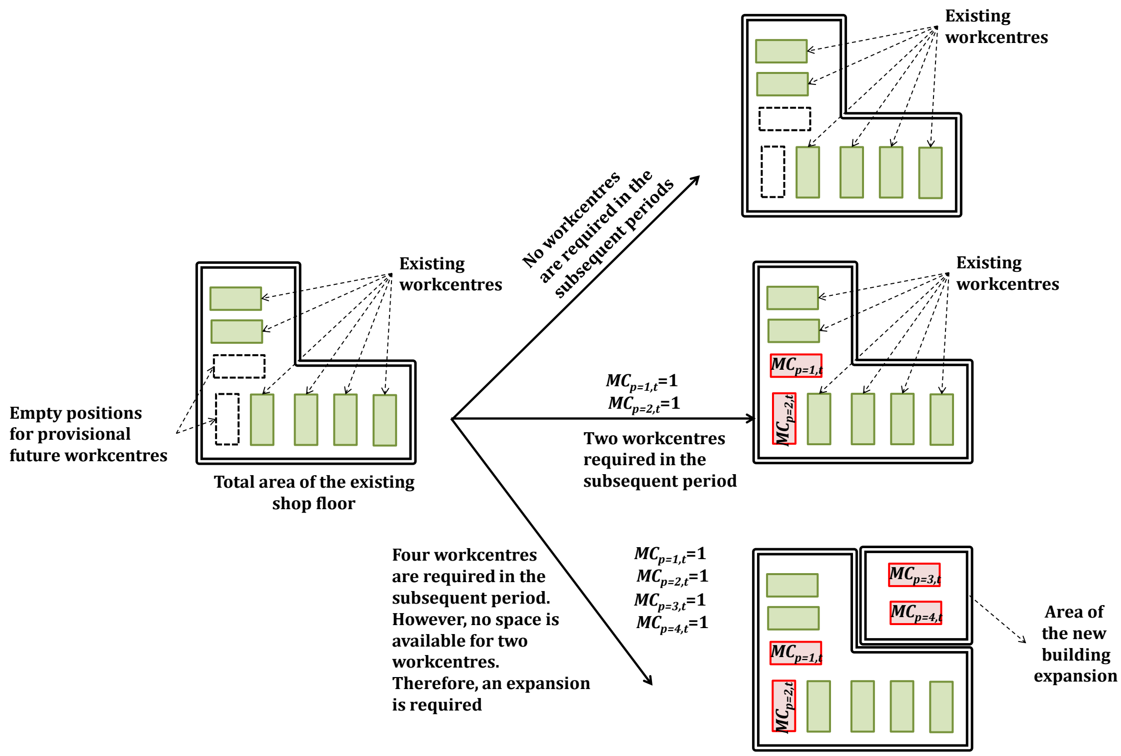

Fig. 22. Illustration of some decision variables in the mathematical model

The third scenario shows a situation in which four new workcentres are required. Two empty positions are available in the existing shop floor. However, the extra two workcentres cannot be added unless a new facility expansion is established.

5.2. Mathematical Model Formulation

This section lists and illustrates the mathematical model implemented in this chapter. The IDEF0 model is shown in Fig. 21. The detailed description of the model, inputs and outputs will be illustrated in the following subsections. The proposed model is non-linear. In order to obtain the linear form and convert it to a Mixed Integer Linear Programming (MILP) model, reader can refer to linearization methods in (FICO, 2009).

The list of input parameters, decision variables, sets, constants objective function, constraints are detailed in this section. The list of input parameters is:

c_f^{BLDG}: cost for investing in building expansion option f (63)

A_o^{EXIST}: Area of existing workcentre o (64)

A_p^{NEW}: Area of new workcentre p (65)

A^{BLDG}: $Total$ area of the existing building shop floor (66)

A_f^{NEW}: Area of option f for building expansion (67)

The rest of the input parameters are identical to the input parameters in chapter 4. The list of decision variables is:

$$x_{f,t}^{EXPANSION} = \begin{cases} 1, \text{ if building expansion option } f \text{ is chosen in production period } t \\ 0, \text{ otherwise} \end{cases} \quad (68)$$

The rest of the decision variables are identical to the decision variables in chapter 4. The objective function is concerned with maximizing the profit in which it is required to minimize the difference between total cost and total selling price. Several assumptions are made while formulating the objective function. For example, raw materials are purchased for each job and therefore, no carrying or holding cost is considered in this dissertation. The objective function is written as shown in (69)

$$
\begin{aligned}
&Min\ Z \\
&\sum_{i=1}^{I}\sum_{t=1}^{T} d_{i,t}Q_{i,t}x_{i,t} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} h_{i,j}y_{j,t}x_{i,t} \\
&+\sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} Q_{i,t}g_{i,o}z_{o,t}x_{i,t} + \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} \frac{\left(k_{i,o}z_{o,t}x_{i,t}\right)}{Q_{i,t}+\varepsilon} \\
&+\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=1}^{T} Q_{i,t}g_{i,p}^{WC\_NEW}z_{i,p}^{WC\_NEW}x_{i,t} \\
&\qquad\qquad + \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=1}^{T} \frac{\left(k_{i,p}^{WC\_NEW}z_{i,p}^{WC\_NEW}x_{i,t}\right)}{Q_{i,t}+\varepsilon} \\
&+\sum_{o=1}^{O}\sum_{m=1}^{M}\sum_{t=1}^{T} c_m^{MOD}Buy_{o,mt}^{MOD} + \sum_{p=1}^{P}\sum_{t=1}^{T} c_p^{MC}\,Buy_{p,t}^{MC} \\
&+\sum_{f=1}^{F}\sum_{t=1}^{T} c_f^{BLDG}x_{f,t}^{EXPANSION} - \sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t}Q_{i,t}x_{i,t}
\end{aligned}
\tag{69}
$$

The mathematical model only considers mechanical and electrical engineering as well as manufacturing as direct labour cost. Factory overhead and indirect costs are allocated to the direct hourly rates. In Equation (69) the first term is the raw material/commercial items cost. The second term is the total engineering cost. In ABC method terms, second term is the product level. The third and fifth terms are the total production cost for the existing and new workcentres, respectively. In ABC method terms, the third and fifth terms are the unit level. The fourth and sixth terms are the total setup cost on the existing and new workcentres, respectively. In ABC method terms, the fourth and sixth terms are the batch level. The seventh and eighth terms are the buying costs of functional modules and adding new workcentres, respectively. The ninth term is the investment cost in order to build a new expansion to the existing building. Finally, the tenth term is the selling cost for each job. In the fourth and sixth terms, the symbol ε is a small number (e.g. 0.0005) to prevent an infinite value for the fourth term in case where $Q_{i,t}$ is equal to zero.

The constraints for the model are identical to the constraints from chapter 4. The additional constraints for this proposed model are:

$$\sum_{o=1}^{O} A_{o}^{EXIST} + \sum_{p=1}^{P} Buy_{p,t}^{MC} A_{p}^{NEW} \leq A^{BLDG} + \sum_{f=1}^{F} A_{f}^{NEW} x_{f,t}^{EXPANSION}, \forall\, t = 1,2..T \tag{70}$$

$$\sum_{t=1}^{T} x_{f,t}^{EXPANSION} \leq 1, \forall f = 1,2..F \tag{71}$$

Equation (70) restricts the number of workcentres within the shop floor (existing workcentres and newly added workcentres) in order not to exceed the total area of the shop floor (i.e. area of existing facility and expansion). Equation (71) requires that one expansion option is used at most once through all production periods. In other words, an expansion option cannot be reused in other areas since its space is already utilized Fig. 22 provides an illustration for some of the major decision variables for this mathematical model.

5.3. Industrial Case Study

The case study discussed in this chapter is adopted from a local machine shop and is part of a multinational machinery builder company situated in Europe. The company shop area is around 5,000 squared meters with various departments such engineering, purchasing, welding, fabrication, machining and assembly as well as shipping/receiving area and storage shelves as shown in Fig. 23. The total available area of the current facility for workcentres is 1,450 meters squared (ABLDG in constraint equation (70)). The inputs to the model are shown in Table 24 and Table 34.The different inputs to the model compared to the previous chapters are the areas for the existing and new available workcentres in Table 31 and the different facility expansion alternatives in Table 32. Based on the areas of the required workcentres, the mathematical model will decide on which facility expansion alternative will be chosen.

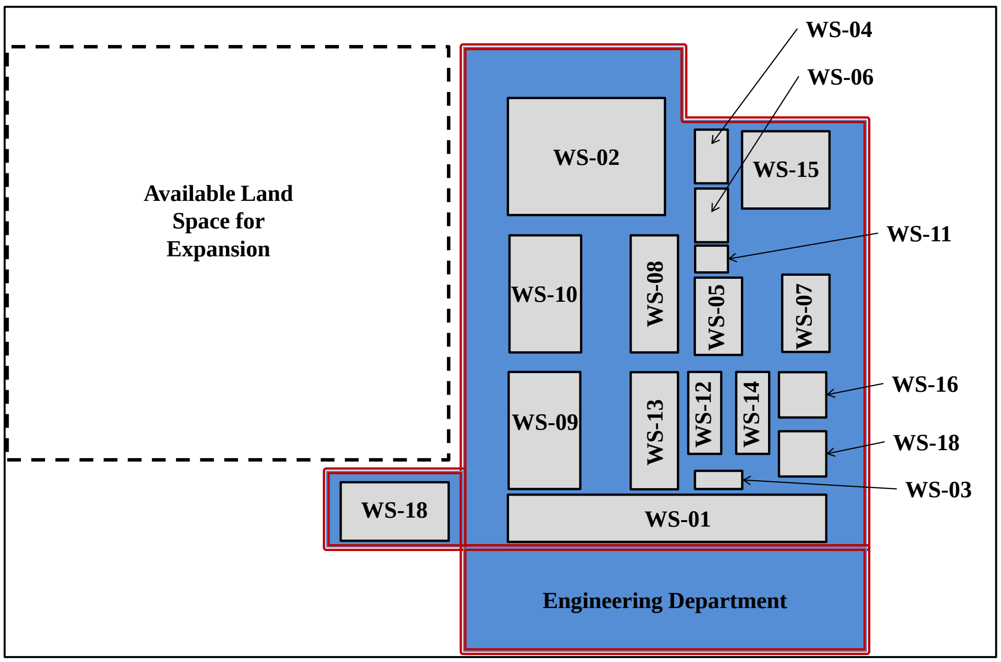

Fig. 23. Facility current plan

The name of each workcentre is described as a symbol WS as actual name of workcentres could not be disclosed, for privacy and business advantage reasons. As per Equation (1) and as previously pointed out, the hourly rate for a certain workcentre at a specific production period is calculated based on the assigned hours for the workcentre in the preceding period and therefore, the hourly rate for existing workcentres and new workcentres for production period 1 are considered constant and the values are shown in Table 24 and Table 25, respectively. The blended costs for existing workcentres, new workcentres and engineering department are taken as \$60/hr. The number production periods considered are six production periods in which each period is considered a quarter of a year. The general assets allocated to workcentres and activities are shown in Table 24 and Table 25.

5.4. Results and Discussions

The objective function is concerned with maximizing the profit in which it is required to minimize the difference between total cost and total selling price. Several assumptions are considered while formulating the objective function. The cost includes the manufacturing cost (engineering design, machining, fabrication and assembly) and does not include installation on customer site nor commissioning and debugging. The Mixed Integer Linear Programming (MILP) model is written using AMPL (http://ampl.com/) and solved using Gurobi in Neos (Czyzyk et al., 1998; Dolan, 2001; Gropp & Moré, 1997). Job number is 9305399 and the value of the objective function is -6268189.395 ($6,268,189.395 in profit). The job mix from the model is listed in Table 33. Since the objective function in the mathematical is to maximize the profit, the mathematical model chooses job number 10 in each production period due to its high selling price as shown in Table 27. While job number 7 is the highest selling price job, however, it was not chosen by the model due to workcentres and/or engineering departments capacities constraints. The hourly rates results for this case study are shown in Fig. 24, Fig. 25, Fig. 26 and Fig. 27 for the engineering department, existing workcentres from WS-01 to WS-09, existing workcentre from WS-10 to WS-18 and new workcentres, respectively. These results are similar to the results from Chapter 4. The only difference is the facility expansion output from the mathematical model in terms of decision variable $x_{f,t}^{EXPANSION}$.. The total area where machines are furnished in the current layout is 1395m2 (as per Table 31) while the total area of machine shop is 1450m2 (given). Based on the decision from the mathematical model, three new workcentres are added with 20, 20 and 30 m2 as shown in Fig. 28.

Table 24. General assets allocated cost to each workcentre and depreciation cost/yr for each workcentre in ($)

index	Workcentre	Hourly rates at t=1	General assets allocated Cost ($)	Depreciation/yr ($)
o=1	WS-01	$62	$20,141.36	$-
o=2	WS-02	$62	$59,057.32	$-
o=3	WS-03	$65	$59,057.32	$-
o=4	WS-04	$100	$14,061.27	$29,180.00
o=5	WS-05	$65	$15,186.17	$110,020.00
o=6	WS-06	$85	$14,061.27	$29,180.00
o=7	WS-07	$85	$8,436.76	$3,440.00
o=8	WS-08	$125	$7,030.63	$73,630.00
o=9	WS-09	$85	$15,186.17	$187,950.00
o=10	WS-10	$62	$20,141.36	$2,710.00
o=11	WS-11	$62	$59,057.32	$-
o=12	WS-12	$62	$59,057.32	$-
o=13	WS-13	$62	$59,057.32	$-
o=14	WS-14	$62	$59,057.32	$-
o=15	WS-15	$62	$59,057.32	$-
o=16	WS-16	$62	$20,141.36	$-
o=17	WS-17	$62	$20,141.36	$-
o=18	WS-18	$62	$20,141.36	$-

Table 25. General assets allocated cost to each new workcentre and depreciation cost/yr for each workcentre in ($)

Workcentre index	Hourly rate at t=1	General assets allocated Cost ($)	Depreciation/yr ($)
p=1	$62	$20,141.36	$29,180
p=2	$62	$59,057.32	$29,180
p=3	$65	$59,057.32	$3,000

Table 26. hours required by engineering departments 1 and 2 to complete job i

		Job									
		i=1	i=2	i=3	i=4	i=5	i=6	i=7	i=8	i=9	i=10
Dept.	j=1	610	690	770	920	560	520	170	760	510	110
	j=2	500	300	810	180	320	280	840	960	390	820

Table 27. Available jobs required machining hours on each new workcentre, selling price in $ and raw material cost in $

Job index	Selling price in ($)	Raw material cost in ($)	new machines available for purchasing		
			p=1	p=2	p=3
i=1	$1,347,660.00	$36,866	400	1755	785
i=2	$1,254,225.00	$97,531	657.5	1040	592.5
i=3	$1,954,684.00	$21,615	400	100	500
i=4	$1,373,779.50	$99,247	400	890	500
i=5	$1,303,530.50	$96,111	400	297.5	250
i=6	$471,852.50	$35,654	600	935	1520
i=7	$1,961,505.50	$32,793	400	200	5539
i=8	$717,165.00	$69,500	147.5	330	55
i=9	$645,540.00	$99,464	195	340	50
i=10	$1,555,845.00	$31,337	135	370	15

Table 28. Available capacity for existing workcentres and engineering departments in production periods 1 up to 6 in hours

	Existing workcentres							Departments	
	1,3,12 13,14 15,16	2	4,6 9,10	5	7	8	11,17 18	1	2
t=1 to t=6	9,600	7,680	4,800	2,880	2,160	3,840	1,920	2,000	2,000

Table 29. Available capacity for new workcentres available for purchasing in production periods 1 up to 6 in hours.

Production periods	New workcentres available for purchasing		
	p=1	p=2	p=3
t=1 to t=6	9600	7680	9600

Table 30. Machining hours required by each available job when functional module m=1 is added to existing workcentres

Job	Available workcentres					
index	o=4	o=5	o=6	o=7	o=8	o=9
i=1	795	40	600	0	0	760
i=2	1,267	1,900	3,365	895	0	600
i=3	0	0	70	300	0	0
i=4	200	105	0	0	0	1,850
i=5	100	100	0	0	0	1,500
i=6	140	505	1,670	472.5	0	720
i=7	0	0	0	0	0	0
i=8	680	750	50	100	150	400
i=9	40	750	250	0	180	400
i=10	110	750	250	200	190	400

Table 31 Cost of new workcentres and areas of new and existing worcentres

	Area of new workcentres (m2)	Cost of new workcentres ($)	Area of existing workcentres (m2)
WS-01	20	$900,000.00	400
WS-02	20	$1,000,000.00	100
WS-03	30	$500,000.00	20
WS-04	-	-	15
WS-05	-	-	40
WS-06	-	-	15
WS-07	-	-	50
WS-08	-	-	100
WS-09	-	-	50
WS-10	-	-	75
WS-11	-	-	10
WS-12	-	-	20
WS-13	-	-	20
WS-14	-	-	100
WS-15	-	-	50
WS-16	-	-	10
WS-17	-	-	300
WS-18	-	-	20

Table 32. Area and cost of the different alternatives for the facility expansion

	Area (m2)	Cost ($)
Alt. 1	500	$3,000,000.00
Alt. 2	1,000.00	$4,000,000.00
Alt. 3	1,500.00	$10,000,000.00

Table 33. Jobs accepted in each production period

		Jobs									
		i=1	i=2	i=3	i=4	i=5	i=6	i=7	i=8	i=9	i=10
Periods	t=1	1	1	0	0	1	0	0	0	0	1
	t=2	1	1	0	0	1	0	0	0	0	1
	t=3	1	1	0	0	1	0	0	0	0	1
	t=4	1	0	0	1	0	0	0	0	0	1
	t=5	1	1	0	0	1	0	0	0	0	1
	t=6	0	0	1	0	1	0	0	0	0	1

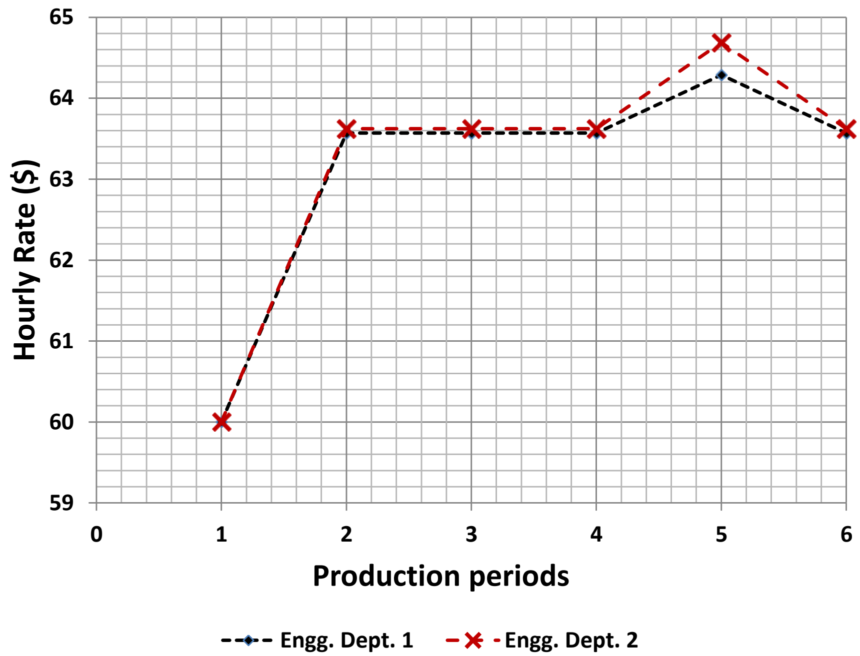

Fig. 24. Hourly rates for engineering departments 1 and 2 during the 6 production periods

These workcentres cannot be added to the current layout since the summation of the total workcentres will exceed the available free area for workcentres addition (1395+20+20+30=1465m2>1450m2). Therefore, the mathematical model requires extending the facility with additional 500m2 (alternative 1 shown in Table 32 ($x_{1,1}^{EXPANSION}=1$).

Table 34. Machining and setup hours (between brackets) required for job i on existing workcentre o

		Workcentre																	
		WS-1010	WS-1020	WS-1030	WS-1040	WS-1050	WS-1060	WS-1070	WS-1080	WS-1090	WS-1100	WS-1110	WS-1120	WS-1130	WS-1140	WS-1150	WS-1160	WS-1170	WS-1180
Job	1	82.048 (2)	1755 (1)	785 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1240 (1)	670 (1)	760 (1)	0 (0)	0 (0)	80 (1)	267.5 (1)	300 (2)	50 (1)
	2	657.5 (2)	1040 (2)	592.5 (2)	0 (0)	0 (0)	0 (0)	895 (2)	0 (0)	0 (0)	0 (0)	760.5 (2)	520 (2)	520 (2)	650 (2)	756 (2)	677.5 (1)	412.5 (2)	0 (0)
	3	60 (2)	100 (2)	150 (1)	0 (0)	0 (0)	0 (0)	300 (1)	100 (1)	0 (0)	100 (2)	150 (1)	0 (0)	0 (0)	0 (0)	50 (2)	0 (0)	100 (1)	200 (2)
	4	145 (1)	890 (1)	137.5 (1)	0 (0)	0 (0)	0 (0)	100 (2)	0 (0)	0 (0)	200 (1)	150 (1)	0 (0)	450 (1)	320 (2)	300 (1)	105 (1)	250 (2)	40 (2)
	5	115 (2)	297.5 (2)	250 (2)	0 (0)	0 (0)	0 (0)	100 (1)	0 (0)	0 (0)	200 (1)	192.5 (2)	0 (0)	450 (2)	220 (2)	300 (2)	100 (2)	200 (2)	110 (2)
	6	30 (1)	935 (2)	1520 (2)	0 (0)	0 (0)	0 (0)	472.5 (1)	0 (0)	0 (0)	90 (1)	1107.5 (2)	100 (1)	0 (0)	460 (0)	82.5 (1)	80 (2)	200 (2)	880 (1)
	7	0 (0)	0 (0)	5539 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	8	147.5 (1)	330 (2)	55 (2)	0 (0)	0 (0)	0 (0)	0 (0)	500 (1)	0 (0)	185 (2)	80 (1)	105 (1)	0 (0)	50 (1)	142.5 (1)	70 (1)	5 (1)	50 (1)
	9	195 (2)	340 (2)	50 (2)	0 (0)	0 (0)	0 (0)	100 (1)	800 (1)	0 (0)	230 (2)	202.5 (1)	150 (1)	0 (0)	50 (2)	167.5 (1)	75 (1)	45 (2)	10 (1)
	10	135 (2)	370 (1)	15 (2)	0 (0)	0 (0)	0 (0)	0 (0)	900 (2)	0 (0)	250 (1)	100 (2)	50 (1)	0 (0)	50 (1)	167.5 (1)	70 (1)	45 (2)	20 (2)

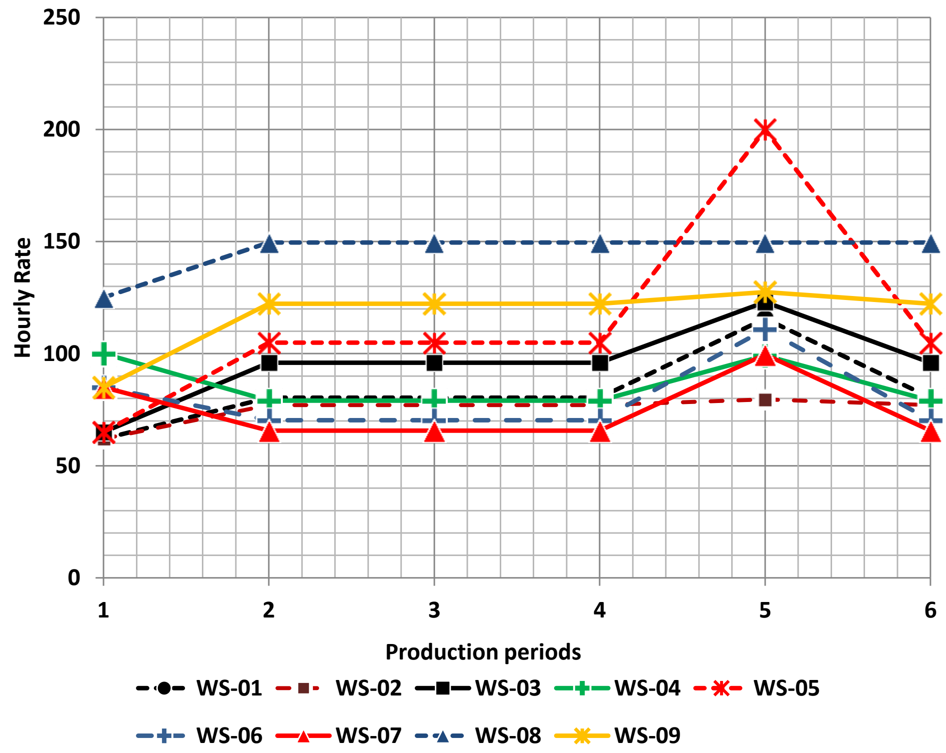

Fig. 25. Hourly rates for existing workcentres WS-01 to WS-09 in the 6 production periods

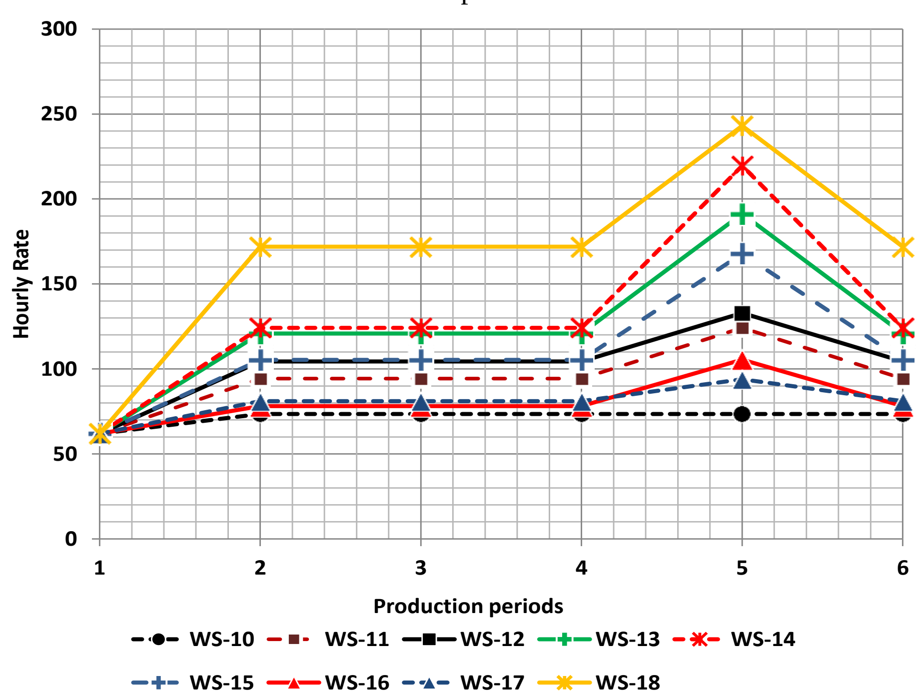

Fig. 26. Hourly rates for existing workcentres WS-10 to WS-18 in the 6 production periods

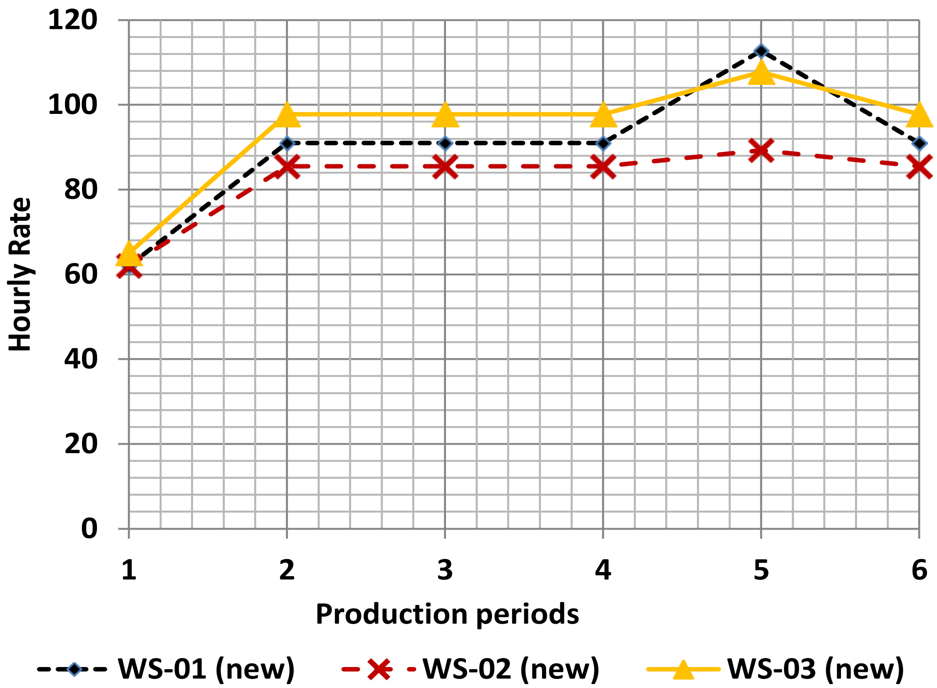

Fig. 27. Hourly rates for the new workcentres in the 6 production periods

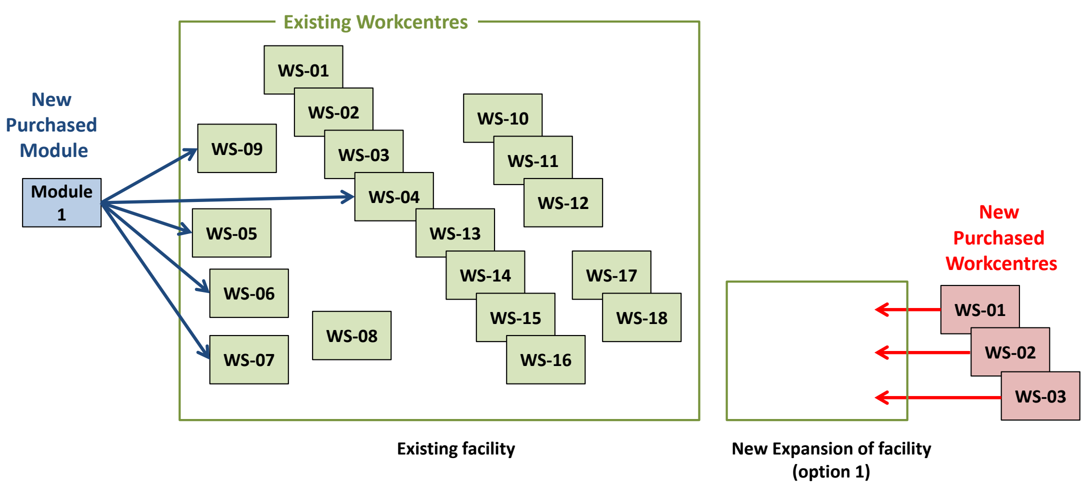

Fig. 28. New purchased modules, new workcentres and facility expansion

5.5. Conclusion

This chapter introduces, yet, another mathematical model for minimizing the difference between design and manufacturing costs on one hand and the revenue on the other hand. The developed mathematical model takes into account the Activity-Based Costing as a cost accounting method for the different manufacturing and assembly operations and engineering departments. In addition, the mathematical model includes the reconfiguration cost on a machine-level (addition of functional modules such as additional axes) and a system-level (in terms of addition of new workcentres). Furthermore, the mathematical model accounts for the cost for expanding the facility to include new workcentres. The mathematical model is applied on a case study from a multi-national company for building hydraulic presses. The minimization of the difference between design and manufacturing cost and the revenue in the objective function takes place as follows: reducing the hourly rates (accepting more jobs will increase the revenue, assigned hours to workcentres as well as decreasing the hourly rates based on the bi-directional relationship between assigned hours to workcentres and hourly rates) and accepting more jobs/projects (however, this is restricted by the capacity in the different departments). The implementation of the model reduced hourly rates for workcentres (in the Industrial Case Study) by up to 23% as a result of accepting more jobs (and accordingly, machining hours) on the available workcentres, and hence, reducing the hourly rates. This implementation has helped the company gain a competitive advantage among rivals since pricing of products submitted to customer was reduced.

The significance of the facility expansion model is multi-fold. First, it provides a decision making tool for managers in companies for accepting/rejecting jobs. Second, it provides management with investment decisions in terms of scaling machines purchasing, functional modules sizing and high-level investments such as building new extension for the manufacturing facility.

CHAPTER 6 A Cost-Benefit Analysis for Industry 4.0 in a Job Shop Environment

6. Overview

As the manufacturing industry is approaching the implementation of the 4th industrial revolution, changes will be required in terms of scheduling, production planning and control as well as cost-accounting departments. Industry 4.0 promotes decentralized production, and hence, cost models are required to capture costs of products and jobs within the production network considering the utilized manufacturing system paradigm. A new extension to the mathematical cost model (discussed in Chapter 3) is proposed for assessing the cost-benefit analysis of introducing Industry 4.0 elements to the manufacturing facility, specifically, integrating and connecting external suppliers as strategic partners and establishing an infrastructure for communicating information between the manufacturing company and its strategic suppliers. The mathematical model considers the bi-directional relationship between hourly rates and total hours assigned to workcentres/activities in a specific production period. A case study, from a multinational machine builder, is developed and solved using the proposed model. Results suggest that though an additional cost is required to establish infrastructure to connect suppliers, the responsiveness and agility resulting from uncertainty outweigh the additional cost.

6.1. Introduction

Manufacturing has been experiencing a dynamically changing environment that presents significant challenges to adapt to these changes effectively and economically for manufacturing companies. Manufacturing changeability, as an umbrella concept, encompasses many change enablers at various levels of an industrial company throughout the life cycle of the manufacturing system. As a result, companies are searching for cost models and tools to assist with investment decisions and improvement opportunities (Kianian, Kurdve, & Andersson, 2019). Within industry 4.0 environment, production processes are moving towards being interconnected, information based on real data in an attempt to increase the efficiency of production facilities (Santana et al., 2017). Fig. 29 shows the different production levels, which include station-level up to network-level. To achieve the highest level of responsiveness within a company is to establish a strategic network of suppliers. System-level change is partly concerned with the addition or removal of machines within the manufacturing system, while machine-level change is concerned with adding or removing machining axes and setup change. With the implementation of Industry 4.0, information and communication technology between machines, tools, services and suppliers, flexible and smart production control can be achieved (Wang, Ma, Yang, & Wang, 2017).

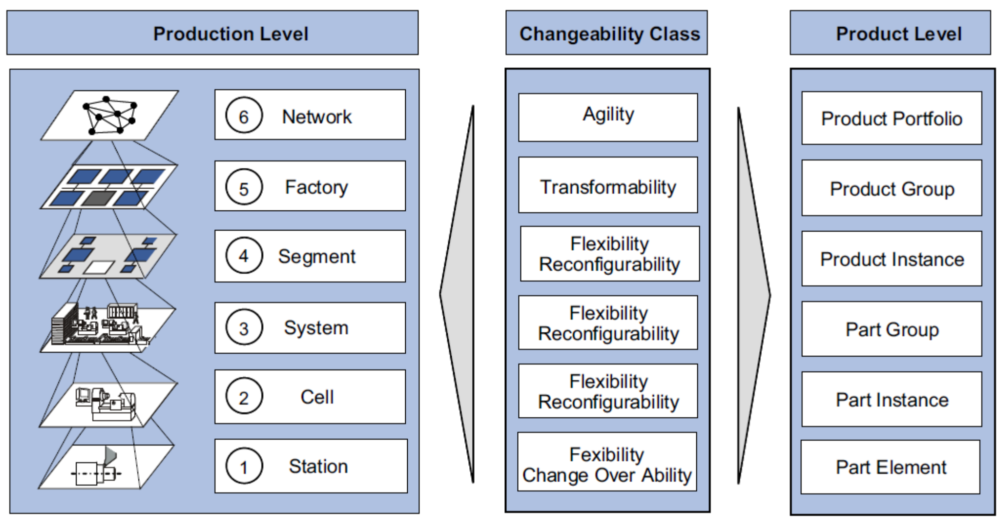

Fig. 29. The different level of production level, changeability class and product level (H. A. ElMaraghy & Wiendahl, 2009)

Furthermore, real-time, intelligent and digital networking of people, machinery and facilities allows the manufacturing company to manage the business model and create value networks (Dombrowski & Dix, 2018). The integration, consolidation and coordination of applications and individual factories are considered one of the critical issues with industry 4.0 (L. D. Xu et al., 2018). As a result, factories within the different industrial sectors and geographical locations will be connected and integrated (L. D. Xu et al., 2018). Liao et al. (Liao, Deschamps, Loures, & Ramos, 2017) defined three integration types: vertical integration, horizontal integration and end to end digital integration. The horizontal integration is defined as the integration between the IT systems within the different production phases as well as the business planning process within a company and several other companies or suppliers in what is known as the value network (Kusiak, 2018).

This chapter focuses on the connectivity aspect and networking between individual factories, manufacturing companies and external suppliers by developing a novel cost mathematical model. The mathematical model developed mainly considers the Activity-Based Costing (ABC) model. The mathematical model considers the bi-directional relationship between the hourly rates of a specific workcentre or activities and the total hours assigned to the workcentre in the previous production period. The mathematical model will also consider the investment decision on infrastructure (i.e. fibre optics, WAN, sensors, ERP software…etc.) required to establish connectivity between the manufacturing company and its strategic suppliers. Fig. 30 shows a conceptual drawing on how integration between a manufacturing company and external suppliers can be achieved. Sensors and actuators (i.e. Cyber-Physical System) within the manufacturing facility establish connections with external suppliers through Internet of Things (IoT).

This chapter is organized as follows: Section 2 is concerned with the model development, Section 3 provides the case study, Section 4 is concerned with the results and discussion of the case study, and finally Section 5 is the conclusion.

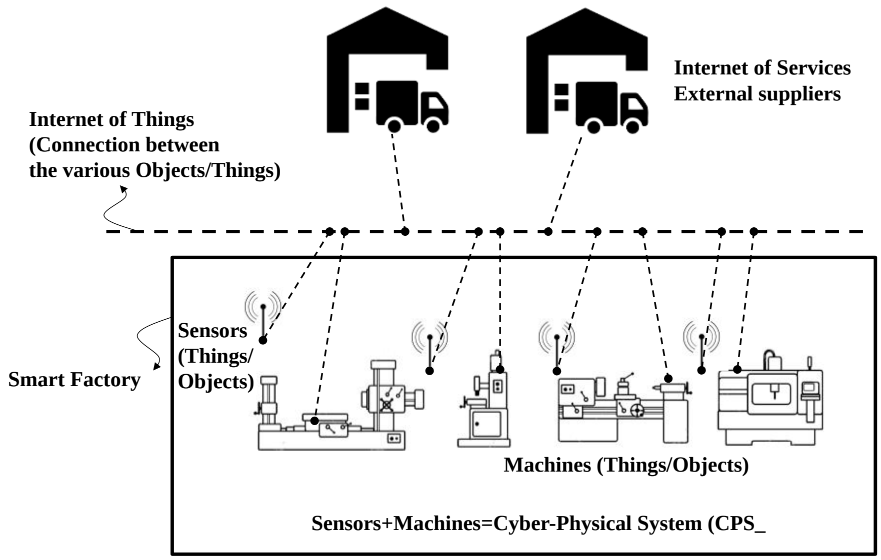

Fig. 30. Main components of Industry 4.0

The benefit of this integration is multi-fold:

- Real-time monitoring of data and information flow between the connected entities.
- The manufacturing company can easily schedule jobs through its different strategic suppliers, and decisions can easily be made on outsourcing to which supplier depends on the lead-time available of the job (see Fig. 31).

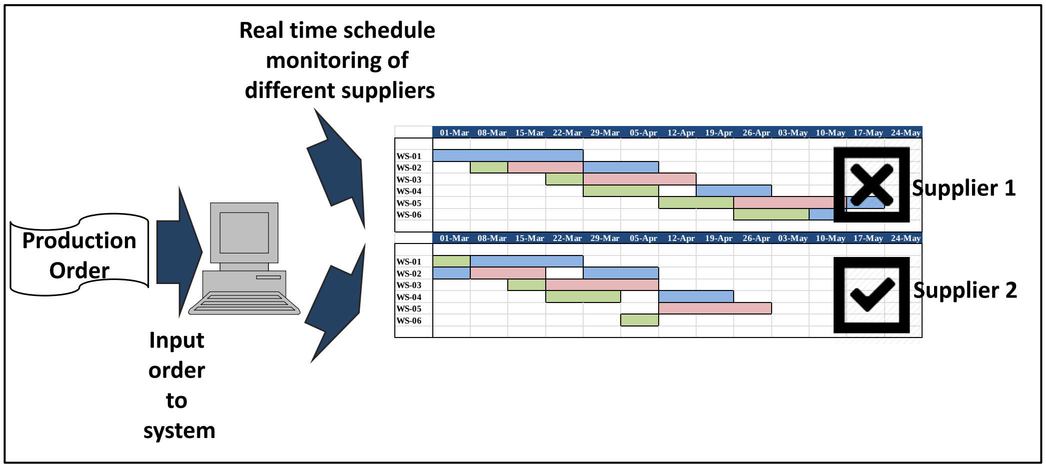

Fig. 31. Example of schedule monitoring

6.2. Model Development

The IDEF0 for the proposed model in this section is shown in Fig. 32. The inputs to the model are:

- The list of available orders in which the manufacturing firm will choose whether to proceed with or not
- The general assets and the equipment depreciation which is required to calculate the hourly machining rate
- The total machining hours for each order/job
- The list of available suppliers in which the manufacturing firm will be outsourcing to

The outputs from the model are:

- Accepted orders by the manufacturing firms
- New calculated hourly rates for machining within the manufacturing firm
- The decision to outsource operations to external suppliers to compensate for insufficient capacity within the manufacturing firm
- The decision to invest in industry 4.0 infrastructure in an attempt to interconnect strategic suppliers.

As shown in the IDEF0 model in Fig. 32, the mathematical model is subject to several constraints related to machining capacity (either internally or externally).

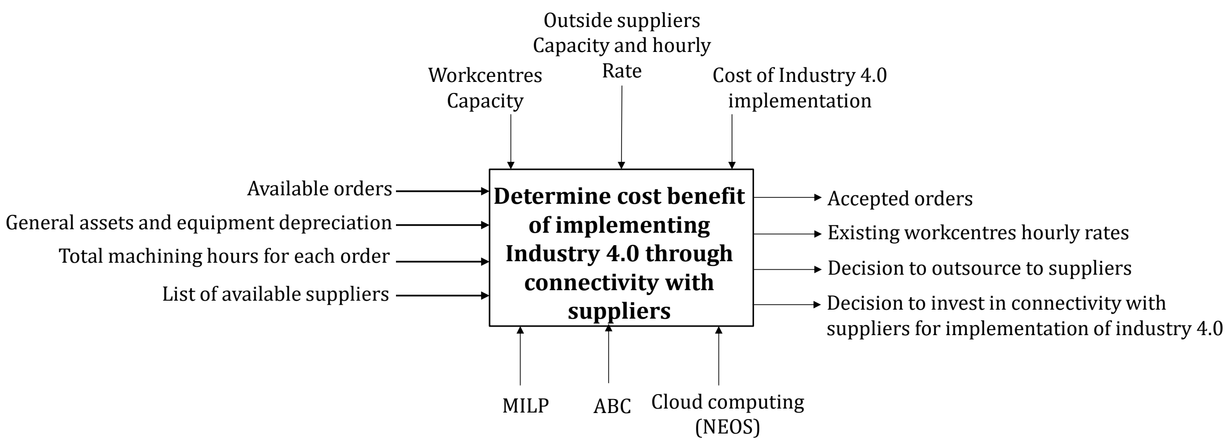

Fig. 32. IDEF0 for the cost-benefit analysis for Industry 4.0 in a job shop environment mathematical model

The proposed objective function maximizes the difference between the total revenue and total expenditures in each production period. The main cost elements considered are engineering, machining costs, and raw and commercial material cost. More costs can also be considered within the mathematical model, such as site installation, commissioning, service and maintenance. The different cost elements within the objective function are proposed as:

- The raw material/commercial items cost.
- The total engineering design cost
- The total production cost
- The total setup cost. In ABC method terms, the fourth term is the batch level
- The subcontracting cost to an external supplier.

The revenue element within the objective function is the selling price of the total projects.

Assume a manufacturing firm, as shown in Fig. 33, with a certain amount of machining resources. To effectively integrate strategic suppliers within the manufacturing firm, infrastructure should be invested in terms of sensors, software, communication protocols (Fieldbus, Profibus)…etc., in an attempt to create Internet of Things and benefit from Industry 4.0. Based on the manufacturing firm's available capacity, jobs and orders will be accepted ($q_{i,t,o}$

is a binary decision variable on whether operation *o* in job *i* within period *t* is executed internally within the manufacturing firm).

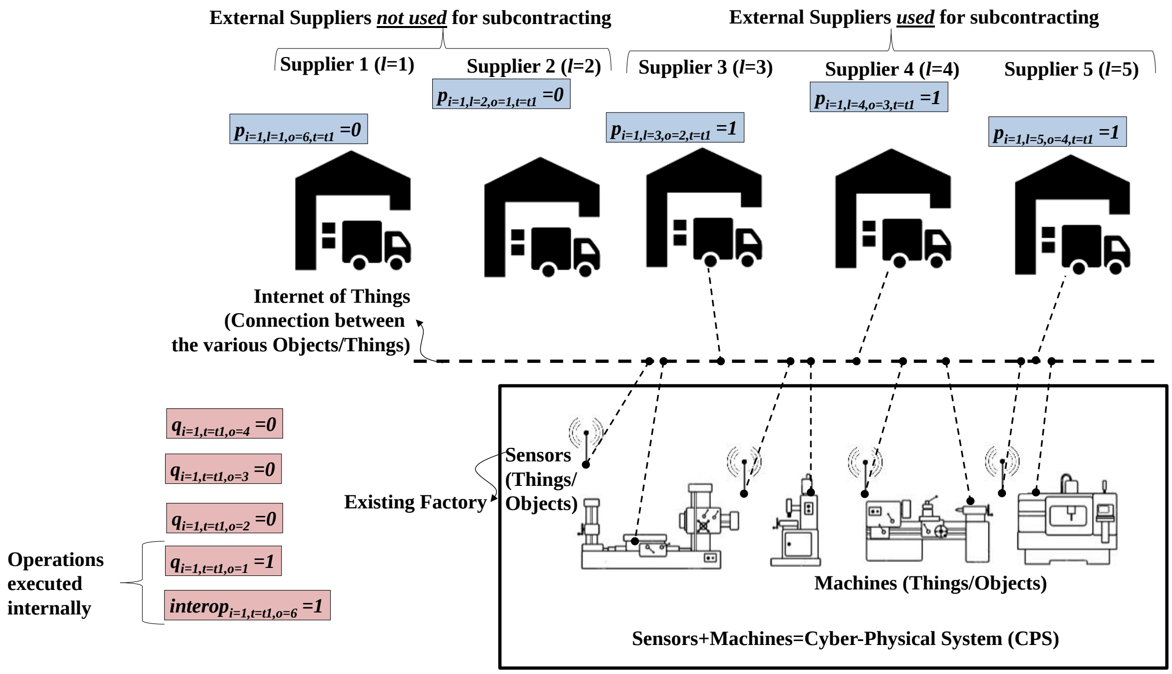

Fig. 33. Illustration of some terms within the mathematical model

If capacity is not sufficient within the manufacturing firm for a certain operation for a specific job, the manufacturing company outsources that operation within that job ($p_{i,l,o,t}$)is a binary decision variable on whether operation *o* in job *i* within period *t* is outsourced to an external supplier *l*). Another essential constraint within the proposed model is operation *o* in job *i* within period *t* is either submitted to supplier *l* or executed internally.

The input parameters for the mathematical model are:

$h_{i,j}$: Quoted/budget hours required for engineering department j to complete job i (72)

$g_{i,o}$: Quoted/budget hours required for workcentre o to complete job i (73)

$k_{i,o}$: Quoted/budget hours required for setup workcentre o to complete job i (74)

$Q_{i,t}$: Production demand/quantity of job *i* in production period *t* (75)

$d_{i,t}$: Raw material/commercial items cost for job *i* in production period *t* (76)

$R_{i,t}$: Selling price of job *i* in production period *t* (77)

$C_{o,t}^{WC}$: Available capacity for workcentre *o* in production period *t* (78)

$C_{j,t}^{ENG}$: Available capacity for engineering department *j* in production period *t* (79)

$c_{o}^{DEP\_WC}$: Depreciation cost of workcentre *o* (80)

$c_{j}^{DEP\_ENG}$: Depreciation of equipment in engineering department *j* (81)

$c_{o}^{GA\_WC}$: General assets allocation cost to existing workcentre *o* (82)

$c_{j}^{GA\_ENG}$: General assets allocation cost to department *j* (83)

c_{o}^{I4}: Industry 4.0 allocation cost to workcentre *o* in period *t* (84)

$c_{l,t}^{sup}$: hourly rate of supplier l in production period t (85)

$C_{l,o,t}^{sup}$: available capacity for operation o at supplier l in production period t (86)

Fig. 33 illustrates some of the decision variables in the mathematical model. Consider a manufacturing company, as shown in Fig. 30, that has a certain amount of machining resources. To effectively integrate strategic suppliers within this manufacturing company, infrastructure should be invested in terms of sensors, software, communication protocols (Fieldbus, Profibus, WAN)…etc., in an attempt to create Internet of Things and benefit from Industry 4.0. Based on the manufacturing company's available capacity, jobs and orders will be accepted ($q_{i,t,o}$) as a binary decision variable on whether operation *o* in job *i* within period *t* is executed internally within the manufacturing company. Suppose capacity is not sufficient within the manufacturing company for a certain operation in a specific job. In that case, the manufacturing company outsources that operation within that job ($p_{i,l,o,t}$) is a binary decision variable on whether operation *o* in job *i* within period *t* is outsourced to an external supplier *l*). Another important constraint within the proposed model is operation o in job i within period t is either submitted to supplier l or executed internally.

The decision variables of the mathematical model are:

$y_{j,t}$: Hourly rate for engineering department j in production period t (87)

$z_{o,t}$: Hourly rate for workcentre o in production period t (88)

$$x_{i,t} = \begin{cases} 1, & \text{if job } i \text{ is chosen in production period } t \\ 0, & \text{otherwise} \end{cases} \quad (89)$$

$$p_{i,l,o,t} = \begin{cases} 1, & \text{if supplier } l \text{ is chosen in production period } t \text{ for operation for job } i \\ 0, & \text{otherwise} \end{cases} \quad (90)$$

$$q_{i,o,t} = \begin{cases} 1, & \text{if operation } o \text{ is processed internally in production period } t \text{ for job } i \\ 0, & \text{otherwise} \end{cases} \quad (91)$$

$$r_{i,o,t} = \begin{cases} 1, & \text{if operation } o \text{ in job } i \text{ is selected in production period } t \\ 0, & \text{otherwise} \end{cases} \quad (92)$$

$$s_{o,t} = \begin{cases} 1, & \text{if operation } o \text{ is subcontracted in production period } t \\ 0, & \text{otherwise} \end{cases} \quad (93)$$

The indices in the mathematical model are:

I [1,…,i,…] = set of jobs/orders

J [1,…,J,…] = set of departments

O [1,…,o,…] = set of workcentres/operations

T [1,…,t,…], [1,…,t_0*,…]* = set of periods

L [1,…,l,…] = set of supplier

As shown in (94), the Objective Function minimizes the difference between the total revenue and total expenditures in each production period. The main cost elements being considered are engineering, machining costs, as well as raw and commercial material cost. More costs can be also be considered within the mathematical model such as site installation, commissioning, service and maintenance…etc.

$Min\ Z$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} d_{i,t} Q_{i,t} x_{i,t} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} h_{i,j} x_{i,t} y_{j,t}$$
$$+ \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} Q_{i,t} g_{i,o} q_{i,o,t} x_{i,t} z_{o,t} + \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T} \frac{k_{i,o} q_{i,o,t} x_{i,t} z_{o,t}}{Q_{i,t} + \varepsilon}$$
$$+ \sum_{i=1}^{I}\sum_{o=1}^{O}\sum_{t=1}^{T}\sum_{l=1}^{L} g_{i,o} c_{l,t}^{sup} p_{i,l,o,t} x_{i,t} - \sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t} Q_{i,t} x_{i,t} \tag{94}$$

In Equation (94), the first term is the raw material/commercial items cost. The second term is the total engineering cost. In ABC method terms, second term is the product level. The third term is the total production cost. In ABC method terms, the third term is the unit level. The fourth term is the total setup cost. In ABC method terms, the fourth term is the batch level. The fifth term is the subcontracting cost to an external supplier. Finally, the sixth term is the selling price of the total projects.

The constraints for the mathematical model is written as follows:

$$y_{j,t} = a_0 + \frac{c_j^{GA\_ENG} + c_j^{DEP\_ENG}}{\sum_{i=1}^{I} h_{i,j} x_{i,t_0}}, \forall j = 1,2..J, t = 1,2..T, t_0 = t-1 \tag{95}$$

$$z_{o,t} = b_0 + \frac{c_o^{GA\_WC} + c_o^{DEP\_WC} + c_o^{I4} s_{o,t_0}}{\sum_{i=1}^{I} g_{i,o} Q_{i,t_0} x_{i,t_0} q_{i,o,t}}, \forall o = 1,2..O, t = 1,2..T, t_0 = t-1 \tag{96}$$

$$\sum_{i=1}^{I} (g_{i,o} Q_{i,t} + k_{i,o}) q_{i,o,t} x_{i,t} \le C_{t,o}^{WC}\ , \forall o = 1,2..O, t = 1,2..T \tag{97}$$

$$\sum_{i=1}^{I} (g_{i,o} Q_{i,t} + k_{i,o}) p_{i,l,o,t} x_{i,t} \le C_{l,o,t}^{sup}\ , \forall o = 1,2..O, t = 1,2..T, l = 1,2..L \tag{98}$$

$$r_{i,o,t} \le (g_{i,o} Q_{i,t} + k_{i,o}) x_{i,t} \ \le Big\ M\ r_{i,o,t}, \forall\ i = 1,2,..I, o = 1,2..O, t = 1,2..T \tag{99}$$

$$\sum_{i=1}^{I} (g_{i,o} Q_{i,t} + k_{i,o}) x_{i,t} \le C_{t,o}^{M}\ q_{i,o,t} + \sum_{l=1}^{L} C_{l,o,t}^{sup} p_{i,l,o,t}, \quad \forall\ i = 1,2,..I, o = 1,2..O, t = 1,2..T \tag{100}$$

$$q_{i,o,t} + \sum_{l=1}^{L} p_{i,l,o,t} = r_{o,i,t}, \forall\ i = 1,2,..I, o = 1,2..O, t = 1,2..T \tag{101}$$

$$\sum_{l=1}^{L} p_{i,l,o,t}\ \le 1, \forall\ o = 1,2..O, i = 1,2..I, t = 1,2..T \tag{102}$$

$$\sum\nolimits_{i=1}^{I} h_{i,j} x_{i,t} \le C_{j,t}^{E}, \forall\ j = 1,2..J, t = 1,2..T \tag{103}$$

$$\begin{aligned} Big\ M \sum\nolimits_{l=1}^{L} \sum\nolimits_{i=1}^{I} p_{i,l,o,t} - Big\ M + 1 \\ \le \sum\nolimits_{i=1}^{I} (g_{i,o} Q_{i,t} + k_{i,o}) x_{i,t} - C_{t,o}^{M} \le Big\ M \sum\nolimits_{l=1}^{L} \sum\nolimits_{i=1}^{I} p_{i,l,o,t}, \\ \forall\ o = 1,2..O, t = 1,2..T \end{aligned} \tag{104}$$

$$s_{o,t} \le \sum_{i=1}^{I} \sum_{l=1}^{L} p_{i,l,o,t}\ \le BigM\ \ s_{o,t}, \forall\ o = 1,2..O, i = 1,2..I, t = 1,2..T \tag{105}$$

$$\sum\nolimits_{i=1}^{I} x_{i,t} \ge 1, \forall\ i = 1,2..I, t = 1,2..T \tag{106}$$

Equation (95) is concerned with hourly rate calculations for engineering activity *j* in production period *t*. Equation (96) is concerned with the hourly rate calculation for workcentre *o* in production period *t*. The term ”$\Sigma_l c_o^{I4}\, p_{l,o,t}$ “ is the partial allocation of the investment in industry 4.0 infrastructure. Equation (97) is the constraint concerned with the internal capacity available inside the manufacturing company. Equation (98) is concerned with the available capacity at the supplier where operation *o* is outsourced. Equation (99) is an indicator function in which $r_{i,o,t}$ takes a value of 1 if operation *o* in job *i* is required in period *t* and 0 otherwise.

Equation (100) restricts the total amount of hours of each job accepted by the manufacturing company that does not exceed to the summation of the available capacities inside the manufacturing company and the outside (at the subcontracted supplier). Equation (101) restricts operation *o* in job *i* within production period *t* to be either done internally or outsourced. Equation (102) ensures a certain operation *o* in a certain job *i* within a production period *t* cannot be split between two suppliers. Equation (103) is the capacity constraint applied to the engineering department(s), in which the total number of hours assigned to engineering department j cannot exceed the available capacity for this department. Equation (104) is concerned with the outsourcing decision in which a certain operation *o* within production period *t* is outsourced if the total hours required for an operation on workcentre *o* exceed the capacity for this workcentre. Equation (105) is used to determine the value of decision variable $s_{o,t}$ (i.e. $s_{o,t}$ is 1, if a certain operation *o* within at least one job is outsourced to at least one supplier in production period *t*, and 0 otherwise). Equation (106) requires at least one job to be accepted by the manufacturing company in any given production period.

6.3. Industrial Case Study

The case study is concerned with cylinder block machining taken from a multinational company for manufacturing wood presses. The total hours required by each available job within the engineering department is shown in Table 35. The available capacity in hours for the workcentres within the manufacturing facility is listed in Table 36. Table 37 lists the machining and setup hours (between brackets) required for each available job (taken from each job's quote). Table 38 to Table 42 lists the available machining capacities for each operation/workcentre.

The hourly rates for suppliers 1, 2, 3, 4 and 5 are \$60, \$70, \$80, \$55 and \$100, respectively. The capacity for internal engineering departments 1 and 2 is 4,000 hours/period. The selling price for each job and the material cost (direct material in the form of raw material and commercial items) are provided in Table 43. Table 44 and Table 45 list the cost of assets, depreciation and industry 4.0 costs allocated to each workcentre within the manufacturing companies. These numbers are taken directly from company’s records. In Table 45, Industry 4.0 cost allocated to the workcentres column has also been taken from the company's records. This cost consists of the total cost to implement connectivity between the different infrastructure suppliers, as SAP software (initial cost of the software, licensing and training).

The total cost of industry 4.0 is then allocated to each workcentre based on the ratio between the hours allocated to each workcentre to the total hours for all workcentres within a one-year period. A similar calculation was carried out when coming up with the numbers of the general assets allocation in which the total general assets was multiplied by the hours allocated to each workcentre, and then divided by the total hours allocated to all workcentres in a one year period. The depreciation per year (assuming ten years depreciation period) per workcentre is calculated based on each workcentre's cost.

Table 35. Engineering hours required by each job

		Dept.1	Dept2
	1	610	500
	2	690	300
	3	770	810
	4	920	180
jobs	5	560	320
	6	520	280
	7	170	840
	8	760	960
	9	510	390
	10	110	820

Table 36. Internal capacity of workcentres in hours

	Workcentres																	
production period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
2	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
3	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
4	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
5	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
6	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
7	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
8	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
9	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
10	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
11	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960
12	4,800	3,840	4,800	2,400	1,440	2,400	1,080	1,920	2,400	2,400	960	4,800	4,800	4,800	4,800	4,800	960	960

Table 37. Machining and setup hours (between brackets) required for job *i* on existing workcentre *o*

		Workcentre																	
		WS-1010	WS-1020	WS-1030	WS-1040	WS-1050	WS-1060	WS-1070	WS-1080	WS-1090	WS-1100	WS-1110	WS-1120	WS-1130	WS-1140	WS-1150	WS-1160	WS-1170	WS-1180
Job	1	82.048 (2)	1755 (1)	785 (2)	795 (2)	400 (2)	600 (2)	0 (0)	1055 (1)	760 (2)	1240 (1)	670 (1)	760 (1)	300 (1)	0 (0)	80 (1)	267.5 (1)	300 (2)	50 (1)
	2	657.5 (2)	1040 (2)	592.5 (2)	1267 (1)	1900 (1)	3365 (2)	895 (2)	100 (1)	600 (1)	0 (0)	760.5 (2)	520 (2)	520 (2)	650 (2)	756 (2)	677.5 (1)	412.5 (2)	0 (0)
	3	60 (2)	100 (2)	150 (1)	0 (0)	140 (2)	170 (1)	30 (1)	150 (1)	0 (0)	100 (2)	150 (1)	0 (0)	100 (1)	0 (0)	50 (2)	0 (0)	100 (1)	200 (2)
	4	145 (1)	890 (1)	137.5 (1)	200 (2)	105 (1)	110 (2)	170 (2)	100 (2)	1850 (1)	200 (1)	150 (1)	300 (0)	450 (1)	320 (2)	300 (1)	105 (1)	250 (2)	400 (2)
	5	115 (2)	297.5 (2)	250 (2)	100 (1)	100 (1)	140 (2)	140 (1)	100 (1)	1500 (1)	200 (1)	192.5 (2)	0 (0)	450 (2)	220 (2)	300 (2)	100 (2)	200 (2)	110 (2)
	6	30 (1)	935 (2)	1520 (2)	140 (1)	505 (1)	1670 (1)	472.5 (1)	250 (2)	720 (2)	90 (1)	1107.5 (2)	100 (1)	850 (2)	460 (1)	82.5 (1)	80 (2)	200 (2)	880 (1)
	7	0 (0)	0 (0)	5539 (1)	0 (0)	170 (1)	540 (1)	100 (2)	100 (2)	0 (2)	100 (1)	230 (1)	300 (0)	450 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	8	147.5 (1)	330 (2)	155 (2)	680 (2)	175 (2)	150 (1)	200 (1)	500 (1)	400 (2)	185 (2)	80 (1)	150 (1)	450 (2)	150 (1)	142.5 (1)	70 (1)	155 (1)	150 (1)
	9	195 (2)	340 (2)	150 (2)	140 (2)	275 (1)	215 (2)	250 (1)	810 (1)	400 (2)	230 (2)	202.5 (1)	150 (1)	250 (2)	150 (2)	167.5 (1)	75 (1)	45 (2)	100 (1)
	10	135 (2)	370 (1)	115 (2)	110 (2)	75 (2)	251 (2)	30 (1)	980 (2)	400 (1)	250 (1)	100 (2)	375 (1)	450 (1)	150 (1)	167.5 (1)	70 (1)	45 (2)	200 (2)

Table 38. Machining capacity for supplier 1

	Workcentres																	
production period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	19,445	10,270	21,170	12,770	24,955	7,970	13,755	19,730	8,035	15,100	8,190	8,630	19,445	10,270	21,170	12,770	24,955	7,970
2	8,805	24,720	20,515	7,940	20,420	6,005	10,040	16,265	8,665	15,940	17,550	6,725	8,805	24,720	20,515	7,940	20,420	6,005
3	21,680	15,600	5,825	18,560	5,245	21,230	5,835	9,615	12,260	15,555	19,225	16,980	21,680	15,600	5,825	18,560	5,245	21,230
4	14,605	18,635	6,220	8,865	23,065	8,745	10,350	23,565	8,585	24,080	14,555	7,740	14,605	18,635	6,220	8,865	23,065	8,745
5	17,585	5,780	19,900	16,875	24,895	11,795	14,700	21,065	6,955	16,515	10,905	22,915	17,585	5,780	19,900	16,875	24,895	11,795
6	5,970	7,120	19,885	21,280	11,270	5,070	7,665	17,085	14,425	7,525	24,625	14,360	5,970	7,120	19,885	21,280	11,270	5,070
7	7,995	12,095	7,520	17,685	20,830	19,675	21,640	11,875	22,525	9,190	18,995	9,810	7,995	12,095	7,520	17,685	20,830	19,675
8	7,585	8,430	18,405	21,110	16,905	5,785	9,930	17,105	22,175	12,275	14,690	10,775	7,585	8,430	18,405	21,110	16,905	5,785
9	8,830	23,240	11,745	13,840	18,720	15,150	19,125	13,135	18,980	16,140	15,615	11,425	8,830	23,240	11,745	13840	18,720	15,150
10	7,815	20,490	9,370	6,095	20,210	20,500	13,795	13,840	5,805	14,280	13,400	15,085	7,815	20,490	9,370	6095	20,210	20,500
11	10,200	10,120	12,440	9,825	20,535	16,985	24,495	5,565	14,765	8,385	22,125	16,385	10,200	10,120	12,440	9,825	20,535	16,985
12	8,455	23,955	19,685	24,490	5,140	12,440	8,750	6,395	19,380	10,125	10,410	19,710	8,455	23,955	19,685	24,490	5,140	12,440

Table 39. Machining capacity for supplier 2

		Workcentres																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
production period	1	20,020	9,800	8,560	7,710	16,975	13,945	20,970	15,515	11960	14,220	16,035	24,405	20,020	9,800	8,560	7,710	16,975	13,945
	2	15,445	24,905	23,520	12,835	24,510	19,080	9,155	11,420	7,730	23,255	18,335	12,515	15,445	24,905	23,520	12,835	24,510	19,080
	3	14,510	19,605	17,895	6,810	11,580	6,420	19,990	11,235	7,650	13,335	8,300	7,710	14,510	19,605	17,895	6,810	11,580	6,420
	4	17,660	22,560	13,620	13,970	18,645	20,110	11,665	6,425	17,840	24,155	14,335	8,170	17,660	22,560	13,620	13,970	18,645	20,110
	5	14,665	18,990	22,980	19,125	13,250	16,540	22,885	20,705	22,775	15,385	5,825	7,750	14,665	18,990	22,980	19,125	13,250	16,540
	6	5,295	17,895	13,405	24,130	5,125	16,460	24,560	24,395	18,190	19,285	8,025	12,525	5,295	17,895	13,405	24,130	5,125	16,460
	7	12,435	12,145	23,215	19,915	9,575	5,625	24,895	7,415	18,360	6,910	7,685	19,785	12,435	12,145	23,215	19,915	9,575	5,625
	8	22,575	14,050	15,070	15,540	10,335	7,700	7,435	22,040	10,550	24,610	24,630	14,465	22,575	14,050	15,070	15,540	10,335	7,700
	9	22,025	23,845	24,750	12,880	6,125	23,535	13,480	13,840	7,775	5,025	6,330	10,390	22,025	23,845	24,750	12,880	6,125	23,535
	10	13,815	18,020	17,095	5,305	18,415	6,680	6,805	9,655	12,425	7,415	18,765	18,770	13,815	18,020	17,095	5,305	18,415	6,680
	11	17,525	11,390	20,175	21,270	19,455	23,580	10,840	22,025	6,285	11,135	13,010	18,130	17,525	11,390	20,175	21,270	19,455	23,580
	12	9,715	11,450	6,815	15,425	15,510	9,365	20,730	15,375	9,810	8,720	8,525	18,230	9,715	11,450	6,815	15,425	15,510	9,365

Table 40. Machining capacity for supplier 3

production period	Workcentres																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	16,365	18,125	19,040	6,100	20,755	22,675	9,690	9,735	9,790	10,100	9,015	12,330	16,365	18,125	19,040	6,100	20,755	22,675
2	16,440	8,360	16,900	9,160	19,630	13,990	9,280	22,970	11,080	8,455	24,335	11,955	16,440	8,360	16,900	9,160	19,630	13,990
3	15,660	22,305	20,070	15,690	20,540	20,565	21,615	8,210	14,740	15,025	6,965	14,520	15,660	22,305	20,070	15,690	20,540	20,565
4	12,370	23,265	18,975	20,620	12,765	20,275	13,920	12,570	23,770	7,245	20,360	23,900	12,370	23,265	18,975	20,620	12,765	20,275
5	22,505	18,360	23,375	13,880	18,010	21,140	14,725	24,090	13,085	5,035	24,305	21,335	22,505	18,360	23,375	13,880	18,010	21,140
6	14,465	13,650	6,555	10,325	15,100	20,030	14,910	16,795	16,730	7,785	8,930	11,630	14,465	13,650	6,555	10,325	15,100	20,030
7	9,105	20,950	21,425	17,880	18,625	10,060	12,220	24,070	7,815	21,835	11,870	8,575	9,105	20,950	21,425	17,880	18,625	10,060
8	12,255	23,145	19,790	24,325	22,610	22,890	16,395	16,470	6,915	8,410	22,140	21,295	12,255	23,145	19,790	24,325	22,610	22,890
9	18,800	19,495	19,515	17,665	14,685	9,820	6,705	6,100	13,130	15,315	7,890	10,990	18,800	19,495	19,515	17,665	14,685	9,820
10	11,820	24,145	8,830	15,465	8,135	20,820	21,050	12,945	14,825	11,635	19,665	24,000	11,820	24,145	8,830	15,465	8,135	20,820
11	19,835	8,820	12,685	9,945	22,370	18,950	11,170	17,480	19,220	13,335	21,660	16,715	19,835	8,820	12,685	9,945	22,370	18,950
12	19,410	14,760	15,470	14,325	18,810	16,115	14,665	13,660	20,210	14,215	12,415	17,915	19,410	14,760	15,470	14,325	18,810	16,115

Table 41. Machining capacity for supplier 4

production period	Workcentres 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	16,490	24,995	7420	5,605	11,765	7,570	13,975	17,060	8,885	12,450	12,170	8,935	16,490	24,995	7,420	5,605	11,765	7,570
2	12,900	12,130	7145	19,885	21,305	15,050	9,710	9,465	18,990	8,375	13,240	12,575	12,900	12,130	7,145	19,885	21,305	15,050
3	11,370	19,625	20330	18,565	22,915	14,985	16,570	18,940	24,215	13,675	6,190	17,865	11,370	19,625	20,330	18,565	22,915	14,985
4	21,675	14,690	6,425	17,335	22,175	23,565	19,160	5,035	18,545	12,335	22,265	5,245	21,675	14,690	6,425	17,335	22,175	23,565
5	6,055	23,365	18,000	6,995	6,185	9,155	10,700	13,055	11,365	18,935	11,010	14,205	6,055	23,365	18,000	6,995	6,185	9,155
6	11,975	16,065	16,275	5,540	22,120	14,755	23,615	7,620	19,960	21,265	6,965	7,010	11,975	16,065	16,275	5,540	22,120	14,755
7	9,475	23,145	20,075	5,845	7,295	20,050	16,630	20,335	22,700	14,910	13,905	23,880	9,475	23,145	20,075	5,845	7,295	20,050
8	9,630	21,880	23,205	17,385	23,970	20,675	15,075	14,085	24,430	17,550	18,500	17,990	9,630	21,880	23,205	17,385	23,970	20,675
9	21,070	13,310	12,665	11,885	9,790	7,565	19,285	21,635	12,875	15,075	7,030	22,335	21,070	13,310	12,665	11,885	9,790	7,565
10	13,090	21,990	6,195	10,865	23,870	9,280	17,160	11,935	11,625	9,085	6,680	19,590	13,090	21,990	6,195	10,865	23,870	9,280
11	7,870	9,480	5,335	24,195	7,785	24,500	5,445	15,970	22,450	14,715	19,475	20,460	7,870	9,480	5,335	24,195	7,785	24,500
12	5,900	17,445	8,170	5,420	10,315	10,230	21,000	21,315	5,025	11,845	18,710	24,435	5,900	17,445	8,170	5,420	10,315	10,230

Table 42. Machining capacity for supplier 5

	Workcentres																	
production period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	12,750	16,515	15,350	13,540	22,905	18,460	16,270	15,135	17,765	14,725	11,465	15,245	12,750	16,515	15,350	13,540	22,905	18,460
2	16,475	10,950	22,980	16,845	11,300	19,140	12,750	14,745	23,525	21,950	6,285	11,630	16,475	10,950	22,980	16,845	11,300	19,140
3	21,805	22,310	21,825	13,260	5,505	16,935	23,250	19,465	12,230	17,805	15,835	22,390	21,805	22,310	21,825	13,260	5,505	16,935
4	21,920	18,080	19,695	6,200	17,705	15,275	11,405	11,735	23,505	12,695	16,845	20,060	21,920	18,080	19,695	6,200	17,705	15,275
5	13,815	18,535	9,160	12,615	15,275	17,925	5,765	16,235	5,290	13,170	9,045	20,150	13,815	18,535	9,160	12,615	15,275	17,925
6	13,805	19,145	22,600	13,310	9,240	10,220	9,025	18,530	5,010	8,605	21,260	24,160	13,805	19,145	22,600	13,310	9,240	10,220
7	5,365	13,515	18,330	9,265	20,900	20,690	23,855	6,475	23,870	14,290	24,175	13,440	5,365	13,515	18,330	9,265	20,900	20,690
8	23,210	19,170	6,875	11,820	22,335	18,180	21,790	21,645	24,915	24,685	22,435	22,805	23,210	19,170	6,875	11,820	22,335	18,180
9	10,360	11,990	6,465	21,500	24,195	18,990	19,655	17,200	17,690	18,370	23,260	11,660	10,360	11,990	6,465	21,500	24,195	18,990
10	20,220	11,230	13,625	18,640	17,325	17,255	7,880	16,570	9,105	14,830	17,820	9,785	20,220	11,230	13,625	18,640	17,325	17,255
11	10,420	17,485	7,605	21,025	18,945	7,305	22,930	18,460	13,490	5,690	14,465	24,110	10,420	17,485	7,605	21,025	18,945	7,305
12	15,025	20,310	10,885	22,200	20,675	15,905	8,915	8,430	14,995	9,080	16,310	11,125	15,025	20,310	10,885	22,200	20,675	15,905

Table 43. Selling price and material cost for each job in ($)

Jobs	Selling price ($)	direct material cost ($)
1	8,567,852	368,660
2	9,645,338	975,310
3	7,953,116	216,150
4	3,736,031	992,470
5	4,571,219	961,110
6	4,415,876	356,540
7	5,964,349	327,930
8	4,306,360	695,000
9	5,700,360	994,640
10	4,298,561	313,370

Table 44. List of assets and cost

Asset	Cost	Years	Cost per year
Building	$ 2,900,000	20	$ 145,000
Office Improvements	$ 24,555	20	$ 1,228
Computers (IT)	$ 80,062	3	$ 26,687
Engineering Assets	$ 13,357	5	$ 2,671
Furniture	$ 23,584	5	$ 4,717
Small Tools	$ 180,287	3	$ 60,096
Auto and Truck	$ 20,633	3	$ 6,878
Machinery and equipment and maintenance	$ 3,219,359	10	$ 321,936
Lifting Equipment	$ 188,645	10	$ 18,865
Industry 4.0 components	$ 455,000	5	$ 91,000

Table 45. List of assets, industry 4.0 cost and depreciation allocated to each workcentre

Workcentre	General assets allocated Cost	Industry 4.0 investment cost allocation per year	Depreciation/yr
WS-01	$20,141.36	$3,116.74	$-
WS-02	$59,057.32	$9,138.73	$-
WS-03	$59,057.32	$9,138.73	$-
WS-04	$14,061.27	$2,175.89	$29,180.00
WS-05	$15,186.17	$2,349.96	$110,020.00
WS-06	$14,061.27	$2,175.89	$29,180.00
WS-07	$8,436.76	$1,305.53	$3,440.00
WS-08	$7,030.63	$1,087.94	$73,630.00
WS-09	$15,186.17	$2,349.96	$187,950.00
WS-10	$20,141.36	$3,116.74	$2,710.00
WS-11	$59,057.32	$9,138.73	$-
WS-12	$59,057.32	$9,138.73	$-
WS-13	$59,057.32	$9,138.73	$-
WS-14	$59,057.32	$9,138.73	$-
WS-15	$59,057.32	$9,138.73	$-
WS-16	$20,141.36	$3,116.74	$-
WS-17	$20,141.36	$3,116.74	$-
WS-18	$20,141.36	$3,116.74	$-

6.4. Results and Discussion

The Mixed Integer Programming model is written by using AMPL (http://ampl.com/) and solved by Gurobi (http://gurobi.com) Mixed Integer Linear Programming (MILP) in NEOS (Czyzyk et al., 1998; Dolan, 2001; Gropp & Moré, 1997). The NEOS job number is 8407382 and was executed on 24th July 2020. The optimum solution of the objective function is -$162,251,041. The results from the model are listed in Table 46 to Table 51, as well as Fig. 34 to Fig. 36. Table 46 lists the values of ”$x_{i,t}$“ (jobs selected by the manufacturing company in each production period). Table 47 to Table 50 lists the values of “$p_{i,l,o,t}$” (operations outsourced to suppliers in each production period for each job). It is evident that the mathematical model assigns jobs to be executed internally rather than outsourcing the jobs to external suppliers. The reason for that decision is attributed to the nature of the hourly rate equations (95) and (96) in which a reduction in hourly rates is achieved by increasing the number of operations assigned to internal workcentres within the manufacturing facility. The reasons for outsourcing those particular operations to an external supplier, as shown in Table 47 to Table 50, are attributed to the results shown in Table 51, which displays the difference between the total available internal capacity on each workcentre, and the total hours assigned to each workcentre.

The white shaded cells represent the surplus in capacity and hence, those particular operations are executed internally within the manufacturing company. The grey shaded cells represent a shortage of capacity in which the total hours assigned to each workcentre exceeds the available capacity. Fig. 34 provides the results for the hourly rate variation in the different production periods for the engineering department. Fig. 35 and Fig. 36 provide the results for the hourly variation in the different production periods for the internal operations executed on workcentres 1010 up to 1180.

In Fig. 35 (hourly rates for workcentres 1010 to 1090), it is evident that there is a spike in the hourly rates for workcentres 1010 to 1090 in production period 12. The reason for the spike is due to the reduced number of hours assigned to workcentres 1010 to 1090 in production period 11 (hourly rates for a certain production period are calculated from the total hours assigned to workcentres in the previous production period). From the results, the summation of the hours for assigned to all workcentres are 11681, 9681, 11681, 11681, 11783.5, 11681, 11681, 11681, 11681, 11681, 6246 and 11681 hours in production periods 1, 2, 3, 4, 5, 6, 7, 8 ,9, 10, 11 and 12 respectively. Hence, the total hours assigned to all workcentres in production period 11 are the lowest, resulting in higher hourly rates in the following production period.

It is also clear that there is a reduction in hourly rates. For example, WS-1080 was reduced from \$125/hour to \$110/hour in some production periods (depending on the hours assigned that workcentre). That accounts for 12% reduction in hourly rates and hence, the company reached a competitive advantage among its rival in regards to the operation performed by WS-1080.

Table 46. jobs mix in each production period

		jobs									
		i=1	i=2	i=3	i=4	i=5	i=6	i=7	i=8	i=9	i=10
Production periods	t=1	0	0	0	0	0	1	0	1	1	1
	t=2	0	0	0	1	0	1	0	0	1	1
	t=3	0	0	0	0	0	1	0	1	1	1
	t=4	0	0	0	0	0	1	0	1	1	1
	t=5	0	0	0	1	0	1	0	1	0	1
	t=6	0	0	0	0	0	1	0	1	1	1
	t=7	0	0	0	0	0	1	0	1	1	1
	t=8	0	0	0	0	0	1	0	1	1	1
	t=9	0	0	0	0	0	1	0	1	1	1
	t=10	0	0	0	0	0	1	0	1	1	1
	t=11	0	0	0	1	0	0	0	1	1	1
	t=12	0	0	0	0	0	1	0	1	1	1

Table 47. Operations outsourced to supplier 4 for job 4 in the different production periods

	Production periods											
Operations/workcentres	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	1	0	0	1	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0

Table 48. operations outsourced to supplier 4 for job 6 in the different production periods

	Production periods											
Operations/workcentres	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	1	1	1	1	1	1	1	1	1	1	0	1
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	1	1	1	1	1	1	1	1	1	1	0	1

Table 49. Operations outsourced to supplier 4 for job 9 in the different production periods

		Production periods											
		1	2	3	4	5	6	7	8	9	10	11	12
Operations/workcentres	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0
	8	1	1	0	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	0	0	0	0	0	0
	13	0	0	0	0	0	0	0	0	0	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0
	15	0	0	0	0	0	0	0	0	0	0	0	0
	16	0	0	0	0	0	0	0	0	0	0	0	0
	17	0	0	0	0	0	0	0	0	0	0	0	0
	18	0	0	0	0	0	0	0	0	0	0	0	0

Table 50. operations outsourced to supplier 4 for job 10 in the different production periods

		Production periods											
		1	2	3	4	5	6	7	8	9	10	11	12
Operations/workcentres	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0
	8	0	0	1	1	0	1	1	1	1	1	1	1
	9	0	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	0	0	0	0	0	0
	13	0	0	0	0	0	0	0	0	0	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0
	15	0	0	0	0	0	0	0	0	0	0	0	0
	16	0	0	0	0	0	0	0	0	0	0	0	0
	17	0	0	0	0	0	0	0	0	0	0	0	0
	18	0	0	0	0	0	0	0	0	0	0	0	0

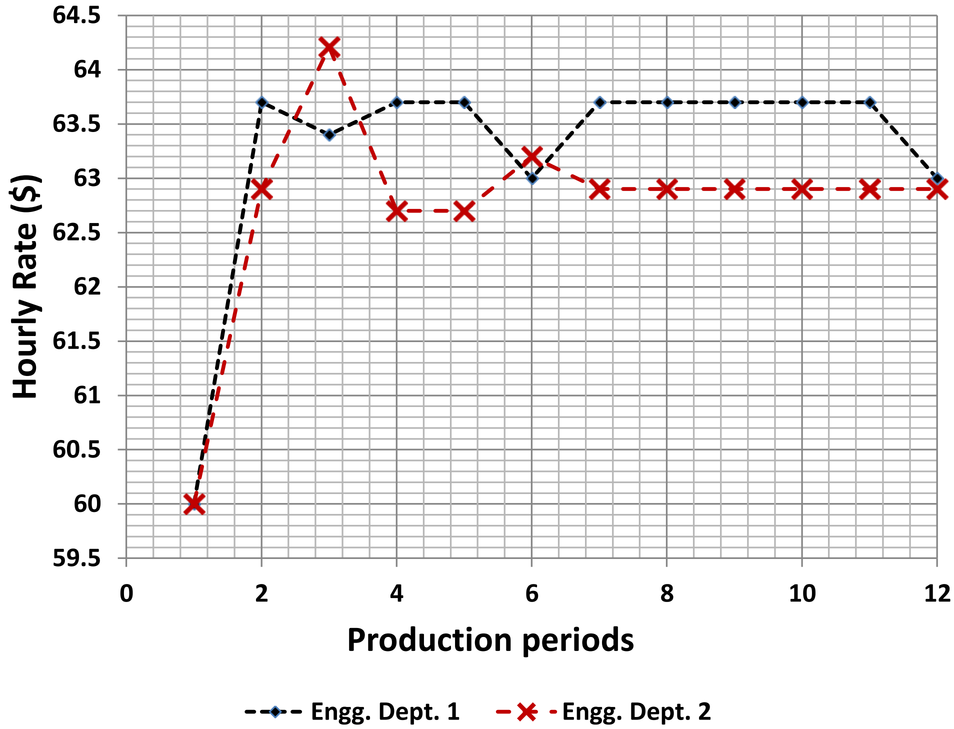

Fig. 34. Hourly rates ($) for engineering departments 1 and 2

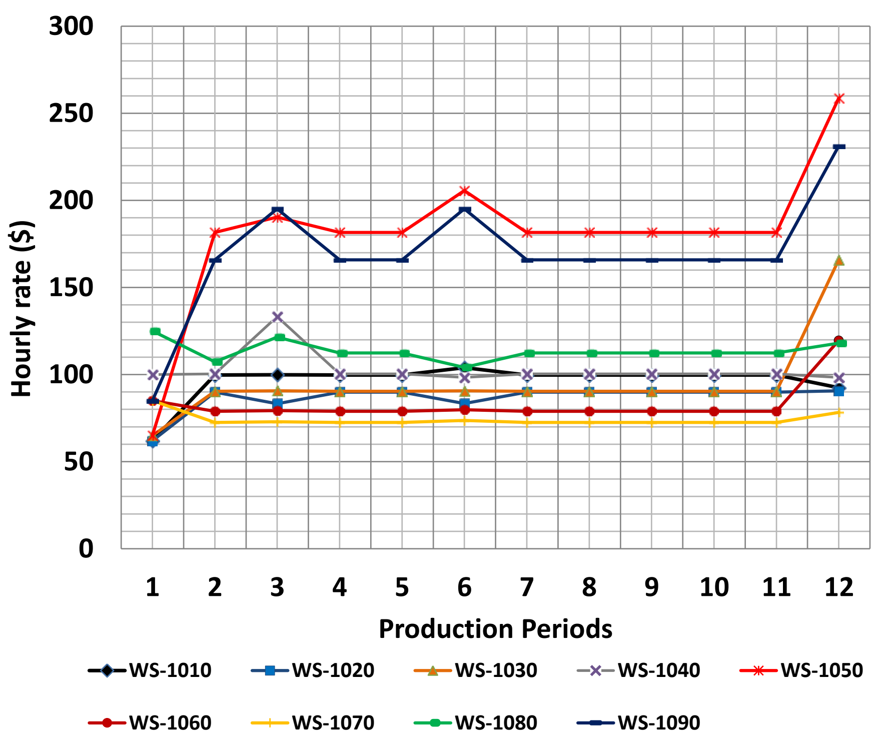

Fig. 35. Hourly rate ($) for workcentres WS-1010 to WS-1090 in each production period

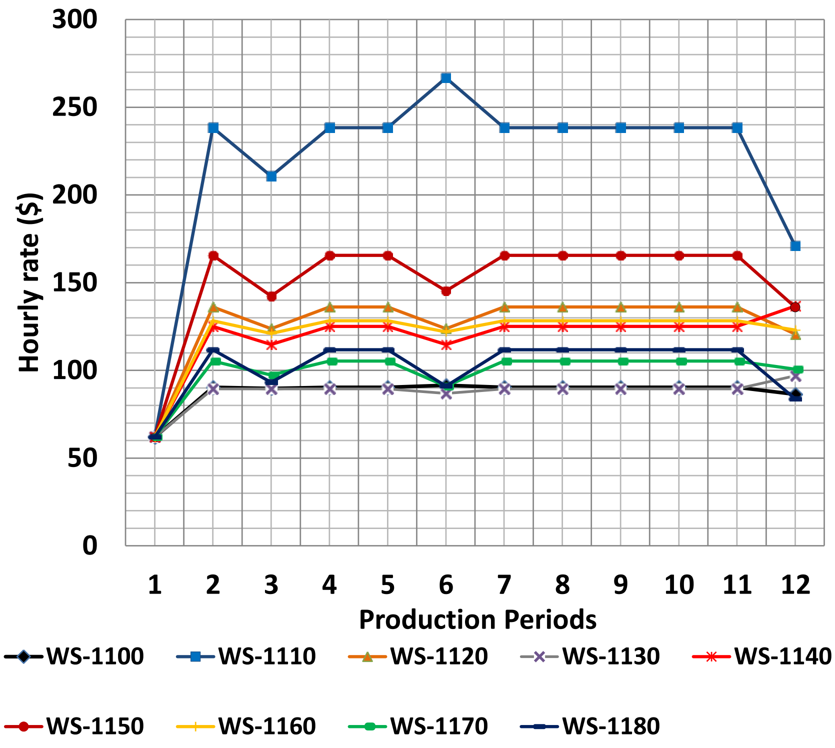

Fig. 36. Hourly rate ($) for workcentres WS-1100 to WS-1180 in each production period

The results of this model, accounting for Industry 4.0 cost/benefit, were considered by running the model twice:

- Model 1: The model was run with the given jobs by considering outsourcing to sub-contractors and investing in implementing Industry 4.0. The solution for the Mathematical programming model, for model 1, was discussed in the previous section (i.e. using equations (72) to (106) in which outsourcing operations to external suppliers is considered while investing in industry 4.0 infrastructure.
- Model 2 is similar to model 1 (Job number 8418783), except considering outsourcing to sub-contractors, but not investing in linking the suppliers' infrastructure (Industry 4.0 cost). This was achieved by omitting the term "$c_o^{I4} s_{o,t0}$" in Equation (96). This model describes the case in which outsourcing operations to external suppliers without investing in industry 4.0 infrastructure. The objective function value is -$162,403,895.40, which is less than the value of the objective function in model 1 (-$162,251,041.00).

Table 51. The difference between the available capacities and the total hours required by each workcentre in each production period

Workcentres	Production Periods 1	2	3	4	5	6	7	8	9	10	11	12
1	4,292.5	4,295	4,292.5	4,292.5	4,342.5	4,292.5	4,292.5	4,292.5	4,292.5	4,292.5	4,177.5	4,292.5
2	1,865	1,305	1,865	1,865	1315	1,865	1,865	1,865	1,865	1,865	1,910	1,865
3	2,860	2,877.5	2,860	2,860	2,872.5	2,860	2,860	2,860	2,860	2,860	4,242.5	2,860
4	1,330	1,810	1,330	1,330	1,270	1,330	1,330	1,330	1,330	1,330	1,270	1,330
5	410	480	410	410	580	410	410	410	410	410	810	410
6	114	154	114	114	219	114	114	114	114	114	1,674	114
7	127.5	157.5	127.5	127.5	207.5	127.5	127.5	127.5	127.5	127.5	430	127.5
8	-620	-220	-620	-620	90	-620	-620	-620	-620	-620	-470	-620
9	480	-970	480	480	-970	480	480	480	480	480	-650	480
10	1,645	1,630	1,645	1,645	1,675	1,645	1,645	1,645	1,645	1,645	1,535	1,645
11	-530	-600	-530	-530	-477.5	-530	-530	-530	-530	-530	427.5	-530
12	4,025	3,875	4,025	4,025	3,875	4,025	4,025	4,025	4,025	4,025	3,825	4,025
13	2,800	2,800	2,800	2,800	2,600	2,800	2,800	2,800	2,800	2,800	3,200	2,800
14	3,890	3,720	3,890	3,890	3,720	3,890	3,890	3,890	3,890	3,890	4,030	3,890
15	4,240	4,082.5	4,240	4,240	4,107.5	4,240	4,240	4,240	4,240	4,240	4,022.5	4,240
16	4,505	4,470	4,505	4,505	4,475	4,505	4,505	4,505	4,505	4,505	4,480	4,505
17	515	420	515	515	310	515	515	515	515	515	465	515
18	-370	-620	-370	-370	-670	-370	-370	-370	-370	-370	110	-370

The difference between the results of model 1 and model 2 is attributed to the omission of the "$c_o^{I4}s_{o,t0}$ " term in model 2 within Equation (96). The percentage of increase in model 2 compared to model 1 is 0.094%. However, by building an infrastructure for industry 4.0 elements (connectivity between the different strategic suppliers and the mother company), the responsiveness and agility of the manufacturing facility will increase due to the real-time data acquisition between the different manufacturing companies, which can be used effectively in production planning and scheduling. Hence, the increased responsiveness and efficient planning outweigh the slight increase in profit (0.094%) of model 2 compared to model 1.

This mathematical model results comply with the actual practical implementation for the production periods t=1 and t=2 (each production period is 6 months). The firm started interconnecting with its strategic suppliers to unify the ERP software used during the first period. Jobs 6, 8, 9 and 10 were accepted in production period 1. In addition, jobs 4, 6, 9 and 10 were accepted in production period 2. In the actual implementation, workcentre 1050 started with $60/hour in production period 1 (same result as the mathematical model as shown in Fig. 35) and increased to $175/hour (around $180 in the mathematical model as shown Fig. 35).

6.5. Conclusion

Industry 4.0 continues to pave the path towards a new manufacturing era, where major changes will occur on how conventional planning and activities are executed in manufacturing companies, such as production planning and cost accounting. This part of the dissertation focuses on these efforts in which a mathematical model for products and job costing is proposed, and a cost-benefit analysis on the feasibility of integration and connection between companies and their suppliers since integration and connectivity are critical issues in industry 4.0. The significance of the output from the model can be attributed to (1) providing a practical costing model which takes into consideration the bi-directional relationship between hourly rates and the total hours assigned to workcentres in each production period and (2) the cost-benefits of introducing industry 4.0 elements in terms of the building of infrastructure to connect manufacturing companies with its strategic suppliers. Though the results show that an additional 0.094% is required to implement Industry 4.0 connectivity. The implementation of the model reduced hourly rates for workcentres by up to 12% as a result of accepting more jobs (and accordingly, machining hours) on the available workcentres, and hence, reducing the hourly rates. This implementation has helped the company gain a competitive advantage among rivals since pricing of products submitted to customer was reduced.

Nevertheless, the benefits of establishing infrastructure to inter-connect manufacturing companies with its strategic suppliers outweigh this additional investment as companies are more agile and responsive to uncertainties. This proposed mathematical model provides manufacturing companies with high responsiveness to uncertain events such as economic crisis, power outage, natural disasters (such as Tsunami, earthquakes, volcanic eruptions) and pandemic spread (e.g. COVID-19). For example, in the case of the current pandemic spread, many suppliers in several countries were suffering from lockdown, which affected the supply chain. However, by establishing an infrastructure to connect strategic suppliers with the leading manufacturing company, the resources and capacity availability are no longer confined or restricted in specific locations. Hence, customer demands can be satisfied with ease.

CHAPTER 7 Model Verification and Validation

7. Overview

This chapter deals with the verification and validation of the mathematical models discussed in this dissertation. This is accomplished by validating and verifying the initial model that was discussed in chapter 3. The rest of the models would be considered verified as they are considered an extension or unique need/application of the model in Chapter 3. Verification of the other models will follow the same procedure herein.

The verification section is concerned with applying the model in chapter 3 to solve a small example, which is easy to grasp in order to make sure that the mathematical model developed provides the expected results that can be calculated easily and make sense. The validation section is concerned with solving the mathematical model twice; the first solution is focused on (1) taking the bi-directional relationship between hourly rates and the annual hours for each workcentre into consideration, (2) distributing the overhead and general assets on each workcentre/department as a percentage of the hours assigned to each workcentre/department and (3) considering the ABC method. The second solution is concerned with (1) ignoring the bi-directional relationship between hourly rates and annual hours for each workcentre/department, (2) assigning overhead and general assets evenly among all workcentres/departments and (3) considering the traditional costing method. The validation model's purpose is to validate the superiority of the proposed model (solution 1) in providing a lower cost than the second solution, which will be evident while comparing the optimal solution of the objective function.

7.1. Verification

This section aims to verify the mathematical model introduced in chapter 3. A hypothetical case study with a few input parameters will be used for this purpose. The inputs to the case study are shown in Table 52 to Table 58. The solution for the mathematical model for the verification purpose is shown in Table 59 to Table 61.

Table 52. Engineering hours required by departments 1 and 2 to design products 1 and 2

Job	Dept. 1	Dept.2
1	200	300
2	100	400

Table 53. Processing (setup) hours for products 1 and 2 on workcentres 1, 2 and 3

	Workcentres		
Job	1	2	3
1	200 (1)	300 (1)	400 (1)
2	500 (1)	600 (1)	700 (1)

Table 54. Planned quantities for products 1 and 2 in production periods 1, 2 and 3

	Production Periods		
Job	1	2	3
1	1	1	1
2	1	1	1

Table 55. Raw material/commercial items cost for products 1 and 2 in production periods 1, 2 and 3

	production periods		
Job	1	2	3
1	$ 10,000.00	$ 20,000.00	$ 15,000.00
2	$ 10,000.00	$ 20,000.00	$ 15,000.00

The selling price for product 1 and product 2 are $50,000 and $75,000, respectively. The yearly depreciation cost for workcentres 1, 2 and 3 is $10,000, $20,000 and $30,000, respectively. The equipment depreciation is considered zero for the engineering departments since there is no major equipment other than the processing unit and computers.

Table 56. Workcentres capacity (in hours) in the different production periods

	Workcentres		
Production Periods	1	2	3
1	1500	2000	3000
2	1000	2000	3000
3	2000	4000	6000

Table 57. Engineering departments capacity (in hours) in the different production periods

	Production Periods		
Department	1	2	3
1	500	500	500
2	500	500	500

Table 58 General assets allocation to each workcentre and engineering departments in the different production periods

		Production periods		
		1	2	3
Workcentres	1	$ 15,000	$ 20,000	$ 25,000
	2	$ 30,000	$ 20,000	$ 35,000
	3	$ 10,000	$ 20,000	$ 25,000
Engineering departments	1	$ 20,000	$ 20,000	$ 20,000
	2	$ 25,000	$ 25,000	$ 25,000

The solution of the mathematical model is shown in Table 59, Table 60 and Table 61. The accepted jobs in the different production periods (jobs mix decision) are shown in Table 59. Job 1 is chosen in production periods 2 and 3, while job 2 is chosen in production period 1. The value of the objective function is $320,565.

Table 59. Accepted jobs in each production period

	Production Periods		
Job	1	2	3
1	0	1	1
2	1	0	0

The hourly rates for the engineering departments and workcentres are shown in Table 60 and Table 61. The hourly rate for engineering departments is $60/hr. in production period 1 while the hourly rates for workcentres 1, 2 and 3 are $62/hr, $62/hr and $65/hr, respectively, in production period 1. The blended cost (Equation (1)) for engineering departments and workcentres is assumed as $60/hr.

Table 60. Hourly rate ($) for engineering departments 1 and 2 in the different production periods

		Production Period		
		1	2	3
Engineering departments	1	60	260	160
	2	60	122.5	143.33

Table 61 Hourly rate ($) for workcentres 1, 2 and 3 in the different production periods

		Production Period		
		1	2	3
Workcentre	1	62	110	210
	2	62	143.33	193.33
	3	65	117.143	185

For example, the hourly rate of workcentre 3 in production period 3 is $185/hr., which is calculated as per Equation (1) in which $General\_asset_{ABC}$=$20,000 for workcentre 3 in production period 2, *Depreciation/yr* =$30,000 for workcentre 3, the *total hours by machine/activity*= 400 for workcentre 3 in production 2 and the *blended cost*=$60 which complies with the result shown in Table 61. The rest of the results in Table 60 and Table 61 can be verified similarly by applying Equation (1).

7.2. Validation from a case study of a wood press machine builder

This section aims to validate the mathematical model derived in chapter 3 with existing models in the literature. For this purpose, the mathematical model (which is the ABC costing model), together with the case study in chapter 3, will be compared with a traditional costing model. The traditional costing model is similar to an extent to the ABC costing model with a few adjustments:

- ignoring the bi-directional relationship between hourly rates and annual hours for each workcentre/department,
- assigning overhead and general assets evenly among all workcentres/departments and
- taking traditional costing method into account.

For the traditional method, the hourly rate in a specific period for a particular workcentre or engineering activity is calculated through:

$$Hourly\ rate\ for\ certain\ machine/activity\_TRAD = \begin{matrix} Blended \\ cost \end{matrix} + \frac{General\ assets_{TRAD} + Depreciation/yr}{total\ hours\ by\ machine/activity} \quad (107)$$

The primary difference between Equation (1) and Equation (107) is the method of allocating of general assets term. For the ABC method, the general asset term ($General\_asset_{ABC}$) in Equation (1) is calculated as the total general assets within a specific year multiplied by the ratio of hours spent by the machine/activity to the total hours spent by all machines/activities. As for the traditional method, the general asset term ($General\_asset_{TRAD}$) is allocated equally among machines/activities. Equation (107) will be applied as a constraint to the traditional costing model, which will replace Equation (18) and Equation (19). Otherwise, the rest of the mathematical model elements (i.e. decision variables, objective function and constraints) will be the same as the mathematical model in this chapter used for validation.

The same case study used in Chapter 3 will be used for the validation. The mathematical model in Chapter 3 will be solved twice; once using the traditional costing method, and the other using the ABC method. The general assets allocation for ABC costing and the Traditional costing method is provided in Table 62 as an input to the mathematical model. For the rest of the inputs, the reader can refer to Chapter 3.

Table 62. General assets allocation for ABC and Traditional costing models

		$c_o^{GA\_WC}$ (ABC)	$c_o^{GA\_WC}$ (Trad)
Workcentre	1010	$ 20,141.36	$ 30,106.58
	1020	$ 59,057.32	$ 30,106.58
	1030	$ 59,057.32	$ 30,106.58
	1040	$ 14,061.27	$ 30,106.58
	1050	$ 15,186.17	$ 30,106.58
	1060	$ 14,061.27	$ 30,106.58
	1070	$ 8,436.76	$ 30,106.58
	1080	$ 7,030.63	$ 30,106.58
	1090	$ 15,186.17	$ 30,106.58
	1100	$ 20,141.36	$ 30,106.58
	1110	$ 59,057.32	$ 30,106.58
	1120	$ 59,057.32	$ 30,106.58
	1130	$ 59,057.32	$ 30,106.58
	1140	$ 59,057.32	$ 30,106.58
	1150	$ 59,057.32	$ 30,106.58
	1160	$ 20,141.36	$ 30,106.58
	1170	$ 20,141.36	$ 30,106.58
	1180	$ 20,141.36	$ 30,106.58
Engineering	Dept. 1	$ 7,030.63	$ 30,106.58
	Dept. 2	$ 7,030.63	$ 30,106.58

The optimum objective function for Equation (17) is -$208,971,000 for the Traditional costing and -$208,960,000 for the ABC method. Fig. 37 and Fig. 38 show the difference in hourly rates for each workcentre and the corresponding production periods. It is evident that eleven out of the eighteen workcentres operate at less cost in the ABC model case than the traditional model. This leads to a competitive advantage for the manufacturing firm by reducing its operating costs, providing competitive quotes to customers and achieving a cost leading strategy. Furthermore, Fig. 39 shows the Mechanical and Electrical Departments' hourly rates when solved with the ABC method and the traditional cost methods. For example, in period 3, the Mechanical and Electrical Engineering hourly rates are $61.7/hr and $61.9/hr for the ABC method compared to $67.3/hr and $68.3/hr for the traditional costing method. Hence, the company will achieve a competitive edge in receiving more jobs due to the competitive hourly rates, which will be reflected in their quotes to customers.

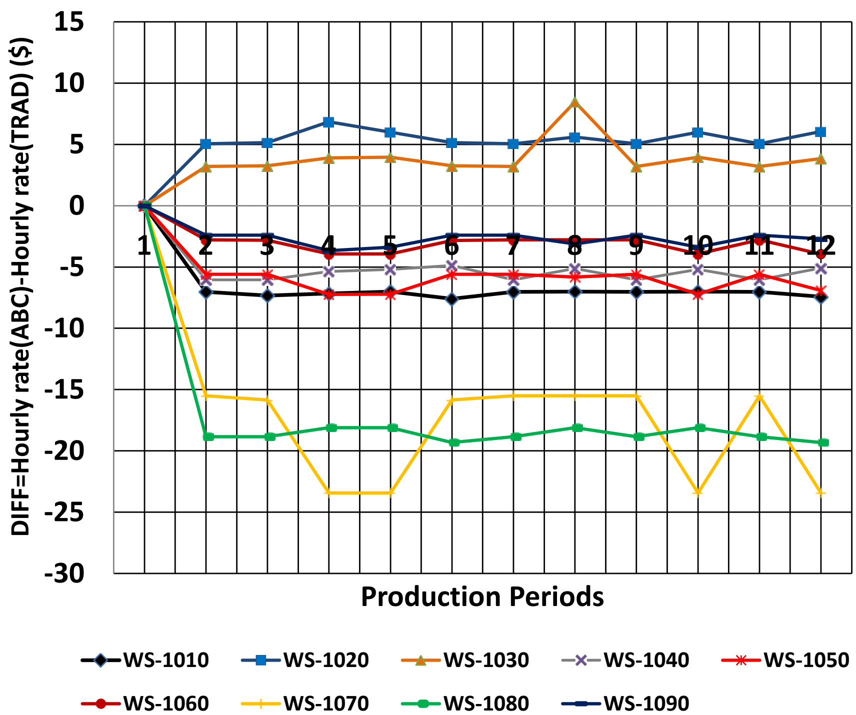

Fig. 37.Difference in hourly rates ($) between ABC and Traditional method of workcentres WS-1010 to WS-1090

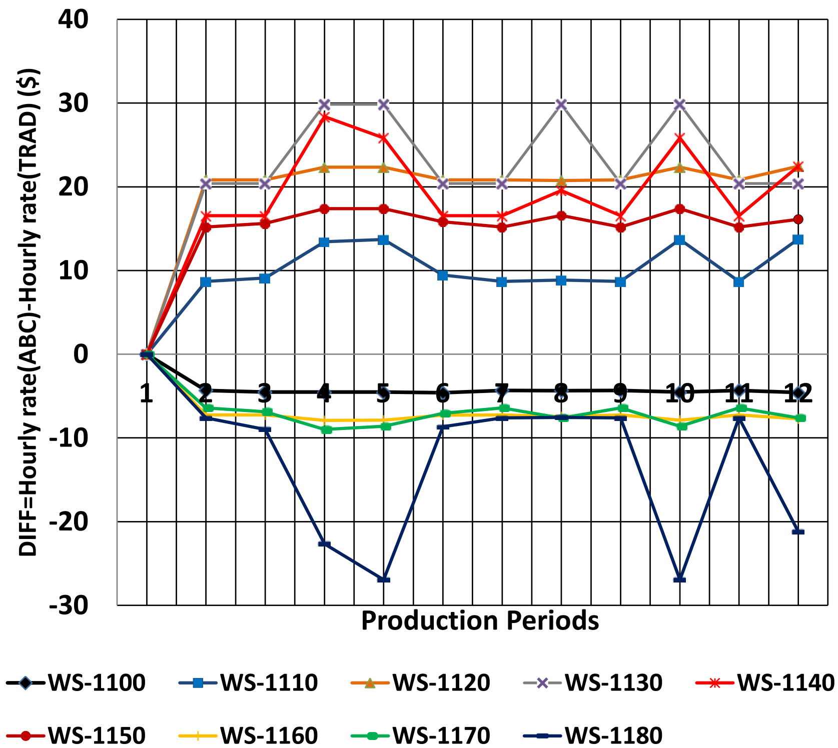

Fig. 38. Difference in hourly rates ($) between ABC and Traditional method of workcentres WC-1100 to WC-1180

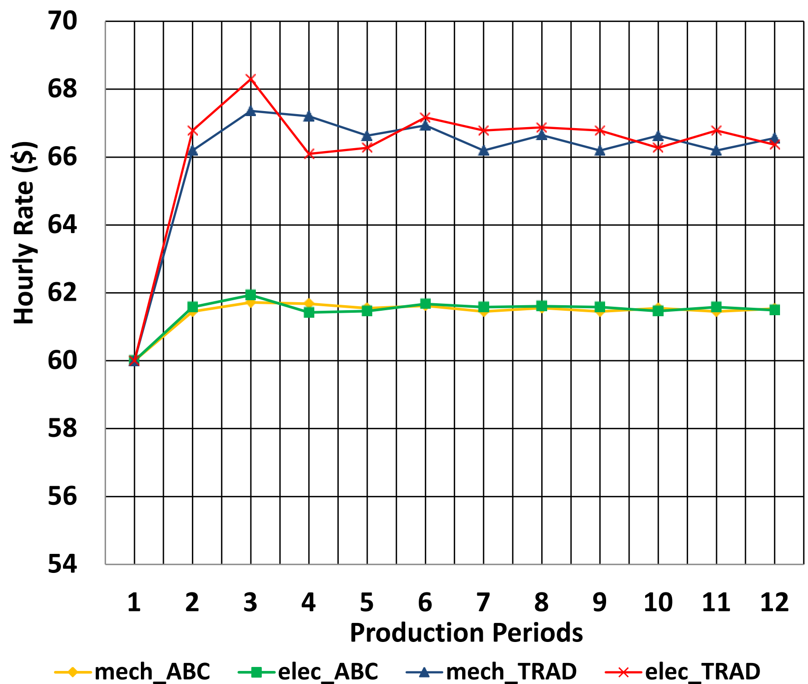

Fig. 39. Proposed hourly rates ($) for Mechanical and Electrical Department for ABC and Traditional method

The mathematical model results was very similar results to the actual practical implementation for the production periods t=1, t=2 and t=3 (each production period is three months). The company started applying the model from that point forward. The results of this section are similar to the real-life implementation of this particular problem. The only difference is job number 8 in production periods 1 and 2. The proposed model rejected this job in production periods 1 and 2. However, these jobs were accepted afterwards. Job 8 belongs to a returning customer, and hence, refusing it is not an option for the company as that might lead the customer to go to a different company for future projects and jobs. This job can be indirectly enforced to the mathematical in the form of constraint (i.e. $x_{8,1}$=1 and $x_{8,2}$=1).

7.3. Validation from a case study of an automation solutions provider company

The purpose of this subsection is to introduce a case study from a local automation solutions provider company, apply the suggested formulation in chapter 3 and compare the results from the models with the actual scenario in an attempt to validate the proposed model. The facility layout is shown in Fig. 40. The shop floor comprises shipping/receiving locations, machining department, a purchasing/crib area and an assembly area (office and design department is not shown). The assembly area is organized as a fixed position layout in which the assembly team and resources are moved about the project’s location, as needed (Nahmias & Olsen, 2015). The company’s primary revenue stream is to provide automation machinery to Original Equipment Manufacturers (OEMs) and Tier 1 suppliers with the automotive industry.

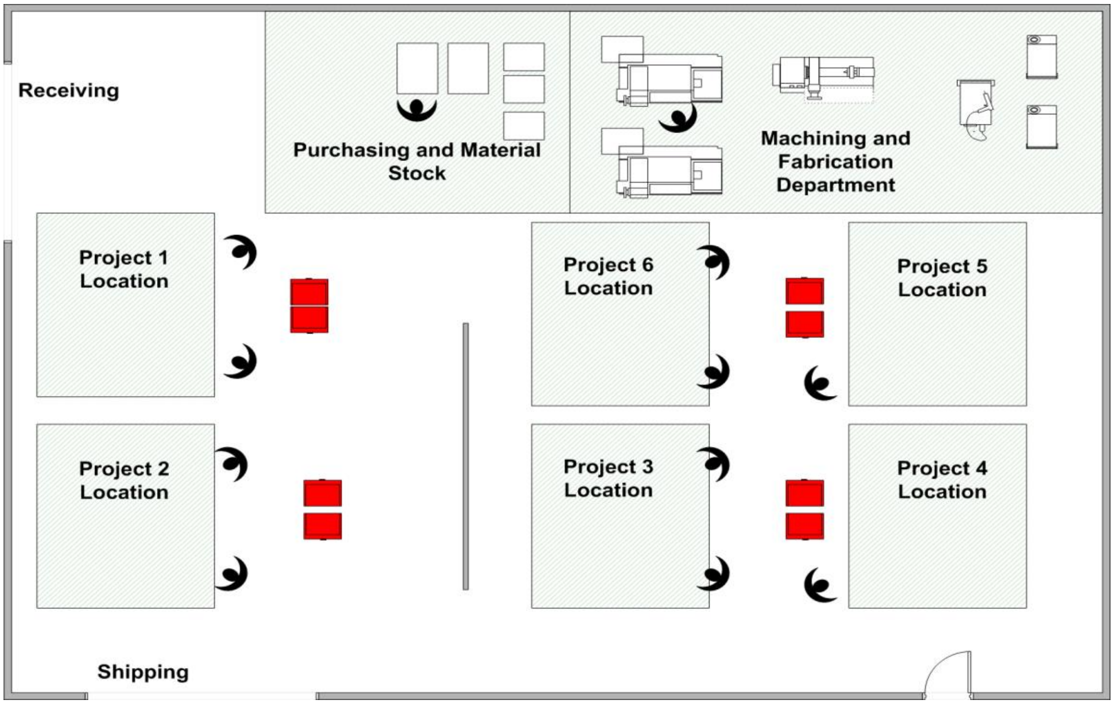

Fig. 40. Plan for the facility with fixed position layout

The inputs to the case study are shown in Table 63 to Table 69. These data are taken from company's records. These inputs are fed to the mathematical model outlined in chapter 3. The mathematical model is written in AMPL (http://ampl.com) and solved using NEOS (Czyzyk et al., 1998; Dolan, 2001; Gropp & Moré, 1997). The job number is 8683696.

Table 63. Quoted/required hours for each workcentre on each job (in hours)

		Workcentres $g_{i,o}$					
		WS-10	WS-20	WS-30	WS-40	WS-50	WS-60
Jobs	1	85	149	0	177.5	370	74
	2	100	170	40	150	400	100
	3	500	1,000	1,000	1,000	300	205
	4	250	500	500	500	150	100
	5	450	850	750	770	500	250
	6	225	400	300	250	250	100
	7	100	150	0	150	200	75
	8	50	100	200	45	100	80
	9	100	75	50	0	0	0
	10	50	100	75	0	0	0

Table 64. Quoted/required hours for each engineering department on each job (in hours)

		Engineering dept. $h_{i,j}$	
		1	2
jobs	1	372	381
	2	380	350
	3	3,400	1,700
	4	1,700	850
	5	1,000	1,200
	6	500	600
	7	300	350
	8	310	357
	9	0	0
	10	0	0

Table 65. Capacity of workcentres in the different production periods (in hours)

		Workcentres					
		WC-10	WC-20	WC-30	WC-40	WC-50	WC-60
Production period	1	3,200	1,600	800	5,000	2,500	2,000
	2	3,200	1,600	800	5,000	2,500	2,000
	3	3,200	1,600	800	6,000	2,500	2,000
	4	3,200	1,600	800	6,000	2,500	2,000

Table 66. Capacity of engineering departments in the different production periods (in hours)

		Engineering depts.	
		1	2
Production periods	1	3,840	3,840
	2	3,840	3,840
	3	3,840	3,840
	4	3,840	3,840

Table 67. List of available jobs in the different production periods and their quantities

		Production periods			
		1	2	3	4
Job	1	1	1	1	1
	2	1	1	1	1
	3	1	1	1	1
	4	1	1	1	1
	5	1	1	1	1
	6	1	1	1	1
	7	1	1	1	1
	8	1	1	1	1
	9	1	1	1	1
	10	1	1	1	1

Table 68. List of assets and depreciation allocated to each workcentre

		General assets allocated to each workcentre in each production period ($)	Workcentre Depreciation in each production period ($)
Workcentres	1	15,000	29,000
	2	15,000	29,000
	3	15,000	29,000
	4	10,000	2,700
	5	10,000	2,700
	6	10,000	2,700

The mathematical model's outputs are shown in Table 70, Fig. 41 and Fig. 42. The job mix decision is listed in Table 70. The job mix decision is chosen based on the following factors:

- The capacity available within the different workcentres and engineering department: the mathematical model will choose the jobs without violating the capacity constraints
- Minimizing the objective function: the objective function in the mathematical model is to minimize the difference between cost and revenue (i.e. maximize profit). Hence, the job mix decision is chosen such that the highest profit can be achieved.

Table 69. Cost of raw material/commercial items in the different production periods ($) and Selling price of job i in the different production periods ($)

		cost of raw material/commercial items in the different production periods ($)				Selling price of job i in the different production periods ($)			
		1	2	3	4	1	2	3	4
available jobs	1	$ 81,304	$ 81,304	$ 81,304	$ 81,304	$ 450,000	$ 450,000	$ 450,000	$ 450,000
	2	$ 75,000	$ 75,000	$ 75,000	$ 75,000	$ 400,000	$ 400,000	$ 400,000	$ 400,000
	3	$ 250,000	$ 250,000	$ 250,000	$ 250,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
	4	$ 125,000	$ 125,000	$ 125,000	$ 125,000	$ 2,000,000	$ 2,000,000	$ 2,000,000	$ 2,000,000
	5	$ 600,000	$ 600,000	$ 600,000	$ 600,000	$ 3,000,000	$ 3,000,000	$ 3,000,000	$ 3,000,000
	6	$ 300,000	$ 300,000	$ 300,000	$ 300,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000
	7	$ 150,000	$ 150,000	$ 150,000	$ 150,000	$ 600,000	$ 600,000	$ 600,000	$ 600,000
	8	$ 175,000	$ 175,000	$ 175,000	$ 175,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000
	9	$ 3,000	$ 3,000	$ 3,000	$ 3,000	$ 40,000	$ 40,000	$ 40,000	$ 40,000
	10	$ 5,000	$ 5,000	$ 5,000	$ 5,000	$ 50,000	$ 50,000	$ 50,000	$ 50,000

Table 70. Jobs decision mix in the different production periods

		Production periods			
		1	2	3	4
available jobs	1	1	1	1	1
	2	1	0	0	0
	3	0	0	0	0
	4	1	0	0	0
	5	0	1	1	1
	6	0	0	0	0
	7	1	1	1	1
	8	1	0	0	0
	9	0	0	0	0
	10	0	0	0	0

Fig. 41 and Fig. 42 show the hourly rate adjustments based on the bi-directional relationship between hourly rates and hours assigned to departments/workcentres in a particular production period, per Equation (1) for workcentres available and engineering departments, respectively. It is evident that workcentres WC-10, WC-20 and WC-40 hourly rates are reduced in production period 3. This is due to the increased number of hours assigned to these workcentres in production period 2 (total hours assigned to workcentres WC-10, WC-20 and WC-40 in production period two are 635 & 1,149 and 1,097.5 compared to 585 & 1,069 and 1, 022.5 in production period 1, respectively). This increase in the hours in production period 2 for workcentres WC-10, WC-20 and WC-40 is responsible for decreasing in hourly rates in production period 3.

The mathematical model results were almost identical to the actual results of the practical implementation for the production periods t=1 and t=2 (each production period is six months). The only difference is job number 4 in production periods 1, and job number 5 in production period 2. The model accepted Job 4 in Period 1, although the actual implementation chose Job 5 in Period 1. In addition, the model accepted Job 5 in Period 2, but the company canceled this job, since the customer announced their plant closure.

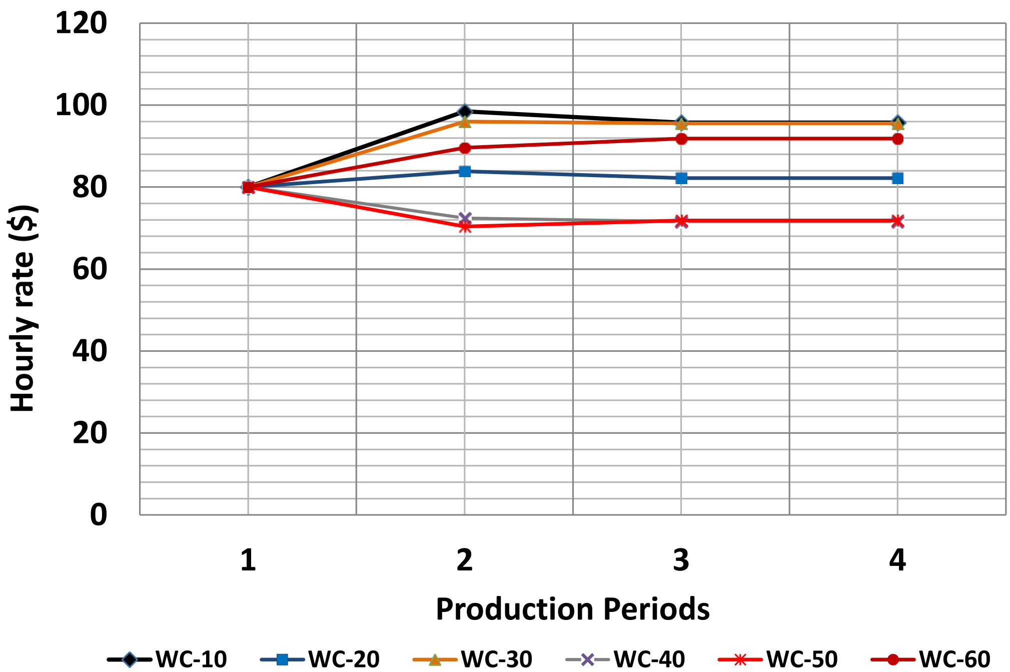

Fig. 41.Proposed hourly rates ($) for the different workcentres in the automation provider case study

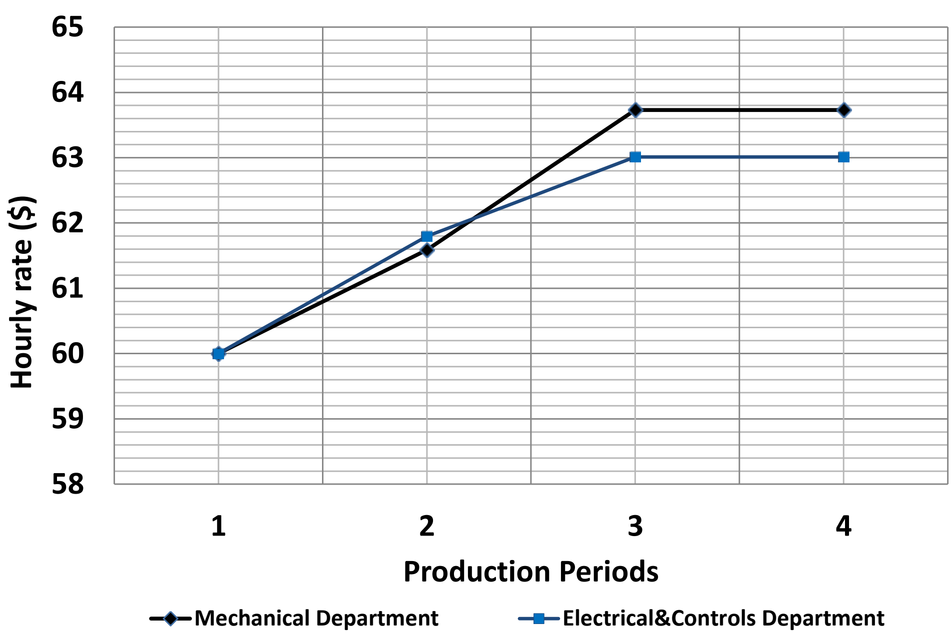

Fig. 42.Proposed hourly rates ($) for Electrical & Controls department for the automation provider case study

CHAPTER 8 Discussion and Conclusion

8. Discussion

This chapter provides the novelty and contribution achieved in this research as well as the industrial significance. Additionally, the research progress will be is presented. Finally, the limitations of the proposed model will be presented, as well as the final conclusions.

8.1. Novelty and Contribution

A new major novel costing model has been proposed in this research, in addition to three extensions to the mathematical model, to fill research gaps in manufacturing system synthesis and costing. The proposed model has been applied to a case study from machine builder concerned with manufacturing of presses for wooden panels. The machine shop receives order from customers in US and Europe. Based on machining capabilities and available capacity, the company makes a decision in regards to accepting or rejecting certain orders. On the other side, the customer decides on sending an order to the company based on pricing. As a result, proposed model enables the company to achieve a competitive advantage among its rivals by reduction of hourly rates reaching up to 25% reduction. Facility expansion was also one of the factors considered in the dissertation since exceeding the footprint of the facility permits adding additional workcentres, which increase the facility’s capacity, allowing more jobs to be accepted and hence reducing hourly rates.

The major contributions to this research are as follows:

- Four new mathematical models have been developed for cost minimization, taking into account the interrelationship between the annual activity hours (e.g. machining, engineering…etc.) and hourly rate. The main cost model incorporated Activity-Based Costing (ABC) method in which product, batch and production levels are taken into consideration. This model focused on a job-shop environment. This mathematical model is beneficial for existing manufacturing firms.

- Another mathematical model extension was developed for cost minimization at strategic, tactical and operational levels, taking into account the same model developed above (in Chapter 3). The cost model incorporated the Activity Based Costing (ABC) method in which product, batch and production levels were all considered. Furthermore, as an extension from the first model, the cost for reconfiguration was also taken considered on a machine-level (i.e. changing functional modules) and system-level (adding/removing machines). In this topic, the cost of reconfiguration is offset by the additional added hours in terms of capacity and capability, reducing the hourly rates. This topic can be applied to existing and new manufacturing firms.
- Another new mathematical model extension was developed based on the original model, incorporating the manufacturing firm building's facility expansion decision to add extra workcentres.
- Finally, another new mathematical model extension was developed for the cost-benefit analysis of introducing Industry 4.0 elements to any manufacturing facility, specifically adding external suppliers as strategic partners and establishing an infrastructure for communicating information between the manufacturing firm and its strategic suppliers.

8.2. Applications and Limitations

This dissertation's proposes mathematical models that can be applied to different production system types such as job-shop, mass production, flexible and reconfigurable manufacturing systems, and various kinds of industries such as machining and assembly. The mathematical models can also provide the decision-makers with investment decisions such as building expansion, as it allows for sharing the information database between different companies (i.e. Industry 4.0 aspect). Furthermore, this dissertation's mathematical models can assist manufacturing firms in operational, tactical and strategic planning, which is reflected in the run time and frequency in executing the model. Given the cases used in this dissertation, the model run times ranged from 30 minutes to 4 hours. Since the results of the model take some time to process and are not available immediately (live), the run time and frequency of the proposed models in this dissertation can be illustrated as follows:

- Operational decisions:
  - Scheduling/operational: this is a short term run is done that is done 3-5 times per month for the purposes of operations scheduling, the decision on the job mix and capacity/human resources planning.
  - Sales tool: the model can be run with a period defined as a week, or month, depending on the size of the quoted job, when needing to decide on which jobs to take from available customers. To make a decision if the job can be accepted, and what affects it has on profitability of the firm. The frequency of running the model would be on as-needed basis.
- Tactical decisions/medium term (once per year): the long term run is done for the purpose of costing. Besides, long term run can also be employed for strategic planning on the jobs to accept or refuse on an extended time horizon (a year or more)
- Strategic decisions/ long term (Every 2 or 3 years) – would be used the same as Tactical with using each period as one year, with running what-if scenarios to help the top leadership of the company to make more informed decisions about the future.

The mathematical model has a few limitations. These limitations are:

- It does not consider customer relationships and jobs to be denied. A job from a returning customer should always be accepted. This limitation can be indirectly addressed in this dissertation. The constraints on the jobs to be taken/refused will be inserted manually in the mathematical model as additional constraints.

- The decision on job mix (accepting or rejecting a specific job) is based on the optimum financial level rather than the operations level. In other words, the model does not consider accepting or rejecting a job based on the job shop schedule or job priority.
- Computational time and complexity can be considered a limitation when applying the mathematical model on large problems with hundreds of different products and over an extended period of time (i.e. years). In order to overcome such a limitation, it is suggested to develop a meta-heuristic approach (though optimal results might not be guaranteed).

8.3. Significance

The significance of this research is not restricted to cost analysis, but also to provide managers in manufacturing facilities with the required decision-making tools to decide on orders to accept, or refuse, and invest in additional production equipment, facility expansion, and Industry 4.0. Also, this research will help manufacturing companies achieve a competitive edge among rivals by reducing hourly rates within their facility. Additional benefits and significance are (1) providing manufacturing companies with a method to quantify the decision-making process for right-sizing their manufacturing space, (2) the ability to justify growing a scalable system (machine level, system-level and factory level) using costing (not customer demand) (3) expanding market share and (4) reducing operational cost and allowing companies a numerical method to justify scaling the manufacturing system. As reported in the thesis hypothesis in chapter 1, companies can achieve a competitive advantage among its rivals through hourly rates reduction by using the developed cost models, and hence, projects, products and jobs can be delivered to customers at a reduced cost. A reduction in hourly rates up to 25% is achieved.

Furthermore, the proposed mathematical models can account for dynamic pricing. In perishable products, dynamic pricing is defined as the change in price implemented by companies producing perishable products (mainly reducing the selling price) when certain products approach the expiry date. This practice is commonly used in the Industry of perishable products to increase revenue and reduce waste (Herbon & Khmelnitsky, 2017). In this thesis's context, the dynamic pricing reflects a premium price for expedited delivery and the regular price for standard delivery. This in turn will change the initial assumption of changing the selling price. However, in most cases the costs acquired by the manufacturing firm to achieve an expedited delivery are reflected in:

- Overtime shifts which will be reflected in the hourly rates
- Increase in the raw material cost as raw materials from suppliers needs to be also expedited by the suppliers
- An increase in commercial items costs, as commercial items from distributors must be expedited by the distributors to meet the new deadline.

8.4. Future Work

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

1- Discrete event simulation and dynamic system analysis: Carrying out simulations to further validate the results from the mathematical models.

2- Supervised machine learning for cost estimation: Supervised machine learning can be used to calculate the cost based on specific inputs (i.e. jobs available, due dates of projects, available departments/workcentres…etc.)

3- Practical implementation: installation of RFID tags and Wireless Sensor Networks within a manufacturing facility and automatically tracking the hours and flow of materials to reduce user's input prone to errors.

4- Now that the proposed models have been verified and validated, the heavy lifting has been completed. One of the limitations of these models remains to be the number of manual steps required to complete the model inputs before running and getting some right and verified decisions. The next steps would be to integrate these models into one, or some, of the currently existing manufacturing software packages being used in the Industry. There are several manufacturing software packages currently existing that can manage inventory, Material Requirement Planning and releases, Enterprise Resource Planning, Supply Chain Management, and Finance, among many other modules used in each of the software packages. Some of the most popular software packages are Sage, Oracle NetSuite, Epicor, Plex, and SAP. Some of these packages are designed to fit Small businesses, Medium, or Large enterprises. The mathematical model developed in this dissertation can be integrated as a module in any/all of these software packages. The integration time and effort needed are dependent on each software package. The software developer would have to complete permission and assistance, as this software is not open code.

8.5. Conclusion

This research proposal introduces mathematical optimization models based on the Activity-Based Costing (ABC) method, which considers the bi-directional relationship between hourly rates and annual hours on each machine/workcentre. Several constraints were considered in the development process of these models, such as cost of reconfiguration (machine and system level in terms of adding functional modules to existing workcentres and adding new workcentres, respectively), capacity, in terms of available machining hours, a decision on facility expansion and a cost-benefit analysis on Industry 4.0 implementation.

The implementation of the model introduced in Chapter 3 reduced hourly rates for workcentres (in the Industrial Case Study) by up to 25% as a result of accepting more jobs (and accordingly, machining hours) on the available workcentres, and hence, reducing the hourly rates.

The implementation of the model reduced hourly rates (in the Industrial Case Study) for workcentres by around to 23% as a result of accepting more jobs (and accordingly, machining hours) on the available workcentres, and hence, reducing the hourly rates.

Finally, though the results show that an additional 0.094% investment was required to implement Industry 4.0 connectivity. The implementation of the model reduced hourly rates for workcentres by up to 12% as a result of accepting more jobs (and accordingly, machining hours) on the available workcentres, and hence, reducing the hourly rates.

Hence, the significance of this research per the thesis hypothesis in this dissertation is:

> *"Manufacturing firms are capable of achieving competitive advantage through accepting specific jobs from customers through reducing hourly rates and investing in additional equipment and applying industry 4.0."*

The results of the mathematical models that were created and comparing the results of these models to actual real-life situations, confirmed that accepting jobs, within limited boundaries, does indeed lower direct labour costs by spreading the fixed overhead costs over more project and a higher number of direct labour hours. With linking these new jobs ends up lowering direct labour costs, which in turn, gives any manufacturing company a competitive advantage over their competitors.

Important conclusions, and observations, derived from this research can be summarized as:

- Manufacturing firms should always strive to accept as many jobs as possible from customers. The reason for that is two-fold. On the one hand, accepting more jobs increases the revenue for the manufacturing firm. On the other hand, due to the bi-directional relationship between annual hours and hourly rates, accepting more jobs increases the yearly (or production period) hours on workcentres/departments. Hence, the hourly rates are reduced. Therefore, manufacturing firms can gain a competitive advantage among its rivals by providing competitive pricing for jobs when submitting quotes back to customers. A reduction in hourly rates up to 25% is achieved when applying the model on case study in chapter 3.
- For reconfiguration decisions (machine, system or factory levels), the manufacturing firm's management or decision-makers should always consider adding/removing additional functional modules to existing workcentres, add/shut down new workcentres and expand building footprint for extra equipment if and only if the added resources will result in increased capacity of the manufacturing facility and hence accepting more jobs which results in increasing revenue and reducing hourly rates. In the model in chapter 4, the jobs with the largest amount of hours were selected in each production period and accordingly, the hourly rates on workcentres were reduced by as much as 23%.
- Though part of this research proposal's extension, a cost-benefit analysis for industry 4.0 implementation is under development. It is evident that investing in industry 4.0 is feasible in increasing revenue (since their internal capacity does not restrict manufacturing firms) and responsiveness due to the interconnectivity with its strategic suppliers (spending on industry 4.0 accounts for only an additional 0.094% of the total revenue and a 12% reduction in hourly rates as per the model results shown in chapter 6).
- The proposed models have proven to be capable, and the results of these models were applied in two different companies in the industry and gave very close results to those that were implemented.

- In chapter 7, the model has been verified and compared with the traditional costing method. The hourly rates in the proposed model showed improvements compared to the traditional costing method by more than $20/hour reduction in hourly rates.

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APPENDIX

GLOSSARY

- *Activity-based costing (ABC):* starts by defining the different activities involved in the production (e.g. setup, machining….etc.), compute the cost for each activity and then allocate each activity to its corresponding product. This type of system works well for companies producing a broad scope of product variants. The ABC method's main drawback is its complexity in identifying the various activities, which is time-consuming and requires high data processing costs.
- *Analogical cost estimation techniques:* is a type of product cost estimation based on similar products
- *Analytical cost estimation techniques:* is a type of cost estimation based on estimating the cost of the product by calculating the total manufacturing cost incurred in each production step of the work.
- *Batch costing:* is a form of job costing. Instead of costing each component separately, each batch of parts is taken together and treated as a job.
- *Blended cost:* it is the weighted average direct cost for a particular workcentre or activity such as engineering
- *Cellular manufacturing systems:* are based on grouping of part families similar in shape, material and manufacturing process and assign them to a group of machines known as cells. A key enabler of cellular manufacturing is group technology.
- *Cloud computing:* is a distributed system which consists of connected and virtual computers being employed on service level between the service provider and customer
- Common practice

- *Convertibility:* quick change-over between variants within a product family and adaptability for future products requirements
- *Cost accounting:* is the process of calculating the cost or price of a product after the product is manufactured
- *Cost estimation:* is the process of calculating the cost or price of a product before the product is manufactured
- *Cost object:* it refers to an entity in which managers and decision-makers want to know how much it costs. These entities can be product, service, project, customer, brand category, activity, department or programme
- *Cyber physical systems (CPS):* the technologies and systems used to manage the interconnected systems between the physical component and the computational resources. In a different context, CPS is defined as the intersection between the cyber and physical domains.
- *Dedicated manufacturing lines (DML) or transfer lines:* are based on affordable fixed automation and produce a company's core products or parts at high volume. Each dedicated line is typically designed to make a single part (i.e., the line is rigid) at a high production rate achieved by the operation of several tools simultaneously in machining stations (called "gang drilling").
- *Detailed cost estimation:* type of manufacturing cost estimation in which the accuracy of estimation varies between +/-5% of the actual cost
- *Diagnosability:* quick identification of errors or malfunctions
- *Direct labour:* the compensate of labours that can be traced to cost objects
- *Direct material:* costs of all materials that become part of a cost object and can easily be traced to cost objects in a feasible way

- *Flexible manufacturing systems:* can produce various products, with changeable volume and mix, on the same system. It is characterized by general-purpose machinery.
- *Focused flexibility manufacturing systems:* it is a hybrid type of manufacturing system in which Flexible Manufacturing Systems (FMS) exist with Dedicated Manufacturing Lines, and hence, flexibility is introduced not only through the individual general purpose machines (e.g. CNC), but from the interaction between the two systems.
- *Generally accepted accounting principles (GAAP)*: Generally accepted accounting principles or GAAP is defined as the sets of rules and regulations that firms should follow while reporting financial information to third parties such as investors, banks and government agencies.
- *Generative approach for cost estimation:* The cost estimate is determined from scratch without considering any previously known cost records. According to Generally Accepted Accounting Practice (GAAP), all manufacturing costs (direct costs, direct material and overhead) must be allocated to the manufacturing firm unit output (e.g. job, product, project,…etc.)
- *Group technology:* is a concept that relies on grouping parts sharing similar design, material and manufacturing processes into part families.
- *Hybrid costing:* Combination of process, job and batch costing
- *Indirect manufacturing cost:* all manufacturing costs are part of a cost object but cannot be traced easily to individual cost objects. Indirect costs are composed of indirect material costs and indirect labour costs.
- *Industry 4.0:* the increase in value-creating networks through the increase of the Cyber-Physical Production Systems (CPPS), which permits machines and plants to adapt to the market (change in orders, demands…etc.) and operating conditions. In a different context, industry 4.0 is also defined as the embedded systems and machine to machine communication, Internet of Things (IoT) and Cyber-Physical Systems (CPS), which

integrate the physical and the cyber/virtual space. There are several characteristics of Industry 4.0:

  - Interoperability: connecting and communicating operators, CPS and CPPS among one another
  - Virtualization: maintaining a virtual copy of CPPS
  - Decentralization: CPPS are autonomous (i.e. decide on their own)
  - Real-Time Capability: The ability to extract real-time data for analysis

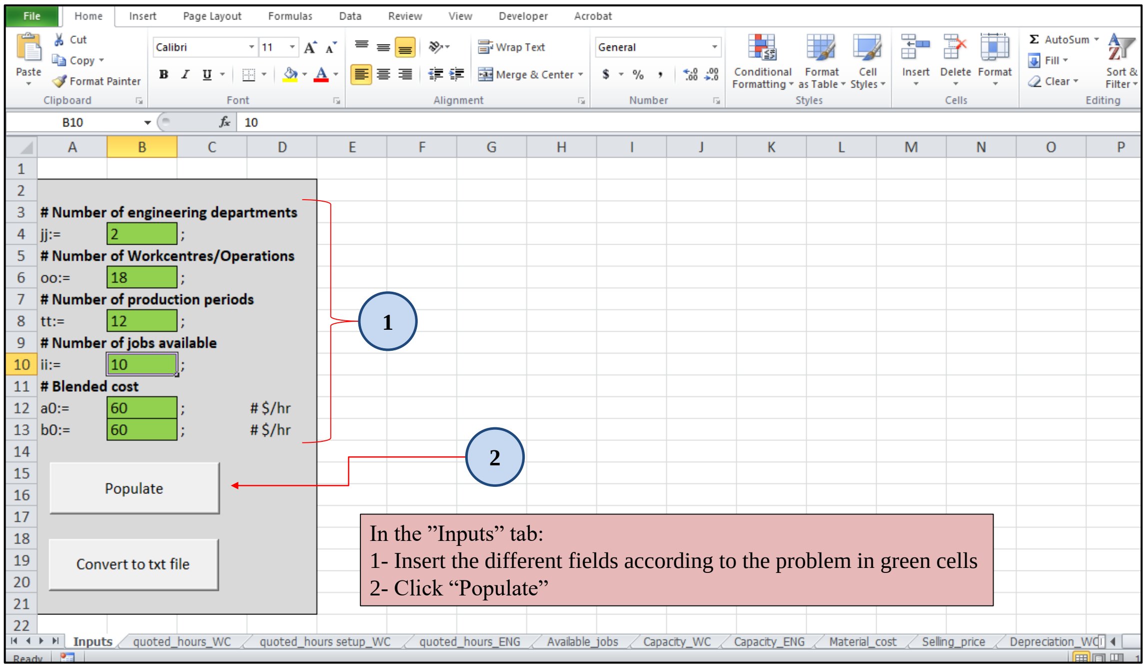
- Modularity: the ease of adding or removing system module in response to new requirements
- *Integrability:* ease of integrating system modules through hardware and software interfaces
- *Internet of things:* it is a means of communication in which the items/objects (machines, sensors, operators…etc.). are connected to the internet through wired or wireless network connections. These emerging technologies will contribute to the self-awareness of the manufacturing system in which human operators and machines can enhance. The main essential elements for enabling IoT are RFIDs and Wireless Sensor Network (WSN)
- *Intuitive cost estimation techniques:* is cost estimation based on judgement and experience.
- *Job costing:* Job costing is concerned with finding the cost of each job or contract.
- *Job shop:* Mainly consists of general-purpose machines (e.g. CNC) and often dedicated equipment to mainly suit low volume production with great variety. Naturally, there is no specific type of flow in job shops due to its nature as a make-to-order type of facility, which depends on the customer's orders (daily orders can vary from full-size presses to small-sized spare parts). This leads to complicated scheduling and material handling within the shop.

- *Lean accounting:* Type of accounting concerned with removing or eliminating waste within the accounting process
- *Modularity:* is a Reconfigurable Manufacturing System characteristic composed of modular system components to facilitate adjustment of the system capacity and capability (adding/removing system components)
- *Order of magnitude manufacturing cost estimation:* type of manufacturing cost estimation in which the accuracy of estimation varies between +/-50% of the actual cost
- *Overhead cost:* marketing, manufacturing (other than direct cost) and administration costs
- *Parametric cost estimation techniques:* cost estimation technique based on developing a mathematical model that relates the cost of a product to one or more parameters of the product such as length, diameter, weight…etc.
- *Preliminary cost e estimation:* type of manufacturing cost estimation in which the accuracy of analysis varies between +/-20% of the actual cost
- *Process costing:* type of cost accounting employed when a standard product is being made, which involves several distinct procedures performed in a definite sequence.
- *Reconfigurable manufacturing systems (RMS):* Type of system characterized by rapid adjustability of functionality and capacity to meet changing demand. RMS provides the ability and capabilities needed as needed
- *Scalability:* The ability to adjust the production capacity of a system through system reconfiguration with minimal cost in minimal time over a broad capacity range at given capacity increments
- *Time-series techniques* are cost estimation techniques that are described as a function of time.

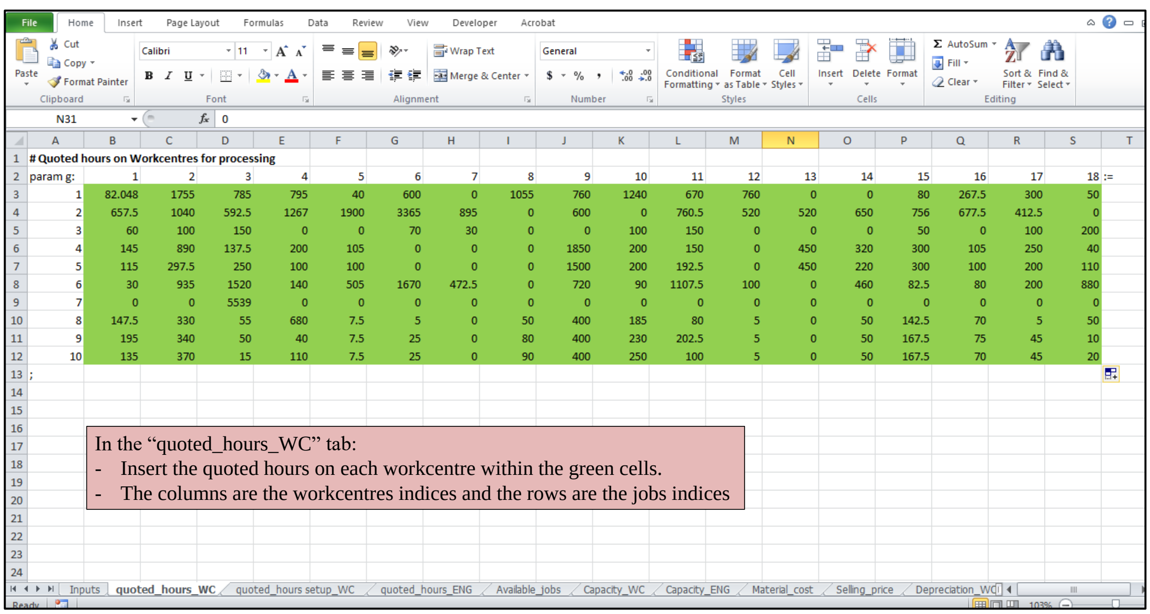
- *Traditional costing method:* Traditional costing system using direct labour, direct material, and overhead to determine the product's cost. Though simple to use yet, the traditional costing system does not correctly allocate the overhead costs to the different products (average allocation of overhead costs)
- *Throughput accounting:* includes direct materials and direct labour, which is used in Just-In-Time manufacturing environment. Throughput is defined as the difference between revenue and the total variable expenses. The main difference between traditional accounting and the throughput of accounting costing is the bottleneck operation or drum. The throughput accounting technique mandates optimizing the bottleneck operation only since any local optimization of non-bottleneck operations will result in buffer accumulation.
- *Variant approach for cost estimation:* which is a cost estimate based on the variation from a previously known cost records
- *Workcentre:* Machines or activities such as assembly within the shop floor belong to a cost center.

WORKING MANUAL

Step 1: Insert the number of parameters in the problem, as described in the Excel spread sheet.



Step 2: Insert the quoted hours on each workcentre for each available job



Quoted hours on Workcentres for processing

param g:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	:=
1	82.048	1755	785	795	40	600	0	1055	760	1240	670	760	0	0	80	267.5	300	50	
2	657.5	1040	592.5	1267	1900	3365	895	0	600	0	760.5	520	520	650	756	677.5	412.5	0	
3	60	100	150	0	0	70	30	0	0	100	150	0	0	0	50	0	100	200	
4	145	890	137.5	200	105	0	0	0	1850	200	150	0	450	320	300	105	250	40	
5	115	297.5	250	100	100	0	0	0	1500	200	192.5	0	450	220	300	100	200	110	
6	30	935	1520	140	505	1670	472.5	0	720	90	1107.5	100	0	460	82.5	80	200	880	
7	0	0	5539	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
8	147.5	330	55	680	7.5	5	0	50	400	185	80	5	0	50	142.5	70	5	50	
9	195	340	50	40	7.5	25	0	80	400	230	202.5	5	0	50	167.5	75	45	10	
10	135	370	15	110	7.5	25	0	90	400	250	100	5	0	50	167.5	70	45	20	
;																			

Step 3: Insert the hours required for setup on each workcentre for each available job

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	# Quoted hours on Workcentres for setup																			
2	param k:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	:=
3	1	2	1	2	2	2	2	1	1	2	1	1	1	1	2	1	1	2	1	
4	2	2	2	2	1	1	2	2	1	1	1	2	2	2	2	2	1	2	1	
5	3	2	2	1	2	2	1	1	1	2	2	1	1	1	2	2	2	1	2	
6	4	1	1	1	2	1	2	2	2	1	1	1	2	1	2	1	1	2	2	
7	5	2	2	2	1	1	2	1	1	1	1	2	2	2	2	2	2	2	2	
8	6	1	2	2	1	1	1	1	2	2	1	2	1	2	1	1	2	2	1	
9	7	1	1	1	2	1	1	2	2	2	1	1	2	2	1	1	1	2	1	
10	8	1	2	2	2	2	1	1	1	2	2	1	1	2	1	1	1	1	1	
11	9	2	2	2	2	1	2	1	1	2	2	1	1	2	2	1	1	2	1	
12	10	2	1	2	2	2	2	1	2	1	1	2	1	1	1	1	1	2	2	
13	;																			

In the "quoted_hours_setup_WC" tab:

- Insert the quoted hours for setup on each workcentre within the green cells.
- The columns are the workcentres indices and the rows are the jobs indices

Inputs | quoted_hours_WC | quoted_hours setup_WC | quoted_hours_ENG | Available_jobs | Capacity_WC | Capacity_ENG | Material_cost | Selling_price | Depreciation_WC

Step 4: Insert the quoted hours for engineering departments for each available job

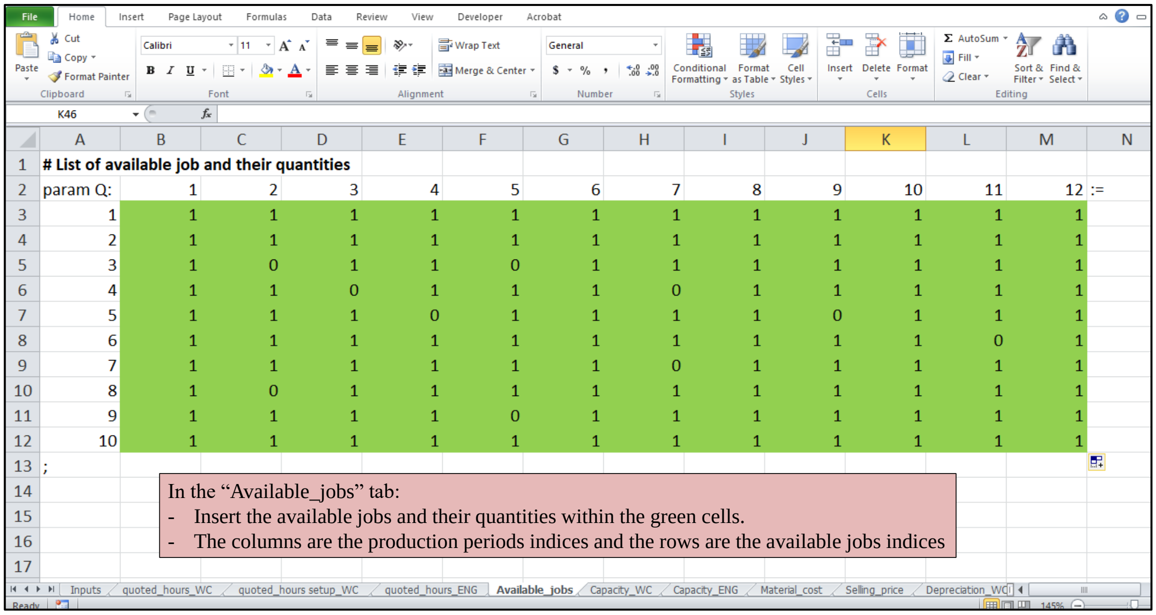
	A	B	C	D
1	# Quoted hours for engineering departments			
2	param h:	1	2	:=
3	1	610	500	
4	2	690	300	
5	3	770	810	
6	4	920	180	
7	5	560	320	
8	6	520	280	
9	7	170	840	
10	8	760	960	
11	9	510	390	
12	10	110	820	
13	;			

In the "quoted_hours_ENG" tab:

- Insert the quoted hours for each job required by the engineering within the green cells.
- The columns are the engineering departments indices and the rows are the jobs indices

Inputs | quoted_hours_WC | quoted_hours setup_WC | quoted_hours_ENG | Available_jobs | Capacity_WC | Capacity_ENG | Material_cost | Selling_price | Depreciation_WC

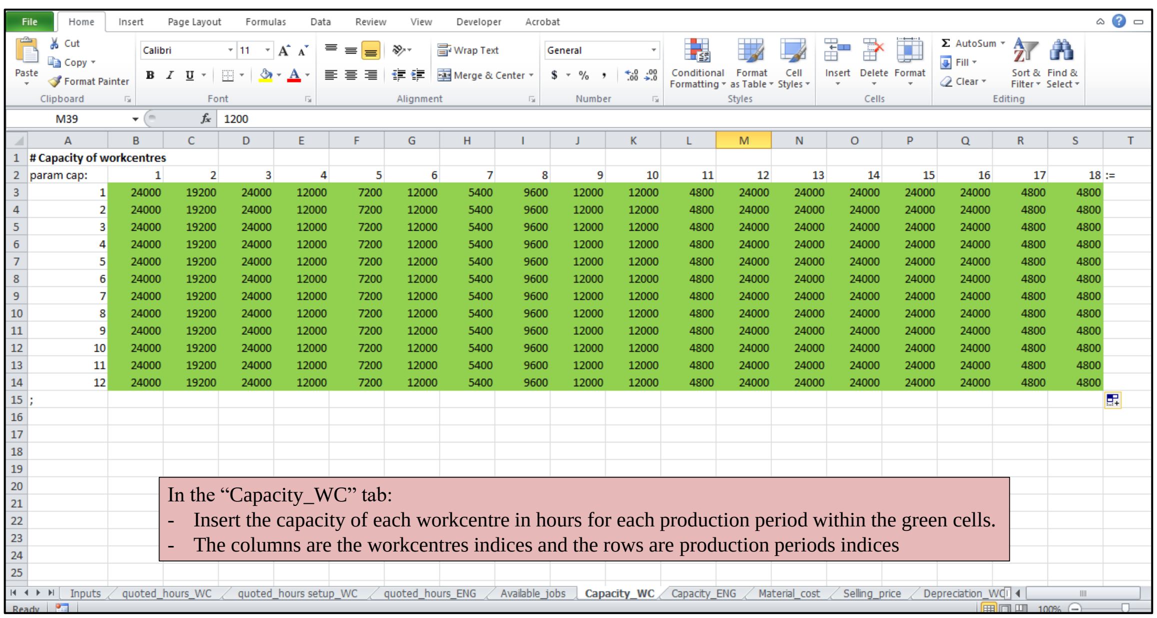
Step 5: Insert the available jobs in the different production per



# List of available job and their quantities													
param Q:	1	2	3	4	5	6	7	8	9	10	11	12	:=
1	1	1	1	1	1	1	1	1	1	1	1	1	
2	1	1	1	1	1	1	1	1	1	1	1	1	
3	1	0	1	1	0	1	1	1	1	1	1	1	
4	1	1	0	1	1	1	0	1	1	1	1	1	
5	1	1	1	0	1	1	1	1	0	1	1	1	
6	1	1	1	1	1	1	1	1	1	1	0	1	
7	1	1	1	1	1	1	0	1	1	1	1	1	
8	1	0	1	1	1	1	1	1	1	1	1	1	
9	1	1	1	1	0	1	1	1	1	1	1	1	
10	1	1	1	1	1	1	1	1	1	1	1	1	
;													

In the “Available_jobs” tab:
- Insert the available jobs and their quantities within the green cells.
- The columns are the production periods indices and the rows are the available jobs indices

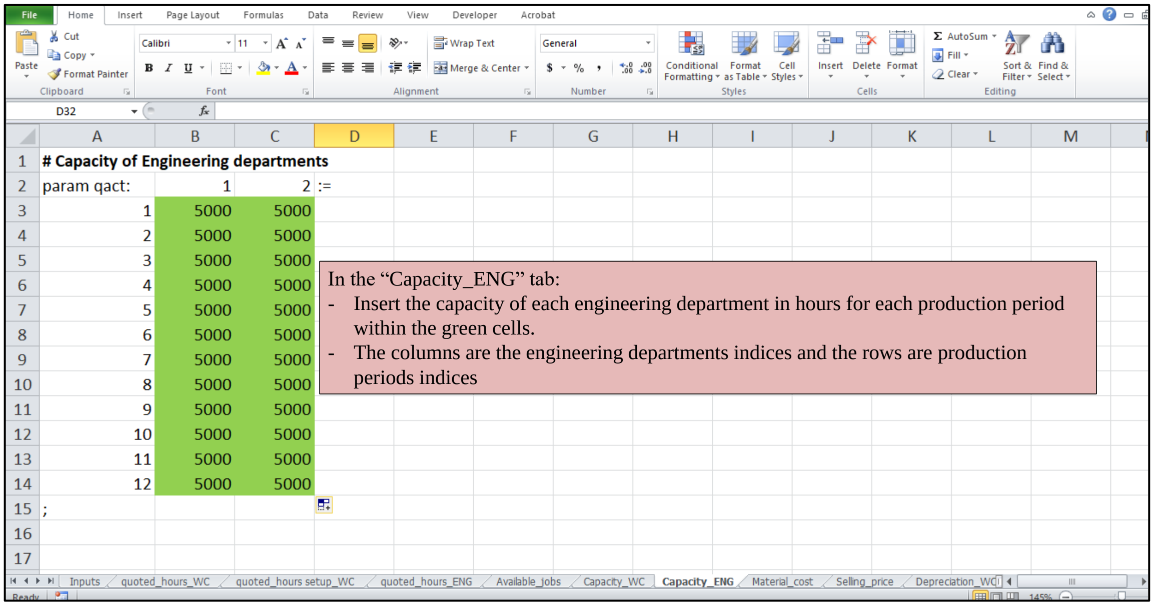
Step 6: Insert the workcentres capacities in the different production periods



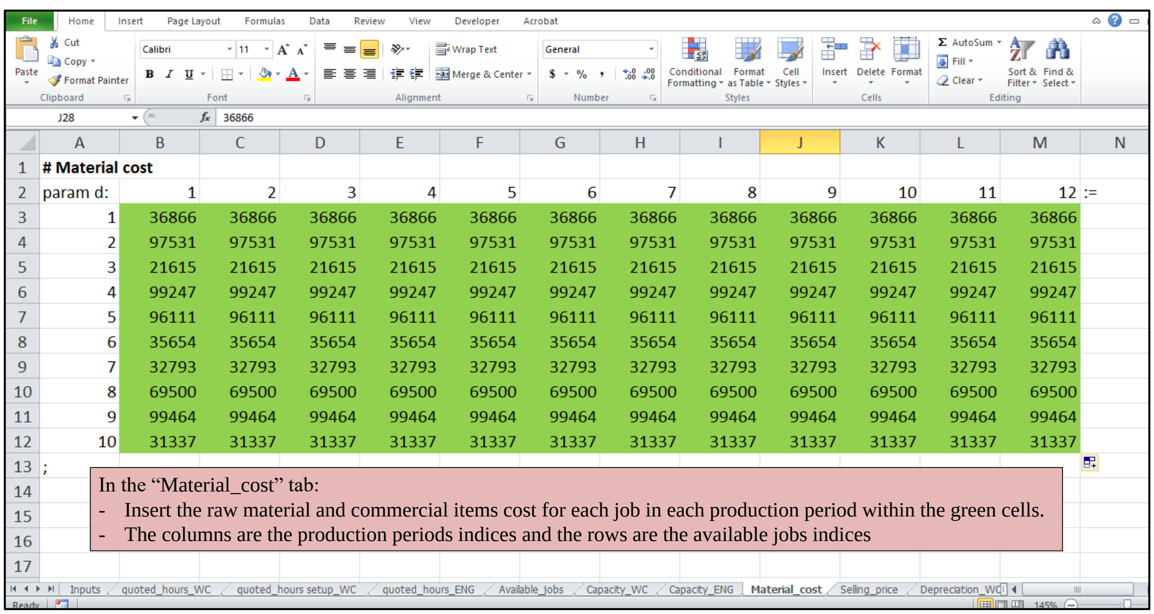
# Capacity of workcentres																			
param cap:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	:=
1	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
2	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
3	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
4	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
5	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
6	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
7	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
8	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
9	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
10	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
11	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
12	24000	19200	24000	12000	7200	12000	5400	9600	12000	12000	4800	24000	24000	24000	24000	24000	4800	4800	
;																			

In the “Capacity_WC” tab:
- Insert the capacity of each workcentre in hours for each production period within the green cells.
- The columns are the workcentres indices and the rows are production periods indices

Step 7: Insert the engineering departments capacities in the different production periods

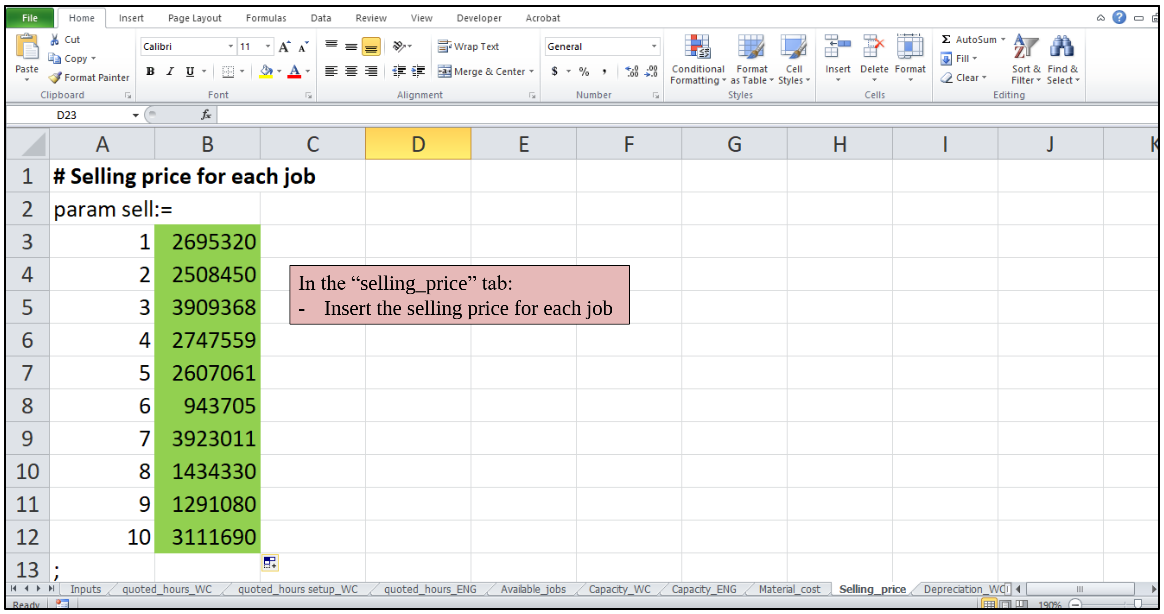


Step 8: Insert the material cost (raw material and commercial items) for each available job in the different production periods

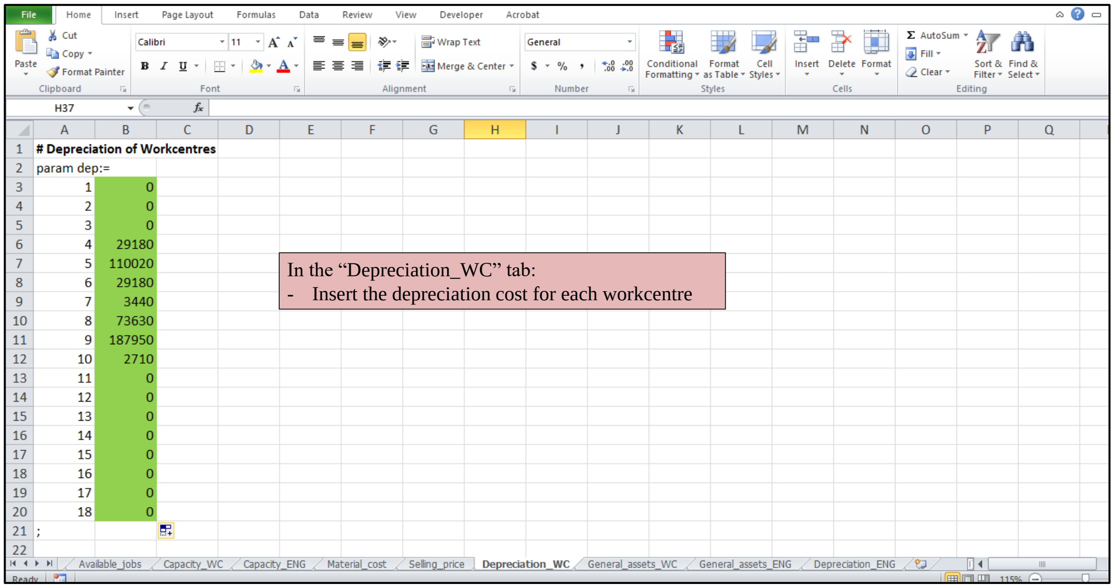


Step 9: Insert the selling price/revenue for the different available jobs

This tab's selling price reflects the dynamic pricing in which pricing is subjected to changing based raw material price increase, an increase in shipping cost and premium price, reflecting expedited delivery. This screen's data can be altered based on requirements from customers (premium or normal pricing).

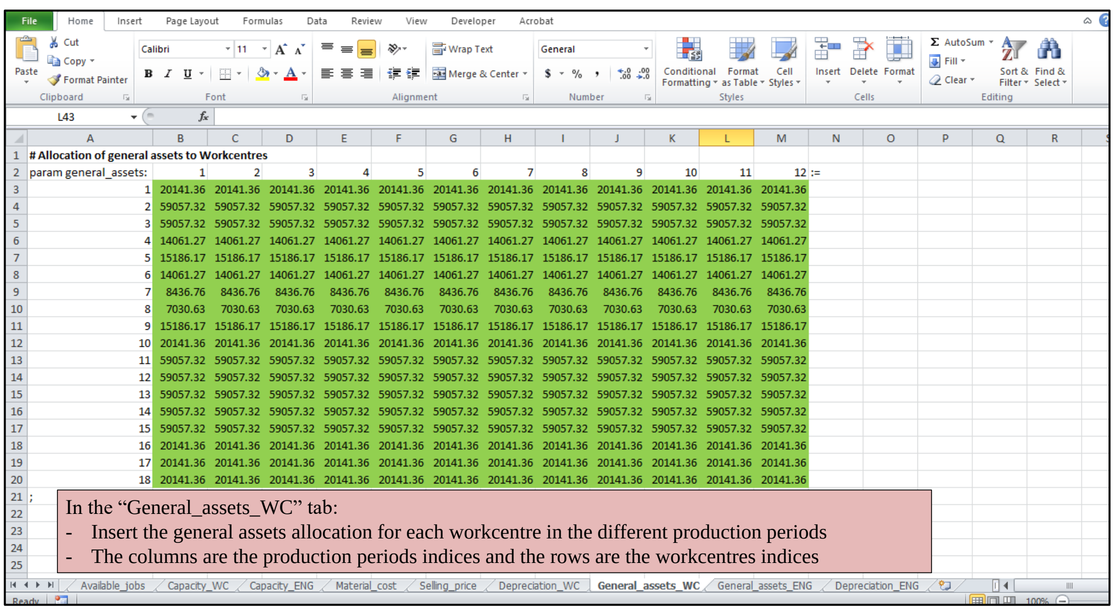


Step 10: Insert the depreciation cost for each workcentre in each production periods



# Depreciation of Workcentres	
param dep:=	
1	0
2	0
3	0
4	29180
5	110020
6	29180
7	3440
8	73630
9	187950
10	2710
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0
;	

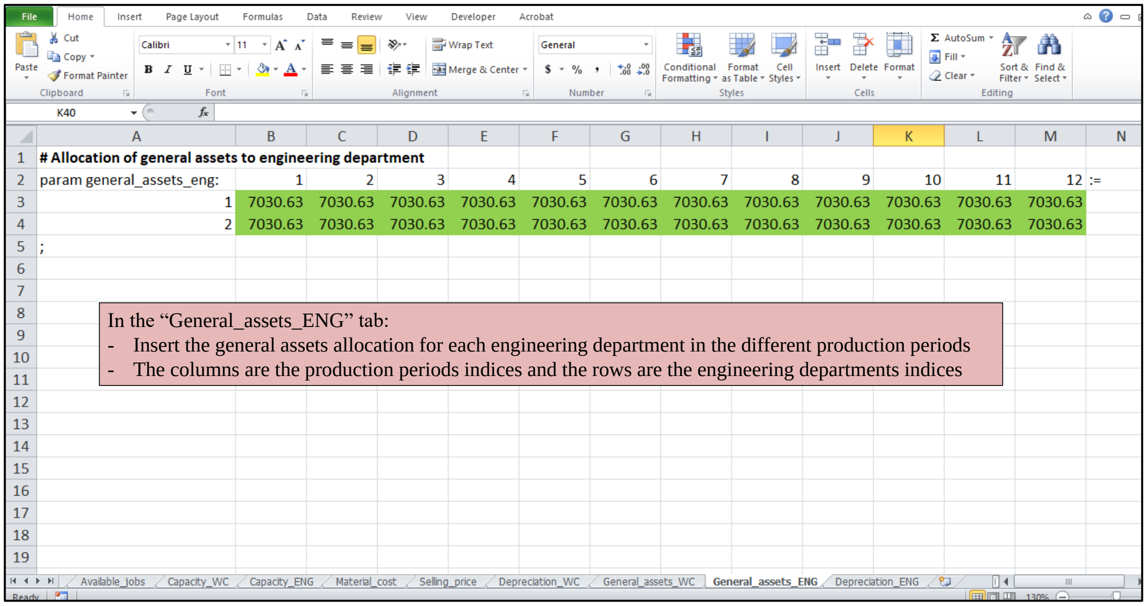
Step 11: Insert the general assets allocation cost allocated to each workcentre in the different production periods



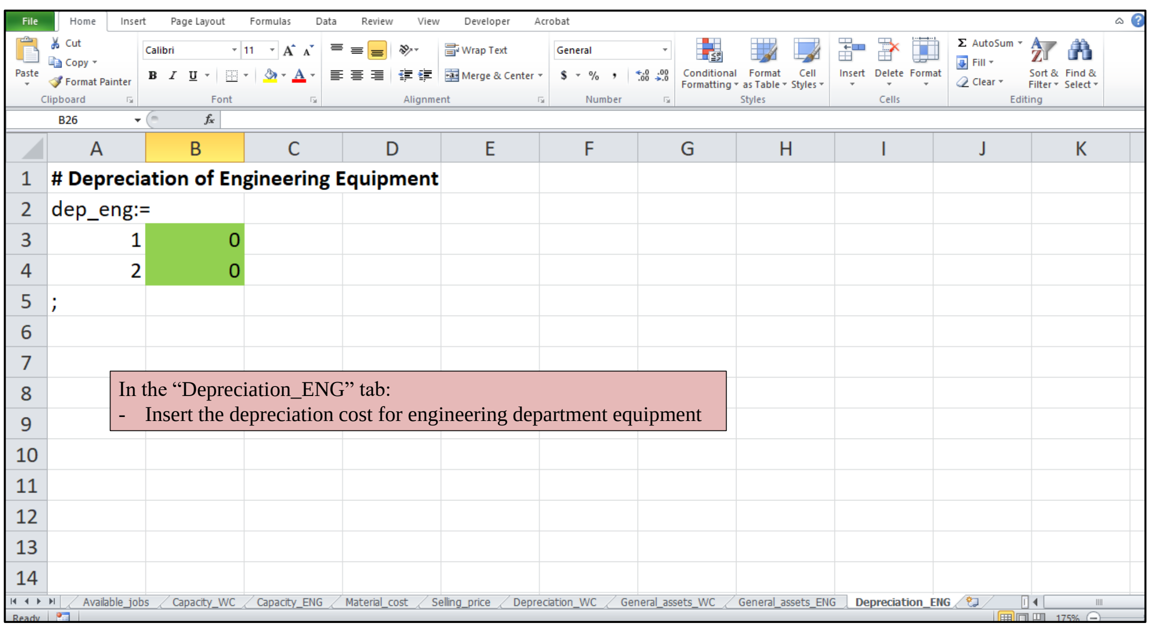
Allocation of general assets to Workcentres

param general_assets:	1	2	3	4	5	6	7	8	9	10	11	12 :=
1	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36
2	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32
3	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32
4	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27
5	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17
6	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27	14061.27
7	8436.76	8436.76	8436.76	8436.76	8436.76	8436.76	8436.76	8436.76	8436.76	8436.76	8436.76	8436.76
8	7030.63	7030.63	7030.63	7030.63	7030.63	7030.63	7030.63	7030.63	7030.63	7030.63	7030.63	7030.63
9	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17	15186.17
10	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36
11	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32
12	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32
13	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32
14	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32
15	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32	59057.32
16	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36
17	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36
18	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36	20141.36
;												

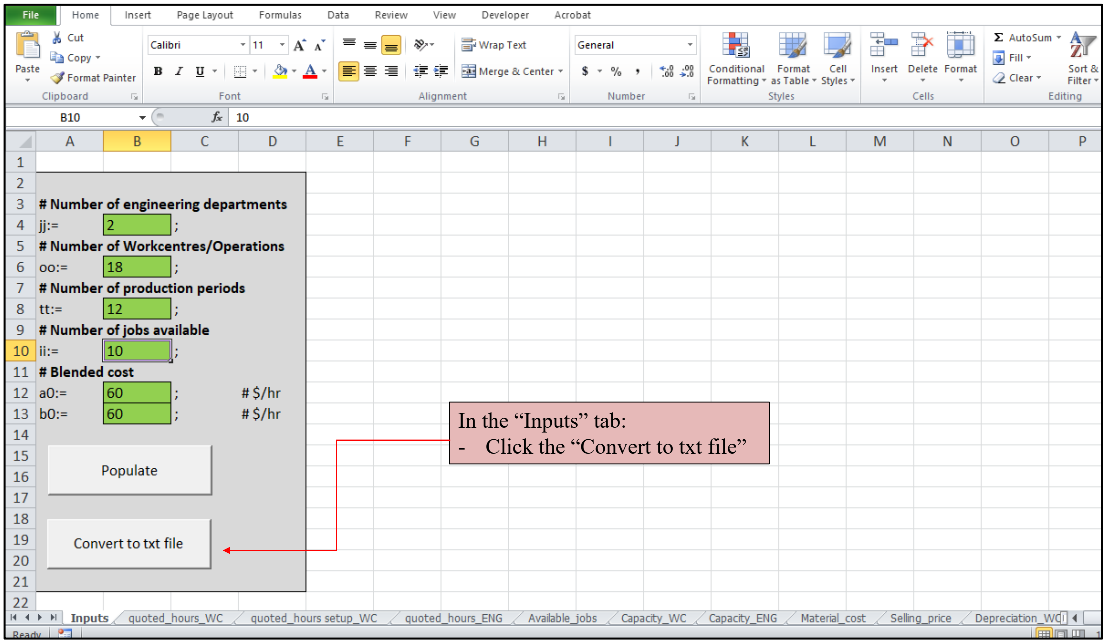
Step 12: Insert the general assets allocation cost allocated to each engineering department in the different production periods



Step 13: Insert the depreciation cost for the engineering department equipment



Step 14: Convert the excel file into a txt file



Step 15: Upload the txt file for the input parameter, the mathematical model file (containing objective function and constraints) and the solution file to the NEOS Mixed Integer Linear Programming solver. Insert an email address to receive the output once the solution is complete.

LINEARIZATION TECHNIQUES

The following linearization techniques are obtained from (FICO, 2009).

First: Product of a binary and a continuous decision variable

Assuming two decision variables X and Y, where X is binary variable such that $X \in \{0,1\}$ and Y is a continuous variable such that $Y \in [0,A]$. The product of the two decision variables X and Y is substituted with Z and hence, the equivalent linear form is written as:

$Z = X\,Y$

$Z \leq A\,X$

$Z \leq Y$

$Z \geq AX + Y - A$

Second: Product of two binary decision variables

Assuming two decision variables X and Y, where X and Y are binary variables such that $X,Y \in \{0,1\}$, The product of the two decision variables X and Y is substituted with Z and hence, the equivalent linear form is written as:

$Z = X\,Y$

$Z \leq X$

$Z \leq Y$

$Z \geq X + Y - 1$

VITA AUCTORIS

NAME:	Darwish Alami
PLACE OF BIRTH:	Jerusalem, Palestine
YEAR OF BIRTH:	1972
EDUCATION:	Bachelor of Applied Science, Program: Industrial Engineering. University of Windsor, Windsor, ON, Canada (1997)
	Master of Applied Science, Program: Industrial and Manufacturing Systems Engineering. University of Windsor, Windsor, ON, Canada (1999)
	Masters in Engineering, Program: Engineering Management Master's Program. Wayne State University, Detroit, MI (2005)

PROFESSIONAL EXPERIENCE:

Company: Navistar International Canada Ltd., Chatham, ON

Industry: *Heavy Duty Truck OE Design and manufacturer*

Position: Industrial Engineer Aug. 1997 – Jan. 1999

Labour assignments and new process implementation

Time studies team leader

Material handling coordination

Balancing production lines to accommodate production rates

Layout changes and ergonomic analysis

Position: Manufacturing Engineering Team Leader Jan. 1999 – Nov. 2000

Responsible for a team of 9 engineers to handle chassis systems and power train

Process improvements and layouts

Process planners supervision

PFMEA and process capability studies

Simulating new processes

Coordinating all related pilot programs

Company: Visteon Corporation/Neapco, Detroit, MI

Industry: *Global Drivelines Systems Tier 1 Automotive Supplier*

Position: Manufacturing Engineer Nov. 2000 – May 2005

Launched new programs with new technologies for Mexican facilities

Provided support and expertise for North American driveline facilities

Design, procure and launch new manufacturing lines for new programs (USD 25M budget)

Implemented Lean manufacturing concepts in 3 manufacturing lines at Lamosa (Mexican facility).

Position: Manufacturing Engineering Manager May 2005 – Oct. 2011

Supervise eight manufacturing and Controls engineers

Relocated 400,000 sq. ft. plant from Monroe (Visteon) to Belleville (Neapco)

Implement and FTT (First Time Through) system for driveline area

Launched F150, Mustang, Expedition, and Dodge Ram prop shaft programs

Took the lead on transferring equipment and transition from Monroe to Belleville

Lead a team of engineers to improve Quality from 228 PPM to industry lead of 18 PPM in 18 months.

Position: General Manager – Group de Mexico Oct. 2011 – Jul. 2016

Overall responsibilities for P&L, Manufacturing, Quality, Finance, Human Resources, PD, Sales and Supply Chain.

Responsible for setting up the infrastructure for our Mexico facility, including the development of Quality Operating System for the plant.

Improved cost structure in the plant, from negative to positive profitability, to establish growing the facility from 60,000 sq. ft. to 350,000 sq. ft.,

Achieved TS-16949 and ISO-14001 certification for the Mexican facility.

Company: Dieffenbacher North America Inc., Windsor, ON

Industry*: OEM of heavy-duty Press and complete production systems for the wood-Panel Industry and Automotive Composite Suppliers*

Position: President/General Manager Jul. 2016 – Feb 2018

Overall responsibilities for P&L, Manufacturing, Quality, Sales and Supply Chain.

Grew Efficiency and Sales in the plant more than 35% in the first year of operations.

Improved communication in NA and implements 5S program.

Company: Absolute Industrial Automation, Windsor, ON

Industry: *Automation Integrator and machine builder for automotive powertrain applications*

Position: V.P. of Operations (Co-Owner) Feb 2018 – October 2019

Responsible for completing M&A transaction by selling the business to a PE firm.

Responsible for leading program management, Finance and Production

Overall responsibilities for P&L, Manufacturing, Quality and Supply Chain.

Grew Business 300%Efficiency and Sales in the plant more than 35% in the first year of operations.

Successfully completed an M&A Transaction by selling the business and transition the operations

PUBLICATIONS: **Journal Papers**

ElMaraghy W. and Alami D., (2020) "Activity-Based Aggregate Job Costing Model for Reconfigurable Manufacturing Systems," International Journal of Industry and Sustainable Development, vol. 1, pp. 1-19.

Alami D. and ElMaraghy W., "A Cost-Benefit Analysis for Industry 4.0 in a Job Shop Environment Using a Mixed Integer Linear Programming Model, Journal of Manufacturing Systems, 2021. (Accepted)

Alami, D. and ElMaraghy, W., "Activity-Based Aggregate Job Costing Model for Reconfigurable Manufacturing Systems and Facility Expansion", International Journal of Engineering Economics. (Submitted)

Conference Papers

Alami, D., & ElMaraghy, W. (2020). Traditional and Activity Based Aggregate Job Costing Model. *Procedia CIRP*, *93*, 610-615.