2017

Product Variants Platform Customization Strategies and Performance of Reconfigurable Manufacturing Systems (RMS)

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by

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A Thesis
Submitted to the Faculty of Graduate Studies through
Mechanical, Automotive & Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada

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Thesis Chapter	Publication title/full citation	Publication Status
3, 4, & 5	Aljorephani, S. K., & ElMaraghy, H. A. (2016). Impact of Product Platform and Market Demand on Manufacturing System Performance and Production Cost. Procedia CIRP, 52, 74-79.	Conference Proceeding (Published)

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ABSTRACT

Customers' demands and needs are changing over time. As a result, manufacturers are seeking new ways to respond to market changes effectively and efficiently. They include offering customers a wide range of product varieties in a reasonable time while reducing associated costs. One of the prime techniques adopted by manufacturers is mass customization and its enablers, such as product family and product platforms. The main objective of this research is to help manufacturers manage a high level of variety by implementing the most suitable manufacturing strategy and product platform design.

Customized Platform To Order (CPTO) has been introduced and compared with existing manufacturing/production strategies, such as assemble to order (ATO). CPTO is a hybrid assemble-to-stock (ATS)/assemble-to-order (ATO) strategy that uses a platform customization approach to increase the efficiency and productivity of manufacturers. The platform(s) design is based on customers' historical demand rather than on commonality between product variants.

In this thesis, the CPTO approach was compared to the ATO and hybrid ATS/ATO strategies. A discrete-event simulation model of the learning factory iFactory in the Intelligent Manufacturing System Centre (IMSC) is developed. The results were then compared with a physical implementation conducted in the (IMS) Centre. The results of this investigation indicated that the CPTO approach provides manufacturers the ability to be more responsive by reducing the lead time by 30% and assembly time by 27% as well as lowering inventory and assembly costs by 24% and 18% respectively for the considered case study. This approach is applicable to products with modular and flexible platforms and both flexible and reconfigurable manufacturing systems.

DEDICATION

To my parents and siblings, for their encouragement and support

To my wife, for her continued love and motivation

To my supervisor, for her help and guidance

ACKNOWLEDGMENT

The author would like to express his great appreciation to his supervisor Professor Hoda ElMaraghy for her guidance and support during this journey. This thesis would not have been at this knowledge level and quality without her sincere effort and time. Her support goes beyond supervising and recommending topics; she encourages her graduate students and researchers to think critically and outside the box. One of the most challenging moments in this journey was selecting a research topic, but with Professor Hoda ElMaraghy, the process was smooth and the topic was innovative.

The author is also thankful for the valuable feedback from all his committee members. Great thanks goes to Professor Waguih ElMaraghy for his valuable comments, recommendations, and feedback during both the Intelligent Manufacturing Systems Centre (IMSC) meetings and the committee meetings.

The author would also like to acknowledge the help and support from his fellow researchers and colleagues at the Intelligent Manufacturing Systems Centre (IMSC). Special thanks goes to Mr. Mostafa Moussa, Mr. Ahmed Marzouk, Dr. Mohammed Abbas, Ms. Jessica Olivares Aguila, Mr. Ashraf Abou Tabl, Mr. Boris Novakovic and Dr. Javad Navaei.

Finally, he would like to acknowledge the assistance funds provided by the Government of Saudi Arabia, administered by the Saudi Arabian Cultural Bureau in Canada. This research would not have been accomplished without the funds and support.

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LIST OF ABBREVIATIONS

ATO	Assemble to order
ATS	Assemble to stock
AS/RS	Automated storage and retrieval system
CPTO	Customize Platform To Order
DFA	Design for assembly
DFMA	Design for manufacturing and assembly
DMS	Dedicated manufacturing system
DSP	Decision support problem
ETO	Engineer to order
FMS	Flexible manufacturing system
FTO	Forecast to order
IDEF0	ICAM definition for function modeling (a function modeling language) where ICAM stands for integrated computer-aided manufacturing
MC	Mass customization
MTO	Make to order
MTS	Make to stock
PLC	Programmable logic controller
POLCA	Paired-cell overlapping of cards with authorization
QFD	Quality function deployment
RMS	Reconfigurable manufacturing system

NOMENCLATURE

AS	Assembly sequence
C_A	Assembly cost
C_p	Production cost
D_v	Variant demand
n	Total number of different components
N_v	Number of variants in a family
PC	Platform components
t_A	Assembly time
t_L	Lead time
t_P	Process time
t_T	Transportation time
U_i	Number of units in the inventory
V_i	Refer to member *i* in the family

CHAPTER 1: INTRODUCTION

1.1 Research Motivation

The trends in customer demands and needs have changed significantly over the years. Customers are increasingly seeking customized and even personalized products and features. Therefore, offering product variety is becoming important to respond to market changes and different customer requirements. These rapid changes in customer requirements have a significant impact on overall production and inventory costs. To cope with this challenge, manufacturers are increasingly shifting from mass production to flexibility, reconfiguration, and mass customization. Manufacturers have embraced mass customization to be able to efficiently and effectively adapt to these conditions to stay competitive and survive (H. ElMaraghy et al., 2013). Figure 1.1 shows the challenges that are facing most manufacturers in the world, from the roles of globalization, technology, and regulations to the changes in customer requirements and needs and the fluctuating customer demands.

Research in mass customization covers a wide area of subjects. These include product families, product platforms, delayed product differentiation (DPD), and design of production and assembly lines. Each area of research attempts to offer strategies and techniques to manage products variety.

A product platform strategy has been adopted by many firms in order to offer a wide range of products, decrease lead times, and reduce production costs. Recently, a new platform approach was developed in which an optimal platform is formed for a product family and is customized for different variants by adding, removing, and/or substituting platform components to form product variants as orders are received (Hanafy & ElMaraghy, 2015), and (Ben-Arieh, Easton, & Choubey, 2009). This approach has allowed companies to efficiently respond to markets and lower production costs.

However, inventory cost plays a major role in how components and platforms are stored and contributes to the total product cost. Therefore, this research is concerned with investigating and finding the effect of product platform customization strategies on inventory costs and lead times under different order fulfillment policies, and how the effect is reflected in overall production costs and manufacturing systems' performances.

Inventory also plays a major role for companies looking to gain a competitive advantage. It is considered one of the major assets of companies. Managers have to deal with inventory very carefully, since holding too much or too little inventory can be a problem for both the productivity and profitability of a company. Holding inventory has various advantages, including meeting fluctuating customer demands, hedging against price increases, meeting variations in production, achieving economies of scale, and taking advantage of quantity discounts. A typical inventory cost can be estimated from 20–40% of the final product price (Stevenson, 2005). This large percentage can affect companies in terms of their survival. According to the *New York Times* (1999), Toys"R"Us Inc. made the decision to reduce its inventories because it was afraid of the consequences of holding excess stock and inventory costs. In that period, Mattel Inc., a major Toys"R"Us Inc. supplier, incurred $500 million in losses from mid-November to December of 1997 because there was an increase in demand for products that Toys "R" Us was not expecting, which costs Mattel a huge financial loss as they could not fulfill these additional orders on time (Candy, 1999). Therefore, keeping the right quantities of inventory is critical for companies to be competitive in the market while paying more attention to the relevant costs associated with holding inventories.

Figure 1.1: Current Manufacturing Challenges

1.1.1 Industrial Motivation

The concepts of mass customization (MC) and product platforms have been utilized by manufacturers to be able to efficiently and effectively adapt to market conditions to stay competitive and survive. Many examples can be found in industry such as laptop computers and their mother boards, Figure 1.2, which can be populated with many different components depending on the required/ordered functionality. The manufacturer can assemble the most common motherboard configurations (platforms) for the most ordered laptops and subsequently add/remove components to customize them to orders.

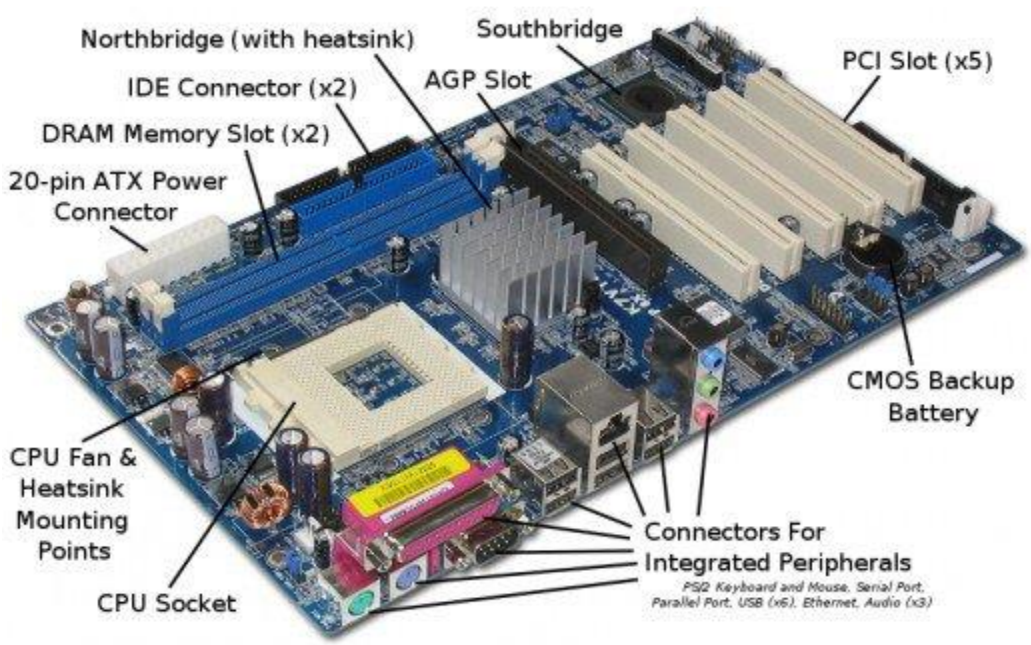

Figure 1.2: Computer Mother Board. Source: https://turbofuture.com/computers/the-motherboard-components

Another example is the Sartorius AG Inc., which is an international pharmaceutical and laboratory equipment supplier based in Germany. Sartorius introduced the first modular design laboratory scale, allowing its customers to have a customized scale. This family of laboratory scales consists of three main modules: a weighing module, a display and control unit, and a draft shield. These three most commonly ordered modules are considered product platform units, which can be assembled prior to customers' orders, as shown in Figure 1.3.

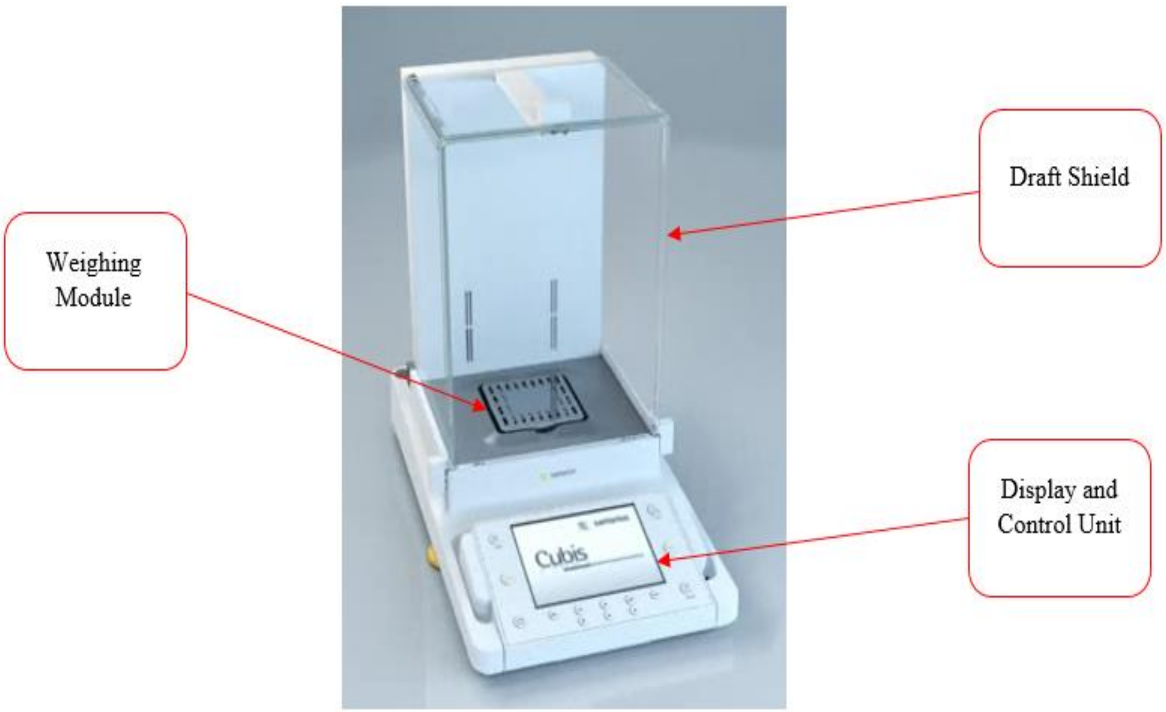

Figure 1.3: Laboratory Scale Modules Source (http://microsite.sartorius.com/index.php?id=12741&L=0)

The laboratory scale family Figure 1.4 consists of 7 draft shield options, 5 weighing options and 3 display and control unit options for a total of 105 scale variants. Modifications to the platform modules take place according to customers' needs and the market's segments. For example, assembly and disassembly of the weighing module can take place to meet a customer's requirements regarding readability among three different types of 0.01 mg, 10 mg, and 1000 mg and different resolutions. In addition, draft shield customization can take place wherein a customer can choose seven different types of draft shields or no draft shield at all if it is not needed. Therefore, the concept of assembling the most commonly ordered modules into a platform which can later be customized by adding/removing components according to demands can be developed when historical demand data are present and a proper forecasting method is implemented in order to decrease inventory costs and customer leads.

This research is motivated by the need for a cost-effective solution for choosing the right platform components for modular products and implementing the right storing policy.

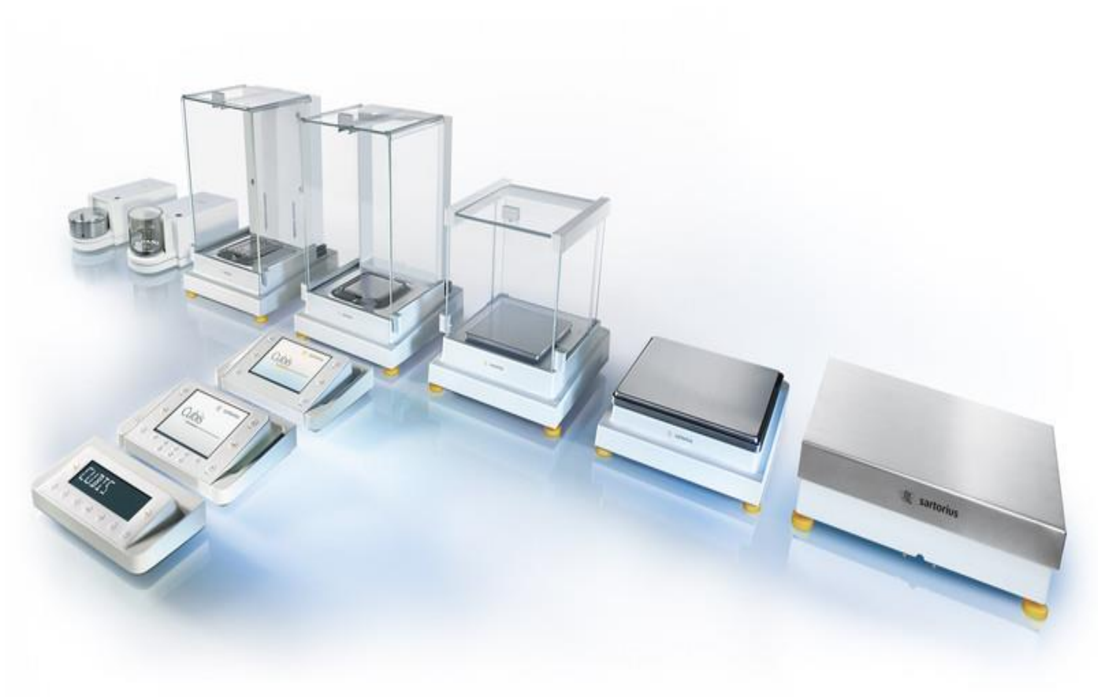

Figure 1.4: Modular Laboratory Scale showing the various modules options to be selected by the customer. Source: (http://microsite.sartorius.com/cubis/modularity.html)

1.2 Statement of Engineering Problem

The main problem is how to integrate the product platform formation and production policies in a simulation model in order to decrease inventory costs, lead times, assembly costs, and times.

1.3 Objectives

This research aims to investigate the above effects using a discrete-event simulation model that integrates product platform formation concepts and assembly policies to determine important system performance metrics such as delivery times and inventory levels. It also aims to investigate the effect of demands/product variants on the choices of platform construction and assembly strategies and overall production costs. It also aims to investigate inventory cost behaviour under three different scenarios: storing individual components without a platform; storing pre-assembled platform components, wherein a platform is the only core component shared by all variants in the product family; and storing pre-assembled platform components using a customized platform concept, wherein platform components consist of various components that are formed according to customers' demands. Finally, to validate the simulation model results, a physical implementation in the iFactory using a desk set family is conducted and the results are compared with the simulation model.

1.4 Scope of Research

The scope of this research and the boundaries of this work are as follows. For production quantity (demand) the demand pattern will be the same for all studied scenarios. For product variety, a desk set product family with five variants will be considered. The production strategy will be based on the Assemble To Order (ATO), hybrid Assemble To

Order/Assemble To Stock (ATO/ATS), and Customize Platform to Order (CPTO) policies. Inventory cost will be investigated under two different platform formation scenarios: by assembly and by assembly and disassembly. Moreover, inventory cost is assumed to be proportional to the number of units stored and the length of time held in storage. The holding costs will be estimated between 20% and 40% of the final product. The manufacturing system type used will be the flexible and reconfigurable manufacturing system (iFactory). It is assumed that disassembled components will be re-usable and are not ruined by disassembly. Finally, the operation type will be a hybrid of automated and manual assembly operations.

1.5 Research Hypothesis

The strategies used for product platform formation and production policies include assemble to stock, assemble to order, and customize product platform to order affect the production lead times and the inventory costs.

1.6 Thesis Structure

This thesis is presented in five chapters, including this Introduction chapter. Chapter 2 summarizes the available research literature on several topics related to this work. In particular, it includes a summary of product family and platform, product platform scalability, manufacturing strategies, manufacturing systems, and mass customization literature. Research gaps identified in the literature review are also presented in this chapter.

Chapter 3 shows the research approach and methodology and the tools used for formulating the problem using the IDEF0 modeling technique. In addition, an illustrative example and a case study are presented. Chapter 4 shows the results and discussion of the case study from the developed simulation model. Finally, Chapter 5 provides a conclusion, a discussion of the novelty of the present research, and suggestions for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

In this chapter of the thesis, a large amount of previous work addressing product platform design approaches, assembly policies, manufacturing systems, and mass customization are reviewed. The first section of the literature survey is concerned with the topic of product families and platforms. It includes a detailed review of modular, scalable, and flexible product platforms. The second section of the literature survey is about manufacturing strategies and assembly policies, and describes the different manufacturing policies in both research and industrial literature. The third and last section of this chapter is about manufacturing system types and characteristics, and which type is applicable to this thesis and the scope of this research.

2.2 Product Families and Product Platforms

Many manufacturers are using the concepts of product families and product platforms to provide sufficient variety to the market. These implementations aim to meet customers' demands and requirements while maintaining both economy of scale and scope throughout the production and manufacturing processes. The term "product family" can be defined as a group of products that share common parts, modules, features, and/or subsystems (Simpson, Jiao, Siddique, & Hölttä-Otto, 2014). (Erens & Verhulst, 1997) defined "modular product platform" as a group of components or modules used to form different products by varying one or more modular component(s). They named modular product platforms as product families' architecture. Additional authors extended the definition to include nonphysical components, such as (McGrath, 1995), who defined "product platform" as a collection of parts, common components, and/or elements (physical and nonphysical)—mainly, the underlying technology that is implemented across a range of products. (Simpson, Maier, & Mistree, 2001) defined “platform” as “a set of common parameters, features, and/or components that remain constant from product to product within a given product family.” This definition covers both concepts of product platforms, which are modular and scalable. Since this research is concerned with modular product platforms, the definition used in this thesis is by (Meyer & Lehnerd, 1997), who defined “product platform” as a “set of common components, modules, or parts from which a stream of derivative products can be efficiently created and launched.”

Figure 2.1 illustrates an assembly and disassembly process of a modular product platform. A family of three product variants (A, B, and C) that share common components are shown in region X, which is considered the product family platform. The assembly and disassembly technique expands the platform region to cover Y, W, and Z. Hence, it gives the manufacturer the opportunity to mass produce a large portion of partial products and to achieve both economy of scale and scope (Hanafy, 2014).

In general, platforms can be classified into four types, shown in Figure 2.2: process platforms, product platforms, knowledge platforms, and people-relationship platforms. The focus of this research is on modular product platforms. However, all product platform categories are reviewed in the next sections.

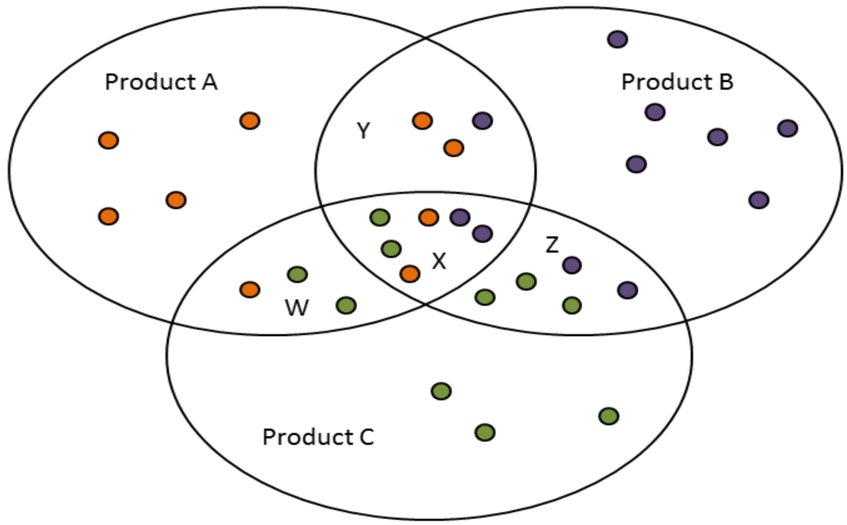

Figure 2.1: Assembly and Disassembly of Modular Product Platform. Source (Hanafy, 2014)

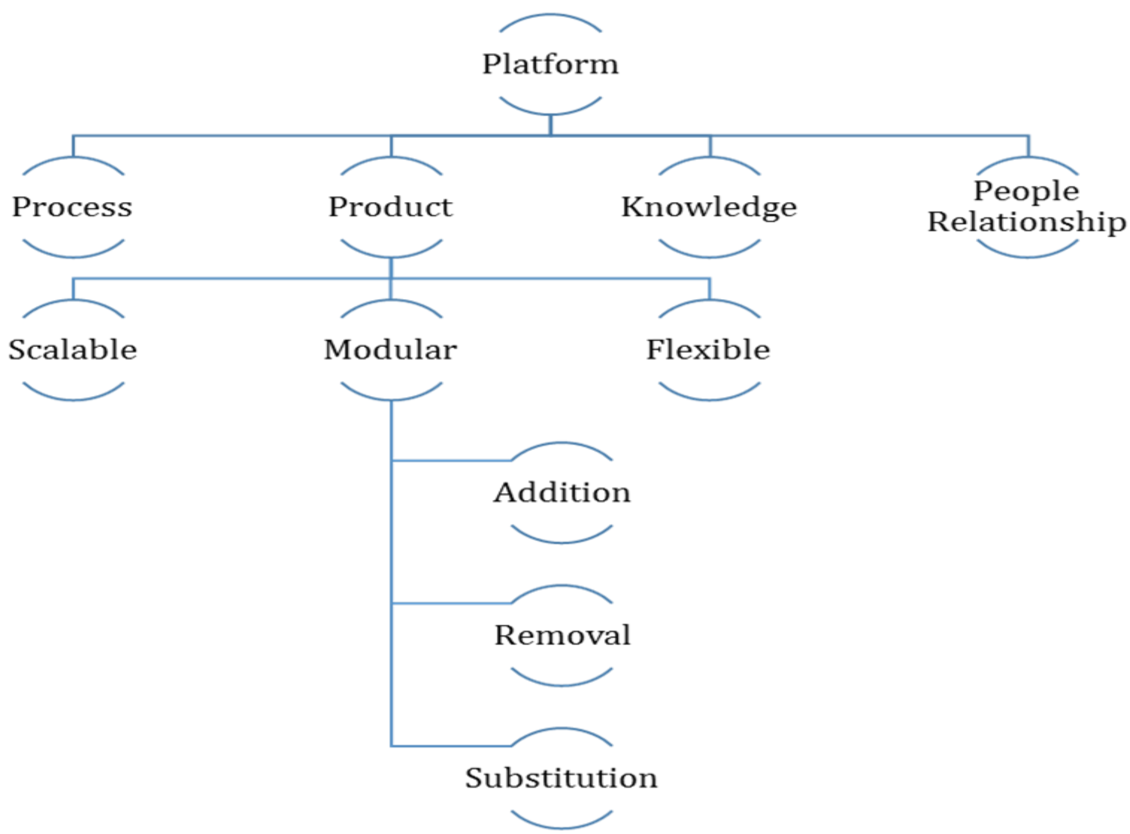

Figure 2.2: Platform Types

2.2.1 Modular Product Platform

"Modular product platform" can be defined as a platform that shares common modules between variants in its family; a variant is formed by adding or subtracting different modules (Simpson, 2003). Hanafy and ElMaraghy (2015) developed a multi-period modular product assembly model to determine the optimal product platform design and the best product family formation while decreasing assembly costs. This novel mathematical model was developed after identifying research gaps in the available literature. All previous mathematical models had aimed at defining a single platform and for a single period, but their model was able to cover multi-period and multi-platform assembly problems. (AlGeddawy & ElMaraghy, 2013) proposed a new model for a reactive platform design of product variants that uses physical commonality rather than commonality indices which were widely researched in literature, to automatically design and redesign product variants. The model was able to find a balance between two conflicting strategies of product modularity and integration, based on using the design for manufacturing and assembly (DFMA). (Gonzalez-Zugasti, Otto, & Baker, 2000) developed an iterative method for optimizing platform design in order to minimize associated design costs. In another paper, (Gonzalez-Zugasti, Otto, & Baker, 2001) developed a technique to assess the value of a platform. The technique allowed designers to assess and quantify the value of different product families and choose the products that were more valuable for the company. (Siddique & Rosen, 2000) focused on assembly, wherein common assembly processes were used to design a product platform from an existing family of products. In their work, a real options technique was used to determine product platform and the possibility of developing product variants. Three years later, (Steuer & Whitcomb, 2003) used the same real options technique in order to assess the flexibility of a modular product platform architecture. In their approach, the focus was on market uncertainty rather than the technical uncertainty. (Moore, Louviere, & Verma, 1999) used a conjoint analysis to design individual products and product platforms to help design product platforms. (Schuh, Arnoscht, & Rudolf, 2010) developed a framework that was able to integrate modular product platform designs which consisted of four steps: (i) planning for product platforms, (ii) structuring designs for product platforms, (iii) modules' development, and (iv) product adaptations and configurations. (Fan, Qi, Hu, & Yu, 2015) introduced a methodology for planning modular product platforms using network science. Two types of networks were used. The first network related parts and components to products, while the other related generic modules to products. However, this model did not guarantee optimality because it was based on judgement.

A number of research papers were concerned with designing product platforms by developing matrix-based methods. (Martin & Ishii, 2002) introduced a method to develop platforms based on quality function deployment (QFD). The main objective of their work was to minimize future redesign efforts and connectivity within the product modules (architecture). They also used the modularity metric to achieve their goal. Similarly, (Fujita, Takagi, & Nakayama, 2003) extended the cost planning framework with QFD, which considered one product variant, and developed an assessment method for the value distribution of several product variants that belonged to a family. Such a tool could be implemented for a whole product family by assigning one for any customer requirement that existed in at least one of the product variants.

2.2.2 Scalable Product Platform

"Scalable product platform" can be defined as "where all product variants share the same parametric description, and a variant can be generated by scaling one or more parameters"(Simpson, 2003). This type of platform is not within this thesis's scope. However, a review has been conducted to cover techniques and models that may be implemented or used in this thesis. (Messac, Martinez, & Simpson, 2002) used a market grid to design product families which provides an effective approach to product family design. This approach facilitated both analysis and decision making during the design phase of product families by converting design problem to physically meaningful terms and preferences. It was assumed that platform components were known ahead of time, and parameters were then identified and scaled to provide product variants. (Nayak, Chen, & Simpson, 2002) attempted to minimize the variation in the design variables in a product family and to optimize the platform using a decision support problem (DSP) approach. (Simpson, Bascaran, & Avila, 2001) introduced a DSP approach that was capable of designing a robust product family while minimizing overall production costs. Lastly, (Seepersad, Hernandez, & Allen, 2000) provided a quantitative approach to determine the number of scalable product platforms for a given market. In addition, the approach was able to determine the distribution of products between multiple platforms at both individual product and system levels.

2.2.3 Flexible Product Platform

The flexible product platform concept combines both modular and scalable product platforms. The term flexibility is "the property of a system that is capable of undergoing specified classes of changes with relative ease" (Moses, 2002). (Simpson, Maier, et al.,

2001) developed a method that facilitated the exploration and synthesis of common product platform concepts that could be scaled into a family of products. The method can be easily implemented by following six steps, as follows: (i) develop a market segmentation grid; (ii) classify factors and ranges by mapping the design requirements and the market segmentation grid to factors, and identifying a corresponding range for each factor; (iii) create a meta-model for the scaling variables; (iv) validate the model generated; (v) aggregate product platform specifications; and (vi) develop a products' family and platform. This procedure was implemented on a case study with a universal motor of ten product variants. (Azarm & Li, 2002) introduced a design process under uncertainty of a product family, which was divided into generation and evaluation stages. It is important to mention that combining the concepts of modularity and flexibility into the product platform formation enables manufacturers to respond to changing needs in the marketplace with a slight increase in investment and complexity (H. ElMaraghy, et al., 2013).

2.3 Manufacturing Strategies & Assembly Policies for Managing Product Variety

Generally, manufacturers are characterized by their policies from an inventory control point of view, as either make to stock (MTS), make to order (MTO), engineer to order (ETO), forecast to order (FTO), or assemble to order (ATO) (Esmaeilian, et al., 2016). The implemented policies depend on the degree to which the manufacturer want to interact with customers, the level of responsiveness they aim for, and the customization level they want to provide. However, some companies use multiple strategies for different product variants. Products in high demand with low production costs are usually produced as MTS, while products in low demand and/or with high production costs are usually produced as MTO.

The ATO approach aims to combine both manufacturing strategies (MTS & MTO) for which parts, components, and subassemblies are made and stocked. The final assembly takes place when customer orders are received. Figure 2.3 shows various production and assembly strategies in various stages of design, production, and assembly.

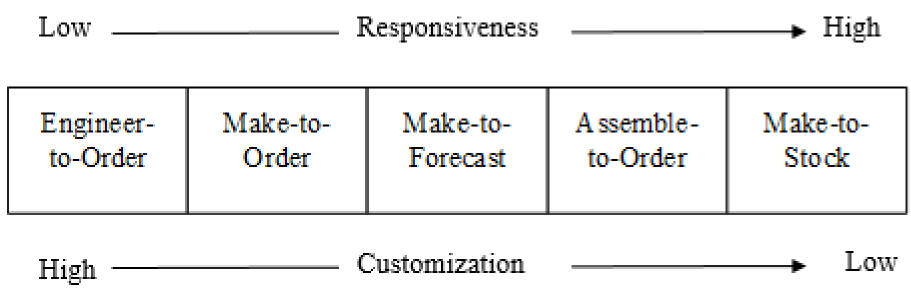

Figure 2.3: Manufacturing Strategies Comparison Source: (Esmaeilian, Behdad, & Wang, 2016)

The ETO manufacturing strategy is characterized by a high level of personalization. Customers usually place product specifications with the manufacturer; the specifications are highly specific to each customer. This policy requires a long lead time and a low manufacturer responsiveness. However, in the MTS approach the manufacturer produces the products and stocks the inventory for customers. The approach has the shortest lead time and there is no room for customers to customize a product.

The MTO, ATO, and MTF manufacturing policies allow customization to take place. MTO is currently the most implemented approach, as manufacturers attempt to reduce finished goods inventories and satisfy customers' different needs (Meredith & Akinc, 2007). This approach is characterized by a high customization level and a lower lead time than the ETO approach. The ATO approach is considered a hybrid of MTS and MTO, wherein products are stored in subassemblies. Components are already manufactured but are not put together to form finished products. For example, Dell Inc. allows customers to build computers from a given list of parts, such as memories and processors, providing some customization to customers from a defined group of parts.

The MTF approach is characterized by a medium customization level and a medium response time compared to the other strategies. Large products, such as heavy machinery and other large equipment, is produced. This is done by implementing a proper forecast method wherein customers' orders are assumed to take place at the beginning or end of the production line. Customization takes place later.

Ericsson et al. (2010), defined the Customize To Order (CTO) as product customization by introducing components changes in order to generate product variants. Changes can take place in software as well as physical components that are not visible to end customer. They compared the CTO approach with Build To Order (BTO) or Make To Order (MTO) and Build To Forecast (BTF) which the same as Make To Forecast (MTF) in an automotive case study. The product considered in the case study is a rear axle subassembly which consists of mechatronic actuators, active stabilizer, rear axle differential, and a Magneto Rheological (MR) dampers. The type of system considered in the case study is flexible production/manufacturing system. They concluded that implementing a hybrid CTO and MTO reduces manufacturers time and costs.

ElMaraghy et al. (2013) provided a comprehensive review of different manufacturing system strategies to deal with variety in production. They introduced MTS as a lean production principle that helps to identify and eliminate waste through the use of takt time control and pull mechanisms. Moreover, while conducting their review, they noted that the lean principles were implemented more in MTS flow shops than in MTO job shops.

(Rajagopalan, 2002) introduced a model to help decide if a particular product should be made to stock or made to order. The decision was based on various factors such as demand rate and available capacity. (Iravani, Luangkesorn, & Simchi-Levi, 2003) developed a quasi-birth-and-death process, a method used to provide a performance measure of assemble to order systems. In addition, they introduced a new approach for measuring and evaluating the satisfaction levels of customers. (Krishnamurthy & Suri, 2009) designed a strategy called paired-cell overlapping loops of cards with authorization (POLCA), which was a hybrid push-and-pull strategy that combined the best of each approach. Their strategy is suited for a large variety of manufacturing environments and/or customized products. (Benjaafar, Kim, & Vishwanadham, 2004) examined the effect of offering product variety, and how it had a direct effect on inventory costs, by implementing the MTS manufacturing strategy. They introduced a model to analyze the behaviours of inventories with multiple product variants. They concluded that there was a direct effect on total costs when increasing the number of product variants.

(Dobson & Yano, 2002) developed a mathematical model for optimizing product offerings, optimizing cycle time decisions, and choosing between MTO and MTS. They concluded that strategic MTO and MTS decisions depend on product holding costs and customers' sensitivities to delivery times and prices. Another study was conducted by(Lu & Song, 2005); they developed a mathematical optimization model to determine favourable levels of stock of different product variants. The main objective of this study was to minimize inventory costs by integrating customer demands in multi-item inventory planning. The solution from the developed model proved that in ATO systems, customers' demands have more effect than lead time variabilities. Based on the literature review above, it can be summarized that many manufacturers are moving from make to stock MTS to make to order MTO due to large inventory and carrying costs. However, as they are part of the competitive manufacturing industry, it is difficult or even impossible for them to compete with others without holding some level of inventory.

2.4 Manufacturing Systems

Manufacturing systems can be divided into three main types, shown in Figure 2.4, dedicated manufacturing (machining) systems (DMS), flexible manufacturing systems (FMS), and reconfigurable manufacturing systems (RMS). DMS is concerned with producing a specific part in which a fixed transfer line and fixed tooling and automation are implemented. This type of manufacturing system is suitable for a low variety of products and a high volume, or mass production (Mehrabi, Ulsoy, & Koren, 2000). It was first introduced by Henry Ford with "the moving assembly line," and reached its peak after World War II (S Jack Hu, 2013). FMS can handle a medium variety level and a medium volume level. A flexible manufacturing system is designed with built-in flexibility for a family of products defined a priori. While the hardware structure is not changeable, its machines are programmable and can perform operations for changeover on a random sequence with minimal effort, time, and expense (H. A. ElMaraghy, 2005).

(Koren, 2010) defined RMS as "designed at the outset for rapid change in structure, and in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements." The main difference between RMS and DMS is that RMS is a manufacturing system with customized flexibility, while FMS is a manufacturing system with general flexibility (H. A. ElMaraghy, 2005). She compared flexible and reconfigurable manufacturing system paradigms. She summarized several manufacturing flexibility types and their applicability for machines, product routings, production volumes, and control systems (H. A. ElMaraghy, 2005).

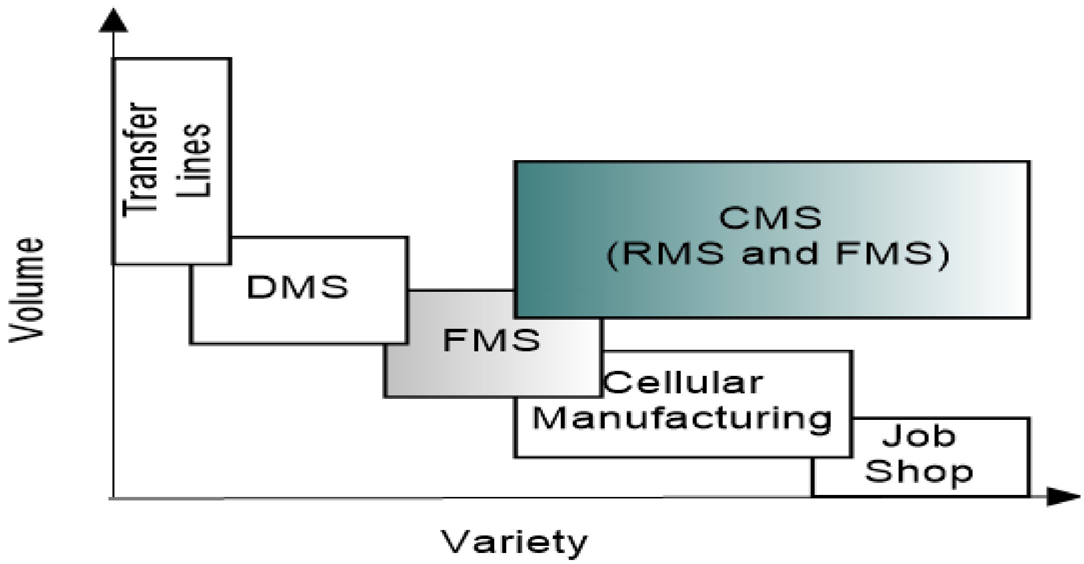

Figure 2.4: Manufacturing System Types Source: (H. A. ElMaraghy, 2005)

2.5 Research Gaps

Several research gaps were identified in the literature review, and are shown in Table 2.1. To begin, research on product families and platforms has not covered the optimal platform configuration. Moreover, relationship between platform configuration and inventory costs have not been mentioned, except by Hanafy in 2014, and effect on assembly lead time has not been previously considered. The available research has only addressed the issue of product platforms' formation by developing mathematical models, metrics, and other techniques. The effect platform formation strategy has on system performance has not been addressed. Additionally, previous research has not related the MTO, MTS, and ATO manufacturing strategies to product platforms and product families, and researchers have not clarified different strategies to be used for fabrication and assembly. Previous research such as (Ben-Arieh, et al., 2009; Hanafy & ElMaraghy, 2015) has assumed constant assembly/disassembly time / costs which is not accurate since assembly time depends on the parts shape, symmetry size, etc. as outlined in the Design for Assembly methodology (DFA) Boothroyd, Dewhurst, & Knight (2010).

Figure 2.5 relates manufacturing strategies to product families and product platforms. ATS is the strategy used when a high volume of products are demanded, and it provides the quickest lead time. In this strategy, products are produced at a high volume using a dedicated machine in order to cope with demand. However, ATO is used when the product volumes are low; thus, it has a longer time to satisfy orders. In the middle, CPTO is used when products have a medium volume. Hence, it is used when assembling platform components, which are the most common components among all variants, or the products in the family with the highest demand. Once the order is placed, customization takes place

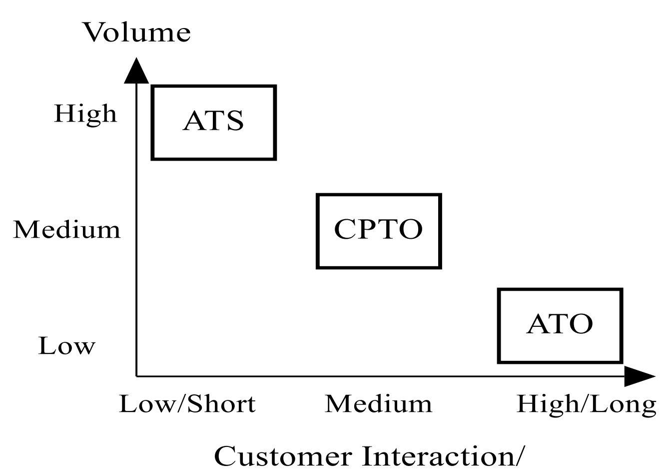

Figure 2.5: Characteristics of Manufacturing Strategies and Assembly Policy

through the addition, removal, and/or substitution of components until variants are fully assembled.

Table 2.1: Research Gaps

	# of Platform(s)		**Formation Model**			**Factor(s) Studied**					**Manufacturing Strategies**					**Solution Type**	
	Single	Multiple	Addition Only	Addition/ Removal/ Substitution	Scaling	Assembly Time	Assembly Cost	Demand	Labour Cost	Inventory Cost	MTS	MTO	ATO	ATS	CPTO	Mathematical Model	Simulation Model
Hanafy, M. & ElMaraghy, H (2015)		X		X			X	X	X				O			X	
Ben-Arieh, Easton & Choubey (2009)		X		X			X	X	X		O					X	
Simpson, T. W. et al (2001)	X				X		X	Θ	O			O				O	
Jin, M. & Chen, R (2008)		X	O				X	X		X		O				X	
Iravani et al. (2003)								O					Θ				
Rajagopalan, S. (2002)										Θ	Θ	Θ					
Benjaafar (2004)								Θ		X	Θ	O					
Dobson & Yano (2002)								X			O	O					
AlGeddawy & ElMaraghy (2010)	Θ		O														

X: Strong relationship

Θ: Moderate relationship

O: Weak Relationship

2.6 Conclusion

In this chapter, relevant research papers were reviewed in the area product family and platform, manufacturing strategies and assembly policies, manufacturing systems, and mass customization. The findings of the extensive literature review indicates that there are gaps to be addressed. Therefore, this thesis addresses one of these gaps by investigating the effects of product platform configuration, under different manufacturing strategies and assembly policies, on assembly and inventory cost and system performance and comparing them with results reported in existing paper such as (Hanafy & ElMaraghy, 2015) and (Ben-Arieh, et al., 2009).

CHAPTER 3: PRODUCT PLATFORM AND MANUFACTURING STRATEGY FOR RMS

3.1 Overview

The current market is readily changing; manufacturers are forced to provide a variety of products to meet customers' changing requirements and needs. These changes come with huge costs, and manufacturers have to respond quickly and efficiently to be competitive in the marketplace. Researchers are motivated to help manufacturers overcome these problems. Therefore, extensive research has been carried out on customization, product platforms, and production policies; however, most of the existing research does not make use of simulation modeling approaches or compare results with actual experiments, drawing robust conclusions. Most research is concerned with developing mathematical modeling approaches, which require many assumptions and can lead to infeasible solutions. In addition, in mathematical modelling, such as optimization modeling, the behaviour of the modeled system is not tracked over time; only the final answers are given, unlike the simulation modeling or discrete-event simulation modeling approaches where the behaviour of the systems are observable and results are shown as the models progresses over time; analyses and improvements to the models can be implemented.

3.2 Introduction

Manufacturers adopt manufacturing strategies that fit their target customers and markets. It is important for firms to effectively position themselves by adapting the right strategies to maximize their profitability. Numerous studies have attempted to explain the different strategies, but have failed to differentiate between fabricating, machining, and the assembly process. Figure 3.1, shows a different manufacturing strategy that was modified from

(Esmaeilian, et al., 2016; Meredith & Akinc, 2007)'s strategy, and includes the MTO, MTS, ETO, MTF, ATO, ATS, and CPTO manufacturing strategies and assembly policies.

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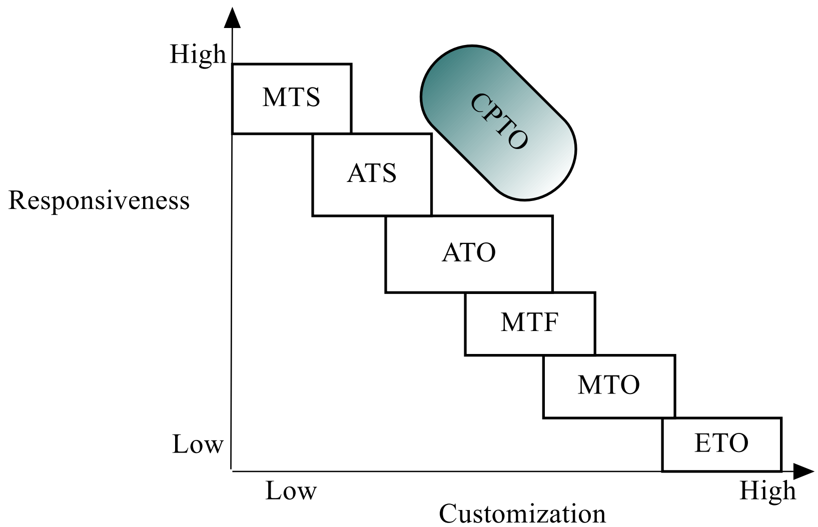


Figure 3.1: Manufacturing Strategy Types, Modified from (Meredith & Akinc, 2007)

Engineer to order (ETO) is a production or manufacturing strategy that takes each customer's specifications and requirements and designs a new product that fits his/her need. It is not only a high level of customization, but is also a high level of personalization. The response and lead times are very long for a high level of personalization to occur.

The make to stock (MTS) approach is characterized by a very short lead time, achieved by holding an inventory of finished goods. Assemble to stock (ATS) is an approach wherein parts are made and assembled and held in inventory. It involve a quicker lead time since the product is made and assembled ahead of time. Assemble to order (ATO) is a manufacturing strategy wherein a product that has already been manufactured needs to be assembled. The assembly can be based on customer requirements, and customization can occur to a certain extent (it has a medium customization level).

The make to order approach is based on fabricating a product according to customers' requirements; it involves a high lead time, but the lead time is still quicker than the ETO approach. Make to forecast (MTF) is slightly different than the MTS and MTO approaches. A good example for illustrating the concept is airplane production and assembly. When an airplane goes through the manufacturing and assembly process and the order is received, the airplane is assembled with slight changes, such as appearance (printing the logo of a company and/or changing the colour of the airplane) (Meredith & Akinc, 2007).

The customize to order (CTO) approach is based on customizing modular components that exists in large variety in which variety can be generated through software enhancement and parameterization which are not visible to end customer (Ericsson, et al., 2010).

Lastly, customize platform to order (CPTO) is a new term inspired by (Hanafy & ElMaraghy, 2015) and (Ben-Arieh, et al., 2009) who introduced the idea of using both assembly and disassembly while forming product platforms. Unlike the CTO, the CPTO is based on customizing product platform components based on customer demand. In this approach, a product is fabricated and the product platform is assembled. When a customer's order is received, customization takes place. The difference between ATO and CPTO is that CPTO involves platform assembly prior to customer orders, while ATO starts the assembly process when the order is received. Platform assembly can be based on demand forecasts and can be optimized by developing a larger and customized platform that is shared by variants with highest demand. In case of new product introduction and/or lack of historical demand data, as is the case for existing products, educated assumption about expected demand can be made based on market research, executives judgement and/or similar products in the market. Modification of product platform can be done by adding, removing, and/or substituting parts to match each customer's order. Figure 3.2 and 3.3 show the difference between CPTO and ATO within the research scope.

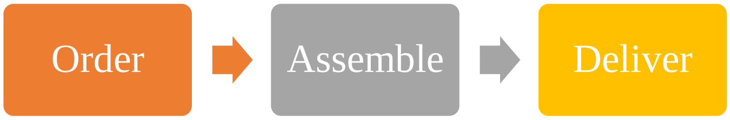


Figure 3.2: ATO Assembly Process

Figure 3.3: CPTO Assembly Process

This chapter is concerned with the construction of a discrete-event simulation model to analyze the statement of the engineering problem. The main purpose of the model is to integrate product platform formation and production policies using FlexSim software. This is to decrease lead times and inventory costs.

3.3 Methodology and Model Development

In order to develop a discrete-event simulation model, it is necessary to identify and analyze the problem. The next section presents an overview of the IDEF0 tool. It is used for the discrete-event simulation model.

3.3.1 IDEF0

The ICAM definition for function modeling (IDEF0) approach distinguishes between inputs, outputs, mechanisms, and constraints, shown in Figure 3.4. Five inputs are required for this model, such as the historical demand data of each variant and the time of the orders were placed. The number of variants to be produced and the demand quantity of each variant are assumed constant. The desk set for this research consists of more than 900 variants; however, to prove the concept, five variants are considered that remain constant throughout the case study. The third input is transportation and assembly times. Transportation time is the time spent on the fixture that holds the variants traveling between stations, while assembly time is the time required to assemble certain components. The fourth input is platform components: how many components are considered a platform that are assembled prior to customer demand. The last input is the assembly sequence of each variant, which is the steps required to convert the components into finished products.

The mechanisms/tools used in the model are Boothroyd and Dewhurst (DFA) and FlexSim, and manufacturing strategies and assembly policies such as ATS, ATO, and CPTO are also used. FlexSim is a discrete-event simulation software that is widely used in the manufacturing and healthcare industries. Boothroyd and Dewhurst (DFA) is a methodology used to estimate the time needed to assemble individual parts to form a complete product variant and simplify the design. This tool helps approximate the assembly costs of variants (Boothroyd, et al., 2010).

In addition, there are two constraints for the model, which are the inventory information and system capability. The inventory information meaning how many space available to store units in the AS/RS while the system capability constraints include the speed of the conveyor, the speed of the robots, the inventory storage capacity, the robot gripper's capability, and more. The goal is to assemble the platform under three different conditions: (i) assembling the actual platform only, which consists of main common components between the variants till demand is received; (ii) assembling a larger platform, and using the concept of platform scalability, or larger platform, which is formed according to the historical demand then disassembling some modules as needed to fulfill demand; and (iii) assembling individual components using one piece flow manufacturing strategy on demand. Lastly, the system's capability. Figure 3.5 shows the research's decoupled node, which contain three phases: data collection and family identification, discrete-event modeling, and experimentation and validation of the results with iFactory.

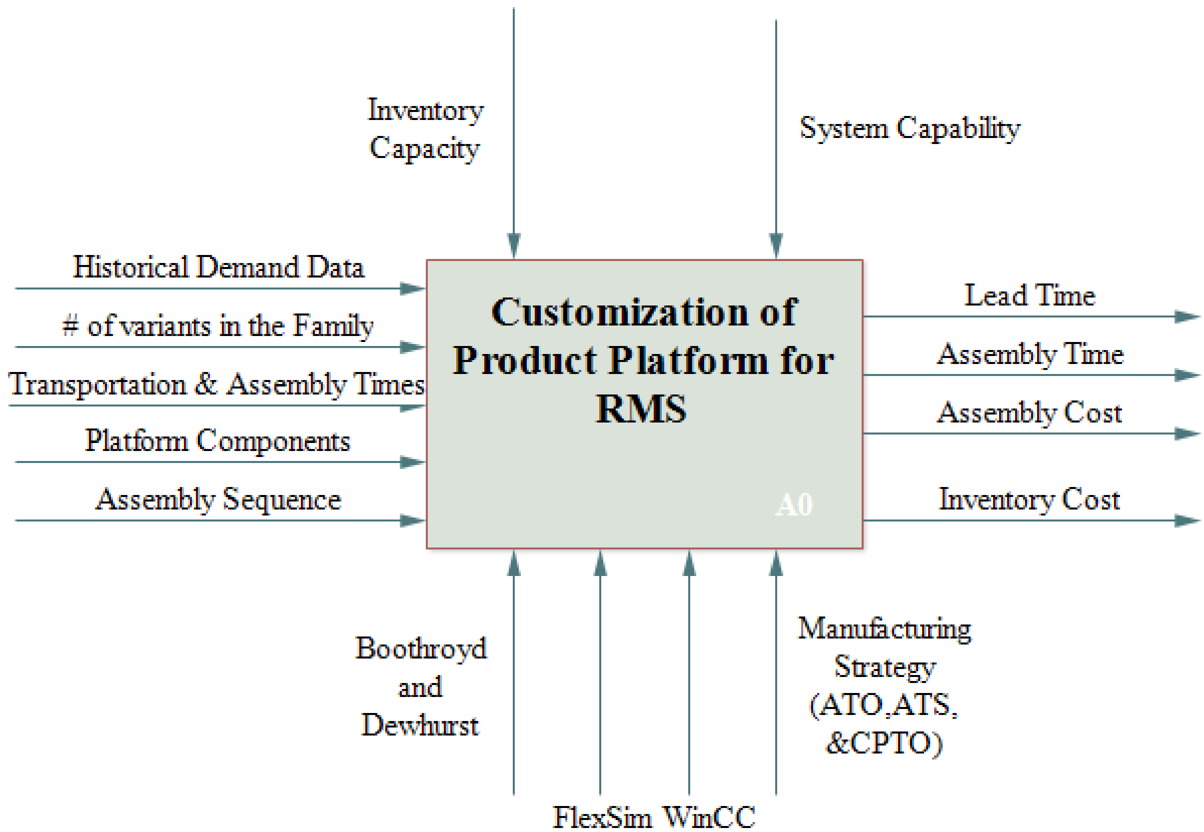


Figure 3.4: IDEF0 of Discrete-Event Simulation Model

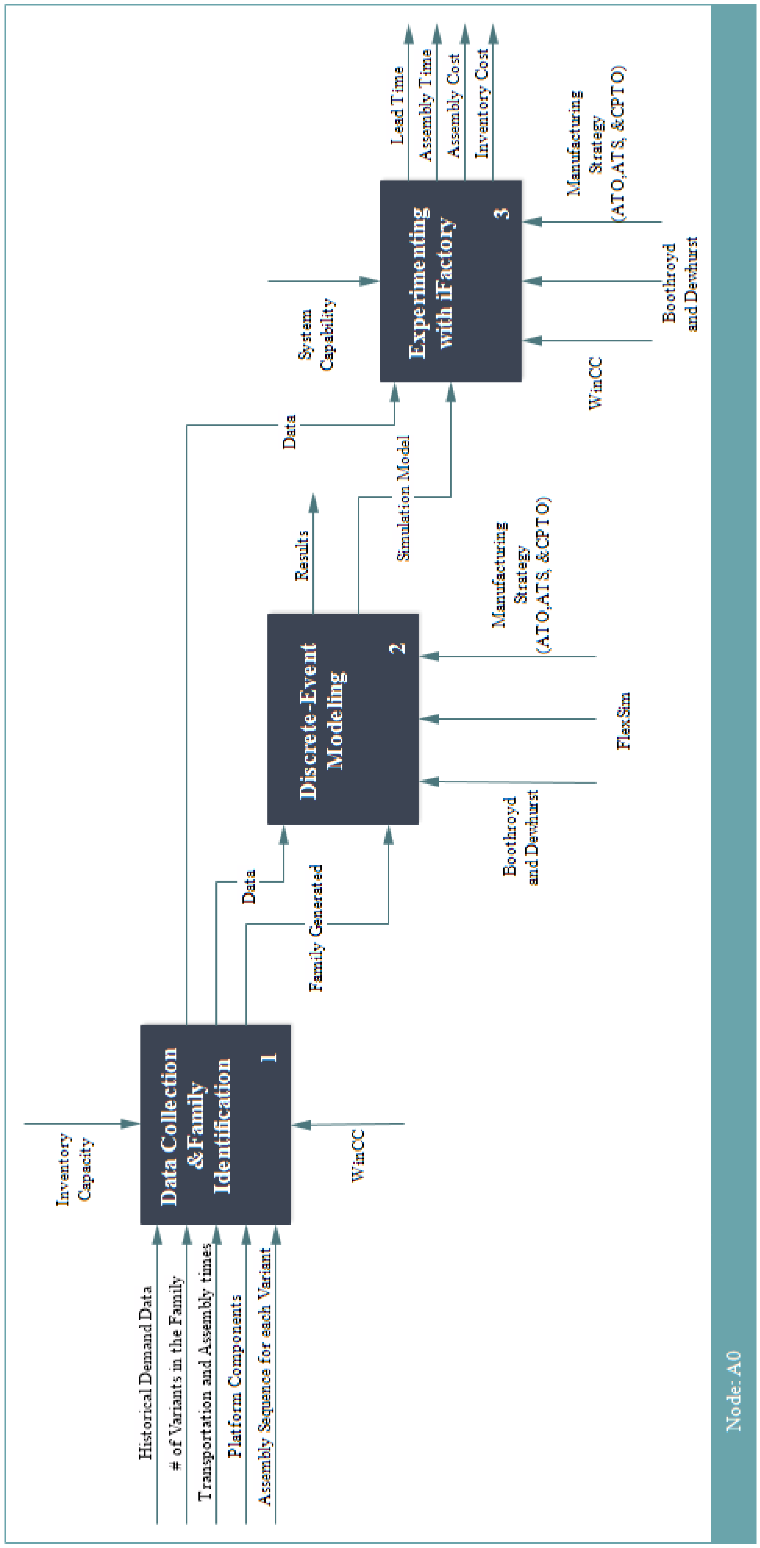


Figure 3.5: IDEF0 Decoupled for Detailed Activity

3.4 Illustrative Example

An illustrative example is provided to gather all the information presented and to present a clear understanding of the challenge at hand, the research scope, and the expected outcome of the research. An example is adapted from Ben-Arieh et al. (2009) for illustration purposes only. Figure 3.6, illustrates a product family with four product variants. Each variant consists of five components from a set of eight (A, B, C, D, E, F, G, and H). Components A and B are the platform components, which are shared by the four variants.

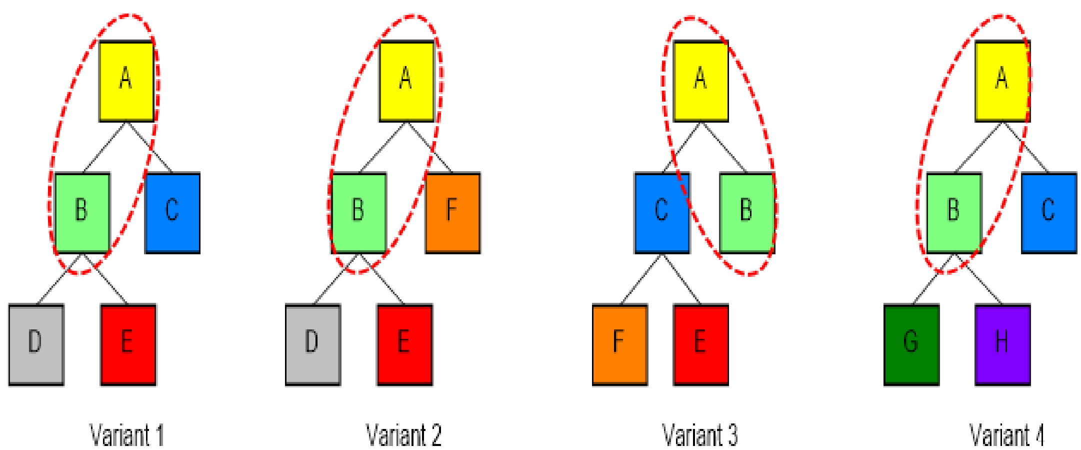


Figure 3.6: Illustrative Example from Ben-Arieh et al. (2009)

A discrete-event simulation is developed to show the effect of changing platform components and its effect on assembly and production costs shown in Figure 3.7. Four different scenarios are considered for investigation purposes. The first is one in which platform components are produced prior to the customer's order (A & B) and the differentiation of the product family is delayed. The remaining components are then assembled once the order is received.

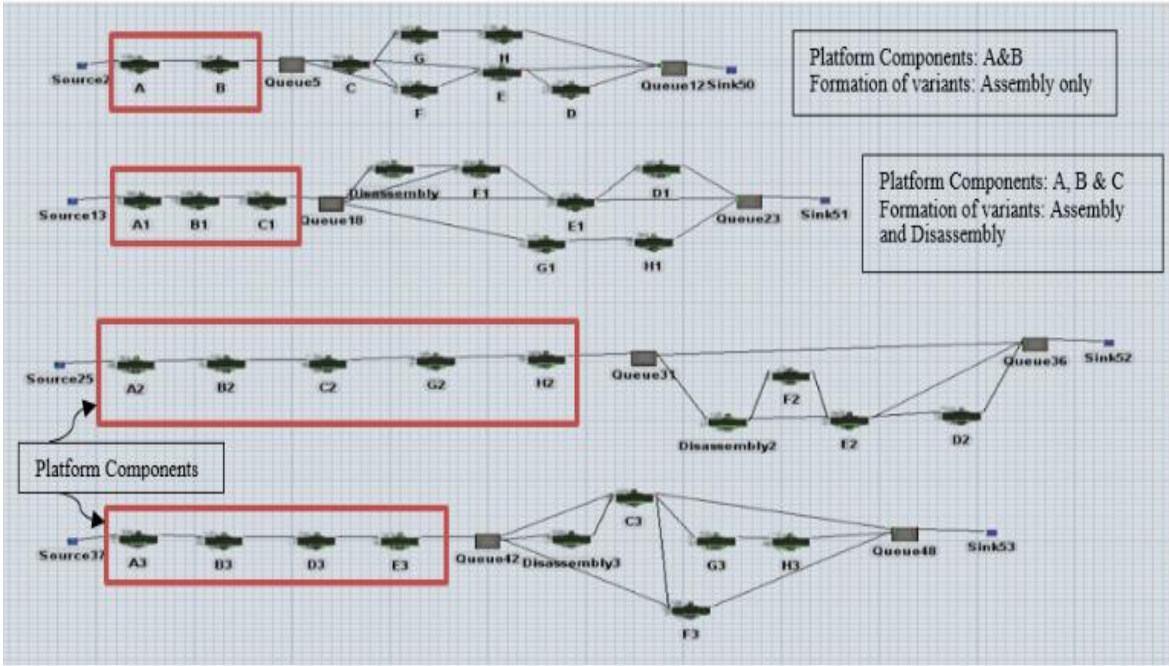


Figure 3.7: Illustrative Example Discrete-Event Simulation

The second scenario considers a larger platform in which components exist in 75% of the product family and 90% of the overall demand. The larger platform is assembled for the whole product family prior to customers' orders. The rest of the products are then assembled once orders are received. Finally, a disassembly station dedicated to dissembling the variants with the lowest demand is created.

The third scenario produces a complete product variant, which represent 92.5% of the total demand and considers it a platform. A disassembly station is then created that modifies 7.5% of the total demand. Finally, the fourth scenario is similar to the second scenario, in which a larger platform is considered based on demand. Disassembly takes place for modifications to meet the variants with the lowest demand.

Table 3.1 shows the monthly demand for the four variants and the overall production, which includes assembly, disassembly, and setup costs. As shown, production costs highly depend on customer demand, and platform components/design configurations are considered when producing each product. It is noticeable that integrating platform formation based on customer demand results in cost savings as high as 5%.

Table 3.1: Demand and Results of Discrete-Event Simulation Model

Variant Demands (D_v) [V_1, V_2, V_3, V_4, V_5]	**Platform Components [C_P($)]**				**Difference in $**
	AB	**ABC**	**ABDE**	**ABCGH**	
[250, 250, 250, 250]	**78,850**	81,600	90,100	112,850	N/A
[700, 100, 100, 100]	77,200	**77,100**	79,300	115,400	100
[25 , 25 , 25 , 925]	81,775	80,250	116,200	**79,775**	2000
[500, 300 , 0 , 0]	61,700	65,900	**58,600**	100,300	3100

After proving that designing platforms based on customer demand result in cost saving, investigating the effect of implementing a different manufacturing strategy is essential. Three different approaches were simulated using a discrete-event simulation model shown in Figure 3.8. The first was the assemble to order (ATO) approach, assembling components using one piece flow when the order was received. No platform was considered. The second was the hybrid assemble to order (ATO) and assemble to stock (ATS) approach. The platform was the common component between all product variants, which were assembled prior to customers' orders. The last was the customize platform to order (CPTO) approach. It is a hybrid ATS/ATO approach. Larger platforms, based on historical demand, were assembled prior to customers' orders. Platform components were based on individual orders, and components had to have at least 75% of the total demand for each variant. Assembly and disassembly then took place after the order was received.

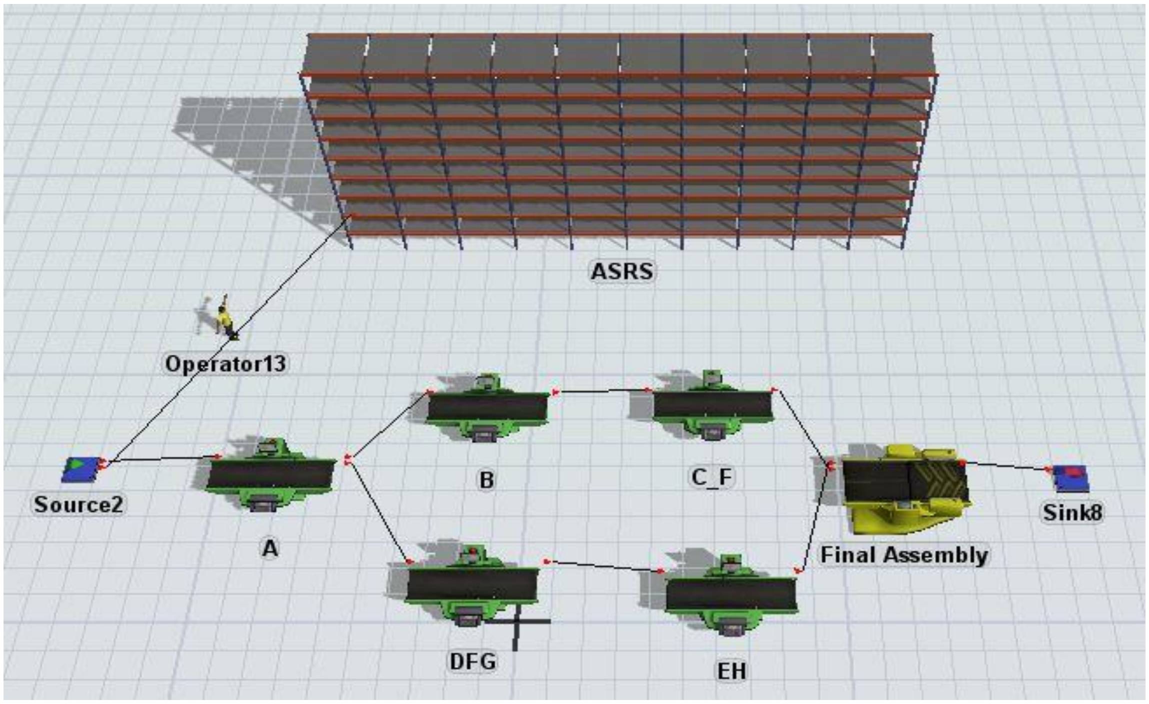


Figure 3.8: Simulation Model for ATO/ATS and CPTO

Table 3.2 presents the results of the simulation model. It shows that by adopting different manufacturing/production strategies, manufacturers can reduce overall production costs. In addition, adopting the ATO and CPTO approaches results in significant cost savings.

Table 3.2: Simulation Model Results of ATO/ATS and CPTO

	Production Costs (C_p) in $				
Variant Demands (VD) [V_1, V_2, V_3, V_4, V_5]	**ATO**	**ATO and ATS (Platform)**	**CPTO (Larger Platforms)**	**Difference in $**	**% Difference**
[250, 250, 250, 250]	108,875	103,675	N/A	5,200	4.8
[700, 100, 100, 100]	106,730	101,530	97,370	9,360	8.8
[25 , 25 , 25 , 925]	112,677.5	107,477.5	101,270	11,407.5	10.1
[500, 300 , 0 , 0]	85,670	81,510	78,000	7,670	9.0

3.5 Case Study

The reconfigurable manufacturing system iFactory, available in the Intelligent Manufacturing Systems Centre (IMSC) at the University of Windsor, was used. It is shown in Figure 3.9. The system consists of several modules, such as AS/RS for storing individual components and finished products; conveyors to move products from station to another; a PLC control unit; a robotic assembly station; sensors; and a manual station.

Figure 3.9: The reconfigurable learning factory at the Intelligent Manufacturing Systems (IMS) Center, University of Windsor, Canada (www.uwindsor.ca/imsc)

The iFactory system is capable of producing a desk set family shown in Figure 3.10. Each desk set has three positions to add different cups (long and short), clocks, and/or gages, allowing each customer to customize his or her desk set to his or her needs and preferences. This product family of a desk set, and the system available in the IMS Centre, both serve the purpose and the scope of this research.

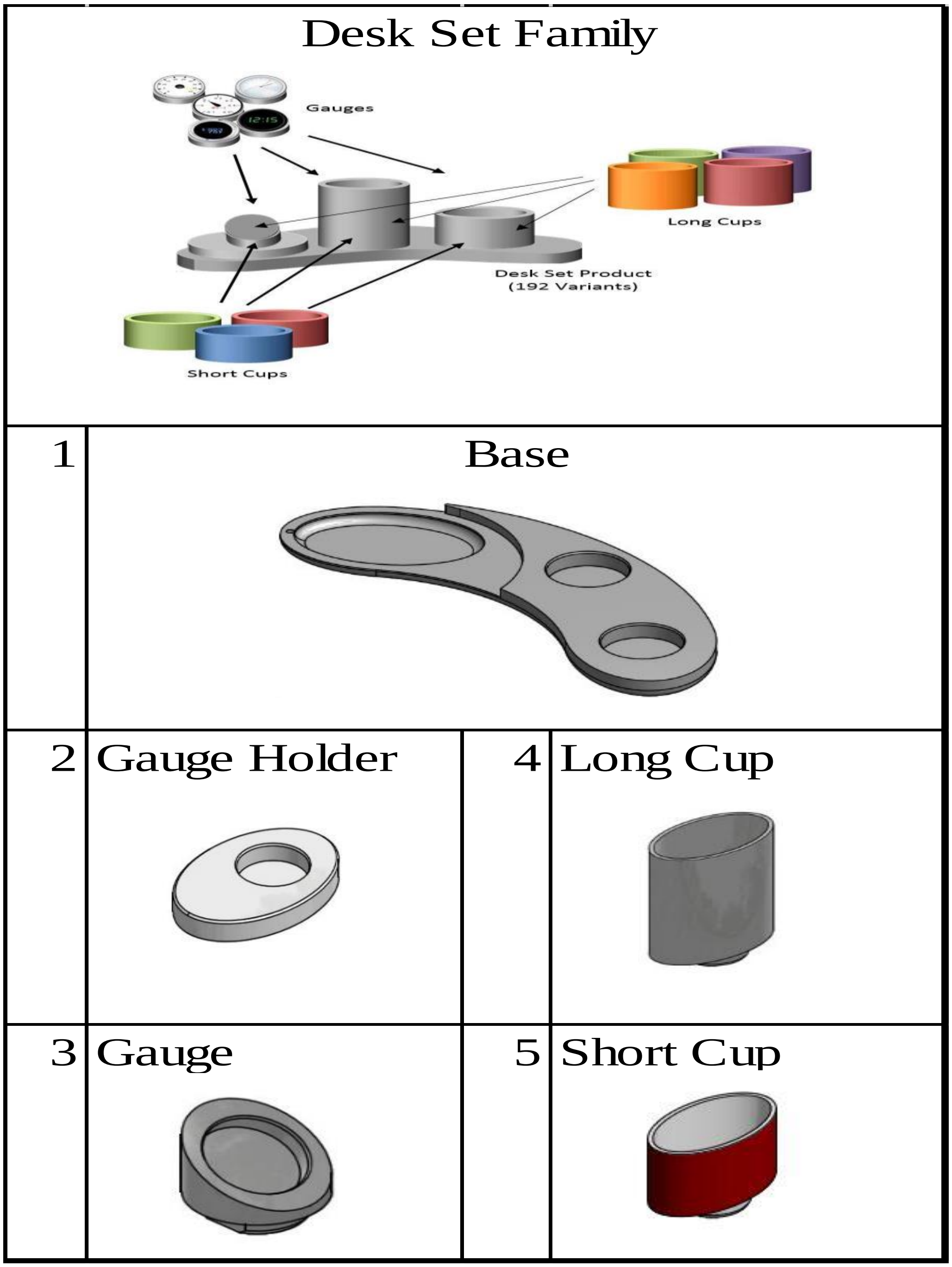


Figure 3.10: Desk Set Family and Components

3.5.1 Desk Set Variants

The desk set family consists of approximately 900 variants. Five different variants are considered in the case study and are shown in Figure 3.11. Each variant consists of five (N_v) components. Variant one consists of a base, a gauge holder, a gauge (clock), a long cup, and a short cup. Variant two consist of a base, a gauge holder, a gauge (pressure), a long cup, and a short cup. Variant three consist of a base, a gauge holder, a gauge (pressure), a long cup, and a gauge (clock). Variant four consists of a base, a gauge holder, a short cup, a long cup, and a short cup. Variant five consists of a base, a gauge holder, and three long cups. Four different platforms scenario are considered based on customer demands as shown in Figure 3.12.

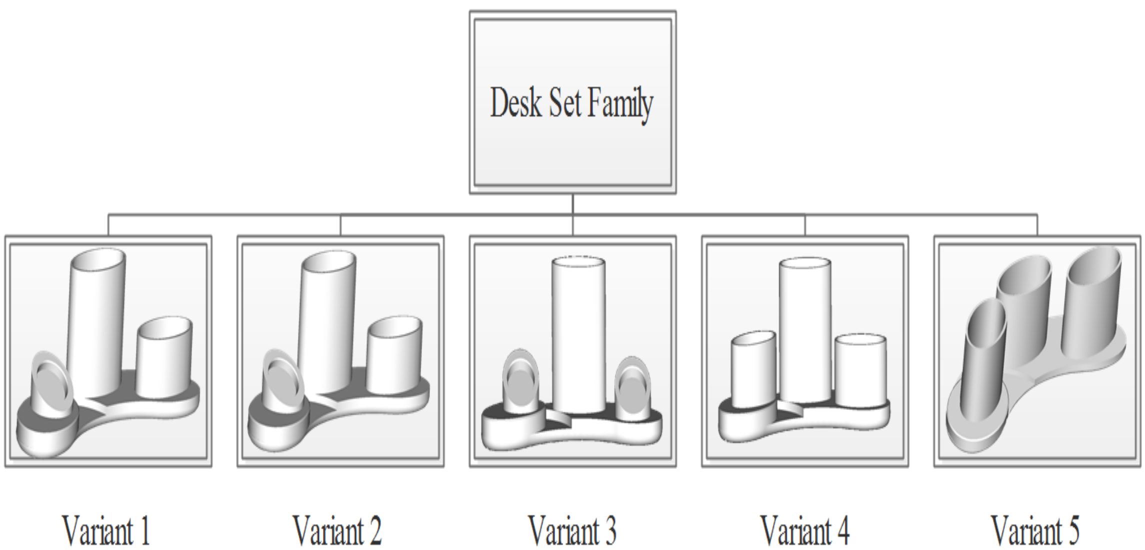


Figure 3.11: Desk Set Variants

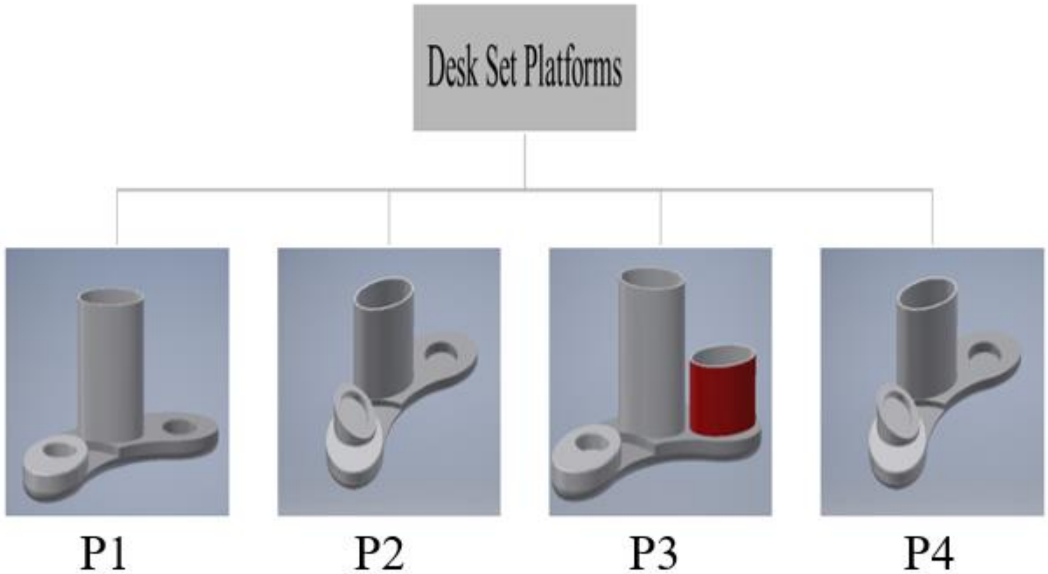


Figure 3.12: Desk Set Platforms

3.5.2 iFactory Simulation Model Development

In order to develop the discrete-event simulation model, an analysis of the real system must be done. The process begins when customer orders arrive through the iOrder website. Then the assembly process begins, as shown in Figure 3.13.

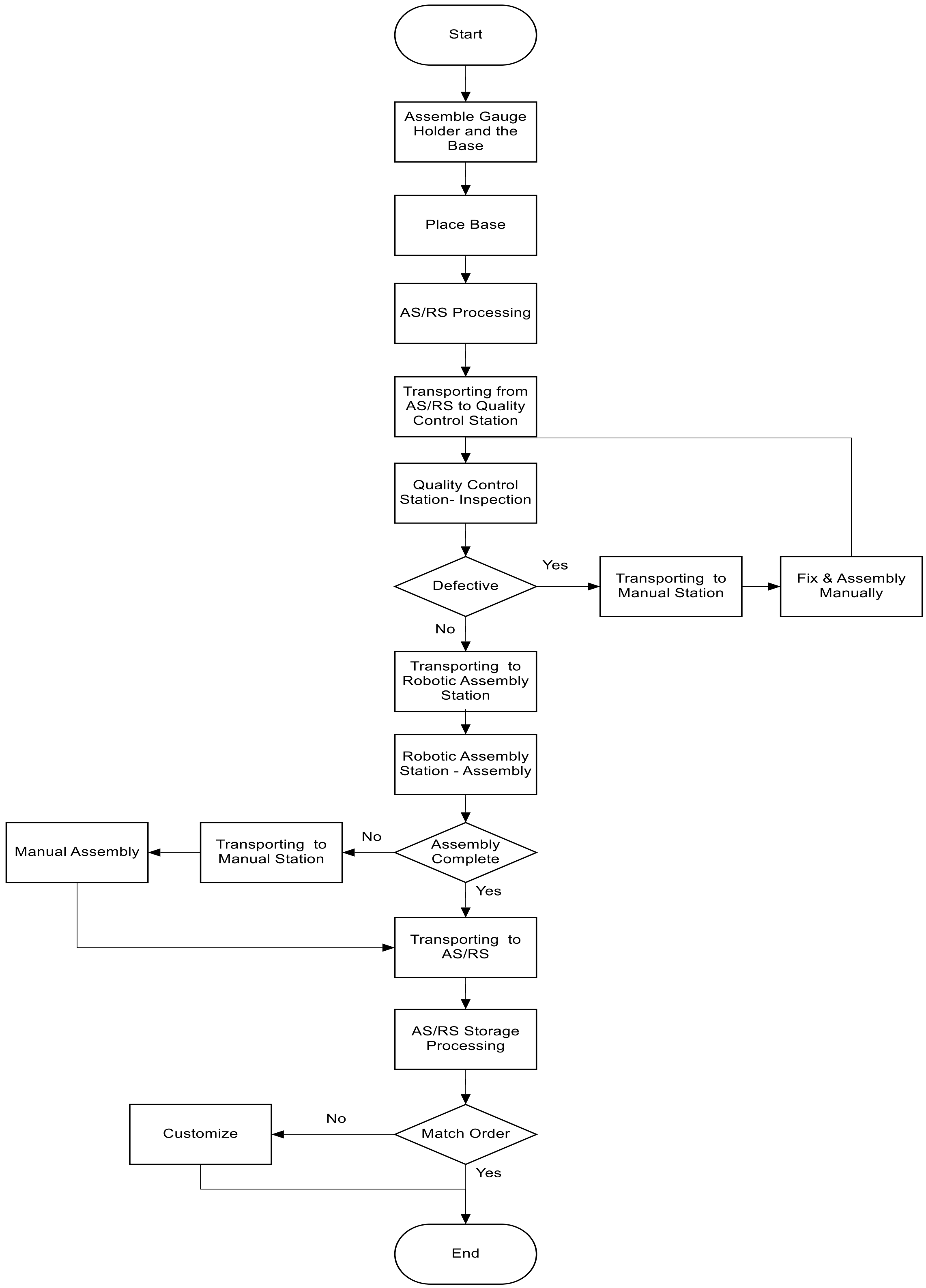


Figure 3.13: iFactory – Desk Set Family Case Study Assembly Flowchart

The process of assembling the deck starts with placing the base in the AS/RS to be processed. Then the AS/RS lifts the base and places it on a conveyor to be transported to a quality control and inspection station. After inspection is complete, the base is transported to a robotic station; however, if the base is defective, it is sent to a manual station to be repaired and for the process to start again. The robotic station is the first assembly station in which cups are assembled. The number of cups and the location of each cup is according to each customer’s order. Next, when the assembly is complete, the cups are transported to the AS/RS to be stored in the inventory. If additional assembly is required—for example, of the gauge—the desk sets are transported to manual assembly, which is the second assembly station, and then back to the AS/RS.

3.5.2.1 Data Collection

An actual run for the iFactory was conducted in order to collect processing and transportation times. Table 3.3 shows the processing time, sequence of operations, and if the process of assembling the desk set family was manual. There are a number of variables in the processing time and sequencing based on each product variant. The first two variables are the robotic assembly station and the manual assembly station, where each cup requires 11 seconds to be assembled, while the processing time for the manual assembly of the gauge is five seconds. Moreover, each variant requires a specific sequence. For example, variant three only requires three cups to be assembled; thus, it does not travel to the manual station. The times are based on the first scenario, ATO, in which no platform is considered.

Table 3.3: Desk Set Assembly Sequence and Process Times

Step	Operation Sequence	Process Time (t_p) in seconds	Automated/Manual
1	Assemble Gauge Holder and Base	2/part	Manual
2	Place Base	2	Manual
3	Process AS/RS	7	Automated
4	Transportation from AS/RS to Quality Control Station	4	Automated
5	Quality Control Station	1	Automated
6	Transportation from Quality Control Station to Robot Assembly Station	5	Automated
7	Robotic Assembly Station	8/cup	Automated
8	Transportation from Robotic Assembly Station to AS/RS	10	Automated
9	Transportation from AS/RS to Manual Station	12	Automated
10	Manual Assembly	3/gauge	Manual
11	Transportation from Manual Station to AS/RS	11	Automated
12	Process AS/RS Storage	7	Automated

3.5.3 iFactory Digital Model Development Using Discrete-Event Simulation

Figure 3.14 presents the layout of the discrete-event simulation model, which was developed by the Intelligent Manufacturing System Centre (IMSC). The model was developed using FlexSim software and is able to visually show different modules of the iFactory and the assemblage of the desk set classic variant (V_1).

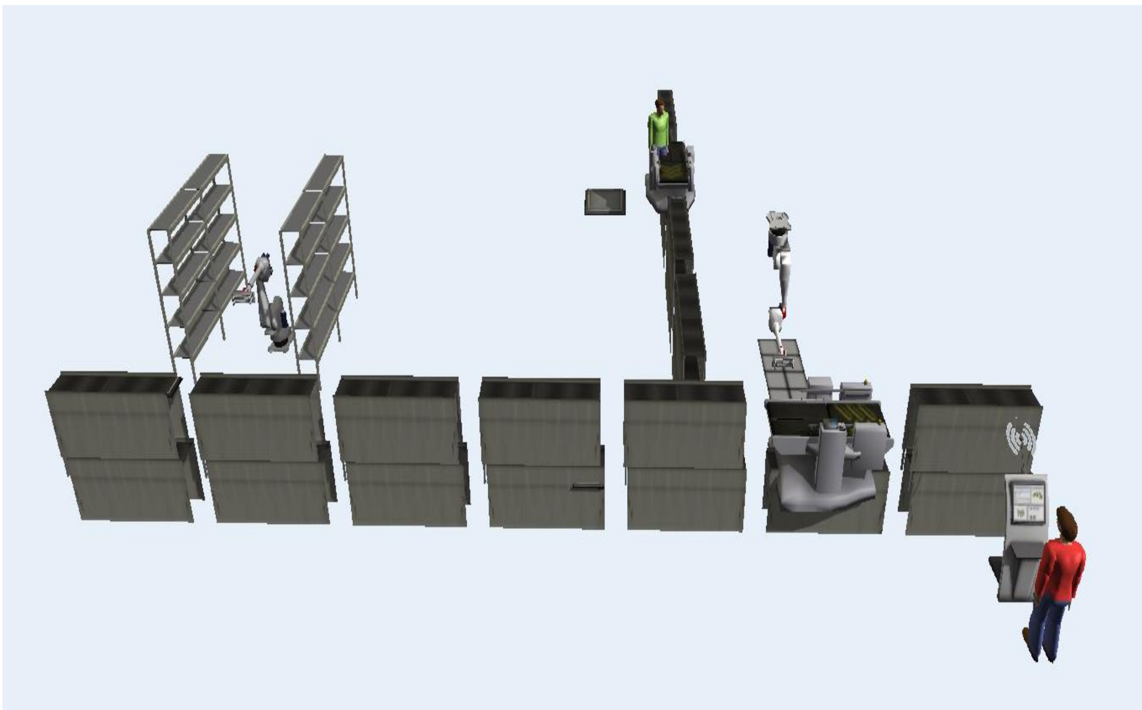
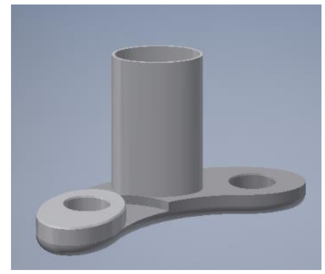
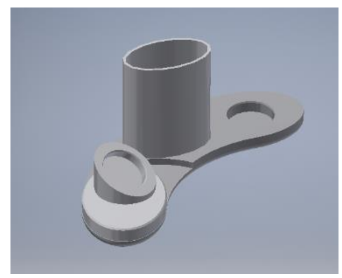
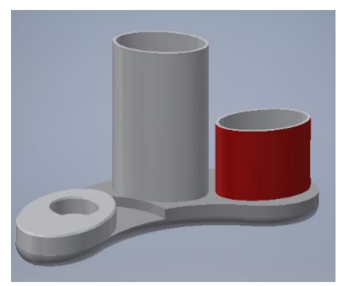
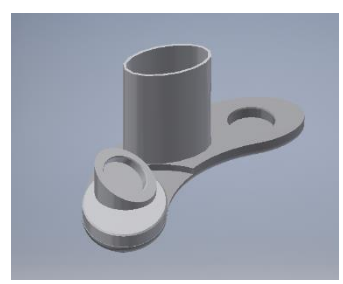


Figure 3.14: Discrete-Event Simulation Layout for iFactory

Four different variants were introduced to the model $V_{2\text{-}5}$, in order to examine the behaviour of the system and to calculate the lead time and inventory units. In addition, three different scenarios were used. The first scenario (Scenario A) used the ATO manufacturing strategy, in which no platform was considered. The second scenario (Scenario B) used the hybrid ATS for platform components, which were the core common components between the variants in the family. The third scenario (Scenario C) used the CPTO approach, wherein platform components were formed based on demand rather than on commonality and were stocked in the inventory. Additional assembly started when orders were received.

Table 3.4 shows four demand scenarios and the platform components, which were assumed. The demand quantity of each variant was carefully assumed to show the behaviour of the system and the effect of choosing the platform based on demand. The iFactory inventory could hold up to 100 units; thus, demand for the five variants could exceed the limit for each order in the study.

Table 3.4: Case Study Demand Scenarios

Variant Demands (D_v) [V_1, V_2, V_3, V_4, V_5]	Platforms (4) and their Components (PC)	
[20, 20, 20, 20, 20]	1 Base, 1 Gauge Holder, 1 Long Cup	
[40, 30, 15, 10, 5]	1 Base, 1 Gauge holder, 1 Gauge (clock), 1 Long Cup	
[25, 25, 7, 43, 0]	1 Base, 1 Gauge holder, 1 Long cup, 1 Short Cup	
[15,15, 50, 10, 10]	1 Base, 1 Gauge holder, 1 Long Cup 1, 1 Gauge (pressure)	

3.5.4 Model Assumptions

There were several considerations and assumptions made when constructing the Flexsim digital simulation model.

1. Demand (D_v) for each variants is constant (unit/day).
2. Only five variants were available to customers, and the time for assembling the individual platform components is 2 sec and non-platform components is 3 sec, while the time required to disassemble any individual component is 2 sec. These times were calculated using the DFA
3. Twenty five (25) product variants were considered in each run, as there were only 25 bases available in the iFactory. However, the actual demand for all variants in the simulation model was 100. To overcome this problem, the average time derived from the actual experiment was multiplied by four.
4. The queue time was integrated with the assembly and transportation times.
5. The calculation of the inventory and the work in progress (WIP) was based on 30 components each of the long cup, the short cup, and the gauge, which were available in the iFactory.
6. Worker's hourly rate used was $12.00 an hour, and the hourly rate for each machine was $18.00 an hour (Groover, 2015). This is a constant which varies depending on the company but it does not affect the studied system performance indicators.
7. The finished goods inventory was assumed to be 0 as it was assumed that products were delivered as soon as their assembly processes were completed.
8. Finally, the customizations by disassembly and substitution for individual variants took place at the manual assembly stations.

3.6 Conclusion

In this chapter, the customize platform to order (CPTO) approach was introduced and compared to other manufacturing strategies using simple illustrative examples by developing discrete event simulation models. The main difference between CPTO and other manufacturing strategies presents in the literature, including the product customize to order (CTO), is that the CPTO is concerned with customizing the product platform according to customer demands based on historical data in case of existing products, or making educated assumptions by conducting market research and seeking experts opinion in case of new products and/or lack of availability of historical data to form a platform. Detailed scenarios and experimentations are presents in chapter 4.

CHAPTER 4: RESULTS OF EXPERIMENT

4.1 Overview

In this chapter, three different scenarios are modeled in the FlexSim software of the iFactory system. In the first scenario, ATO was implemented and no platform components were considered. In the second scenario, hybrid ATS and ATO were implemented; the core common components shared between all five variants of the desk set family were considered a platform. The components were the base, the gauge holder, and the long cup centred in the middle of the base. The platform components were manually assembled and placed in the AS/RS before the iFactory started the assembly process. In the third and final scenario, the hybrid ATS/ATO was used, but ATS was concerned with the formation of platforms based on historical demand. This manufacturing strategy was called the CPTO strategy. For example, if a product variant experienced a high demand which showed at least 75% of the whole family demand, it was considered a platform. It was assembled manually and placed in the AS/RS before the assembly started, and modifications and customizations were later done in the manual station according to customer orders. It should be noted that the assembly of the desk set components required more time than the disassembly process, for reasons such as alignments and grapping the components from the inventory, which required the manual station to bend. Hence, the assembly time was increased. In the desk set case study, there were three inventories in the system: the AS/RS, the manual station (gauges), and the cups in the robotic station. These units showed a cost, which was added to the production cost.

The outcome of this chapter was to capture the results of the three scenarios, to consider them, and to compare it with a real physical implementation of the iFactory for verification.

Observing the system behaviours and comparing both results in terms of inventory costs in units and lead times.

The lead time was based on the time it took between the placement of the order in the iFactory to the completion of the assembly process and the item's storage in the inventory. It included the assembly time (t_A), the transportation time (t_T) from one station to another, and the queue time (t_q).

$$Lead\ Time\ (tL) = tA + tT + tq$$

The inventory costs (units) was based on the number of individual units stored in the AS/RS and the work in progress (WIP) inventory at each assembly station (the robotic and manual assembly stations). Inventory cost is assumed to be proportional to the number of units stored and the length of time held in storage.

$$Inventory\ Cost\ (Ci) = number\ of\ individual\ units\ in\ AS/RS\ + WIP$$

Total assembly time was calculated by adding the time it took to assemble a component in the two assembly stations (robotic and manual) and the time to customize a product variant if needed (Scenario C). These data are observed during an actual run of the iFactory.

Total Assembly time (tA)=Robotic Assembly + Manual Assembly + Customization (Assembly and Disassembly)

Assembly costs (C_A), were calculated by implementing the DFA tool; they were calculated based on the total assembly time for auto and manual operations.

*Assembly cost = (Manual Assembly time*labour rate) + (Robotic Assembly Time* Machine Rate)*

4.2 Simulation Model Results

Three manufacturing strategy scenarios were implemented in the simulation models ATO and ATS/ATO, with platform components as the core common components, and in the simulation model ATS/ATO, with platform components according to customers' demands (CPTO). The results of the discrete-event simulation model are shown in the following sections.

4.2.1 Simulated Lead Time

Table 4.1 shows the lead time data for the four demand scenarios under three manufacturing strategies and platform conditions. Data were extracted from the model by placing the demand orders for each of the scenarios and recording order times at the end. Figure 4.1 presents a summary of the lead times for the three manufacturing strategies.

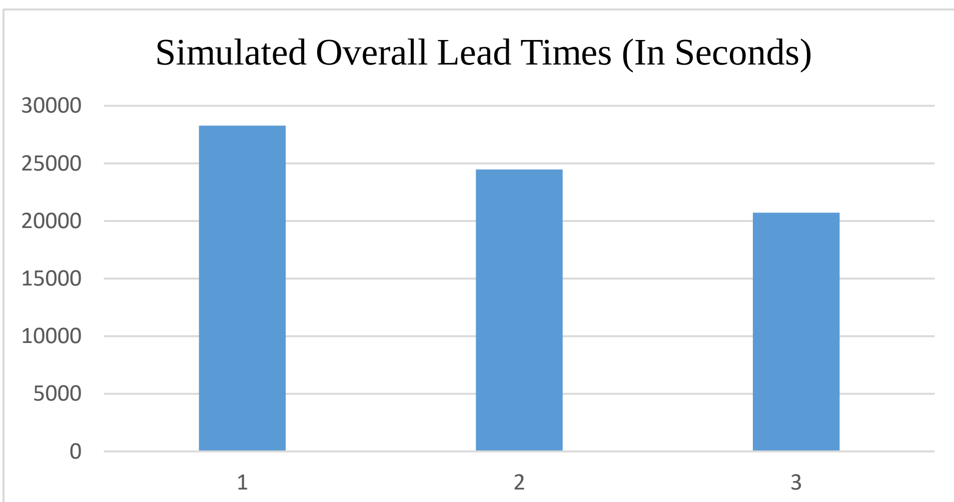


Figure 4.1: Overall Lead Times for 3 assembly scenarios

Table 4.1: Simulated Lead Time Data

	Manufacturing Strategy (Assembly Policy)/Lead Time (In Seconds)					
	ATO (No Platform)	**Hybrid ATS/ATO**	**CPTO (Larger Platforms)**			
	No Platform	**Same Platform**	**P1 for D1**	**P2 for D2**	**P3 for D3**	**P4 for D4**
Demand 1	6891	6062	6062	-	-	-
Demand 2	7328	6512	-	5019	-	-
Demand 3	6971	6113	-	-	4873	-
Demand 4	7097	5789	-	-	-	4759
Overall Lead Time (Seconds)	28287	24476	20713			

4.2.2 Simulated Inventory Units

Work in process (WIP) of individual components were traced in the simulation model by stopping the model at the end of each simulated hour and recording the inventory units for individual components. Table 4.2 illustrates the results of the total WIP in the systems for each scenario. Also, Figure 4.2 shows a comparison between the three scenarios.

Table 4.2: Simulated WIP Comparison Over Tome in Hours

Time (hrs.)	WIP (ATO)	WIP (ATO/ATS)	WIP CPTO	% Difference
0	2000	2000	2000	0
1	1748	1637	1595	9.15345
2	1425	1333	1287	10.177
3	1207	1151	1092	10.0043
4	968	936	883	9.18422
5	679	667	631	7.32824
6	491	479	454	7.83069
7	240	224	195	20.6897
8	116	102	91	24.1546

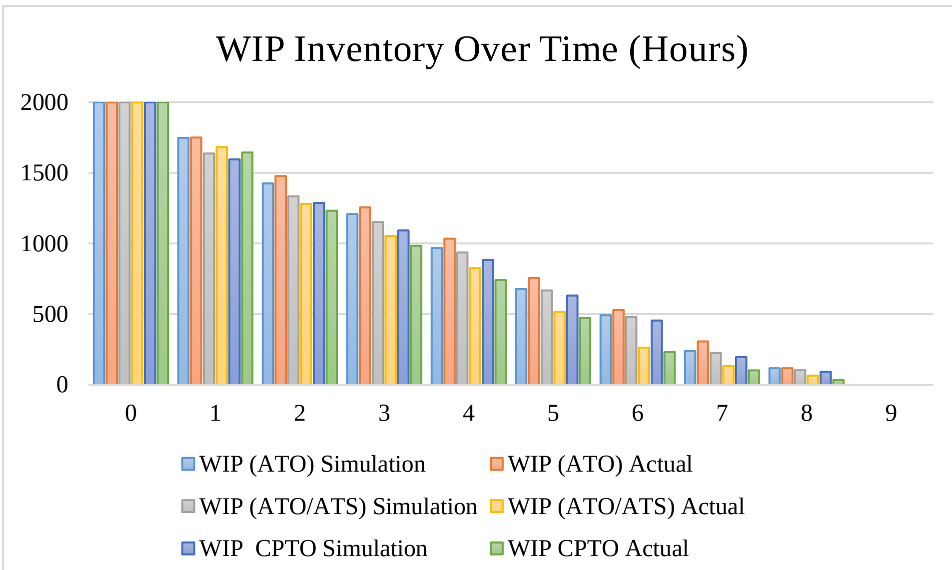


Figure 4.2: Simulated WIP Comparison Over Tome in Hours

The CPTO approach had the least number of WIP inventory compared to the other two manufacturing strategies. The percentage difference shown in Table 4.2 represents the difference in WIP between the CPTO and ATO approaches. WIP difference ranges from 7-24% depending on the demand and assembly time which affect the WIP. The highest difference in WIP inventory occurs in the last hour because variant three has the highest demand and the least assembly time in the last demand scenario.

4.2.3 Simulated Total Assembly Time

The total assembly time results from the simulation model were the same as the actual experiment lead times, in section 4.3.3 below. Total assembly time consists of both assembly and disassembly operations for each manufacturing strategy. The process times were observed in the real experiment and provided as an input for the simulation model. Table 4.3 and Figure 4.3 show summaries of the assembly times for the three different manufacturing strategies.

Table 4.3: Simulation Model Total Assembly Times

Manufacturing Strategy (Assembly Policy)	**Assembly Times (In Seconds)**
ATO	8858
ATS/ATO (Small Platform)	6930
CPTO (Larger Platforms)	5941

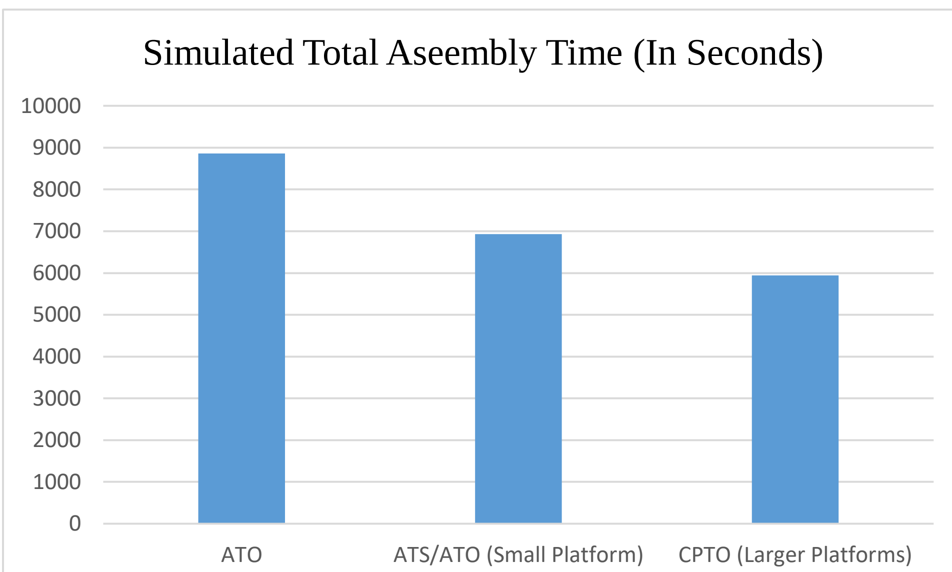


Figure 4.3: Simulation Model Total Assembly Times for the 3 Scenarios

4.2.4 Simulated Assembly Cost

In order to calculate the assembly cost in the simulation model, a label called "AssemblyCost" was created in the source. Once a variant went through the assembly process and entered the sink, a constant number was added to the label. For example, variant 1 consists of five components base, gauge holder, gauge, long cup, and a short cup. Three components are manually assembled and each requires 3 seconds. The two remaining components are assembled in the robotic station and require 8 seconds each. These times are converted to dollars by implementing the DFA tool and multiplying each time by its rate stated in the assumption section 3.5.4. Thus Cost ¢11.00 dollars to be assembled. Each time variant 1 entered the sink, ¢11.00 were added to the total cost label. Table 4.4shows the assembly cost results for the three different manufacturing strategies.

Table 4.4: Simulation Model Assembly Costs

Manufacturing Strategy (Assembly Policy)	**Assembly Cost ($)**
ATO	1200
ATS/ATO (Small Platform)	910
CPTO (Larger Platforms)	740

4.3 Actual Experiment Results

In order to validate the results obtained by the simulation model, an actual experiment was conducted in the Intelligent Manufacturing System Centre (IMSC). The following sections in this chapter show the results of the actual experiment for the different scenarios, which include lead time, assembly time, assembly cost, and inventory cost (in units). Appendixes A–C show a detailed computation of the lead times collected during the actual experiment for the scenarios.

4.3.1 Actual Lead Times (t_L)

Table 4.5 shows the lead times, which were observed by conducting actual experiments for each scenario. It shows the time it took to satisfy an individual order. The first strategy, ATO, had no platform and had the highest lead time. The second strategy, the hybrid ATS/ATO, with one platform as the core common component between the five variants, had a lower lead time than the first strategy. Lastly, the ATS/ATO, with a platform for each order, had the lowest lead time. Figure 4.4 summarizes the lead time results for all demand scenarios for different manufacturing strategies. Appendix A shows the observations and calculations of the lead times for the three scenarios A, B, and C.

Table 4.5: Lead Time Results from Actual Experiment

	Manufacturing Strategy (Assembly Policy)/Lead Time (In Seconds)					
	ATO (No Platform)	**Hybrid ATS/ATO**	**CPTO (Larger Platforms)**			
	No Platform	**Same Platform**	**P1 for D1**	**P2 for D2**	**P3 for D3**	**P4 for D4**
Demand 1	7380	6400	6400	-	-	-
Demand 2	7855	6970	-	5345	-	-
Demand 3	7391	6658	-	-	5178	-
Demand 4	7590	6040	-	-	-	5230
Overall Lead Time (Seconds)	30216	26068	22153			

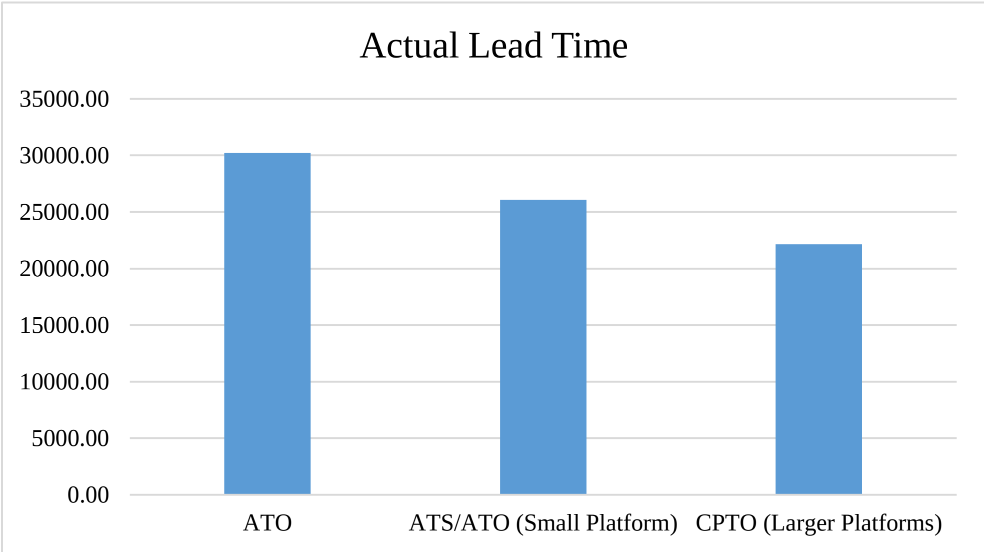


Figure 4.4: Lead Times Results from Actual Experiment

4.3.2 Actual Inventory Units

Table 4.6 presents the data collected for the inventory calculations. It includes the beginning inventory, the demanded components, and the ending inventory.

Table 4.6: Actual Experiment Inventory Data

Components	Inventory (In Units)						
	Demand 1	Demand 2	Demand 3	Demand 4	Beginning Inventory	Needed	Ending Inventory
Base	100	100	100	100	400	400	0
Gauge Holder	100	100	100	100	400	400	0
Gauge (Pressure)	40	45	32	65	182	182	0
Gauge (Clock)	40	55	32	65	192	192	0
Long Cup	140	110	100	120	470	470	0
Short Cup	80	90	136	50	356	356	0

Appendix B shows the data obtained from looking at the inventory behaviour over time for individual components. It was noted that inventory units in the ATO strategy resulted in the highest inventory components over time, while the hybrid ATO/ATS, with one small platform, had a decreased number of individual units stored in the inventory. Lastly, the CPTO strategy had a significantly decreased number of units stored in the inventory over time, as shown in Figures 4.5–4.10.

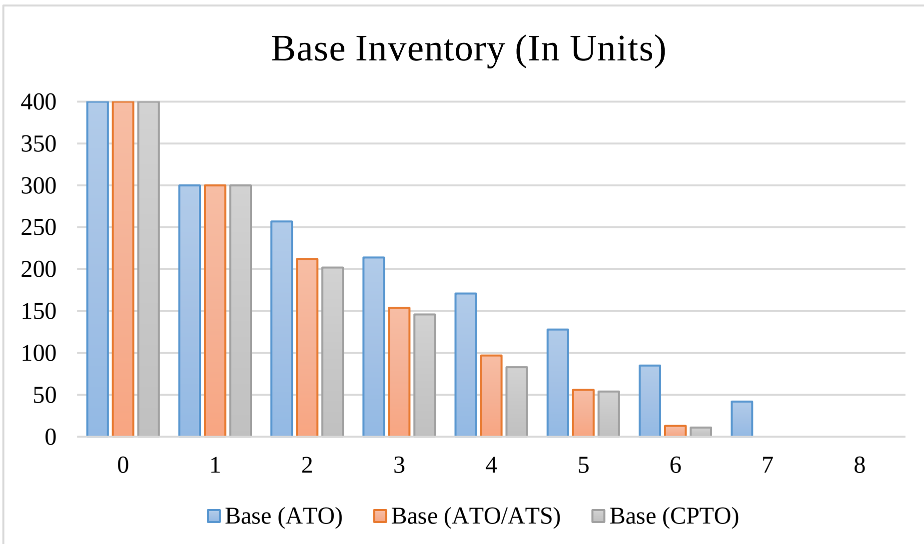


Figure 4.5: Actual Experiment Base Inventory Over Time

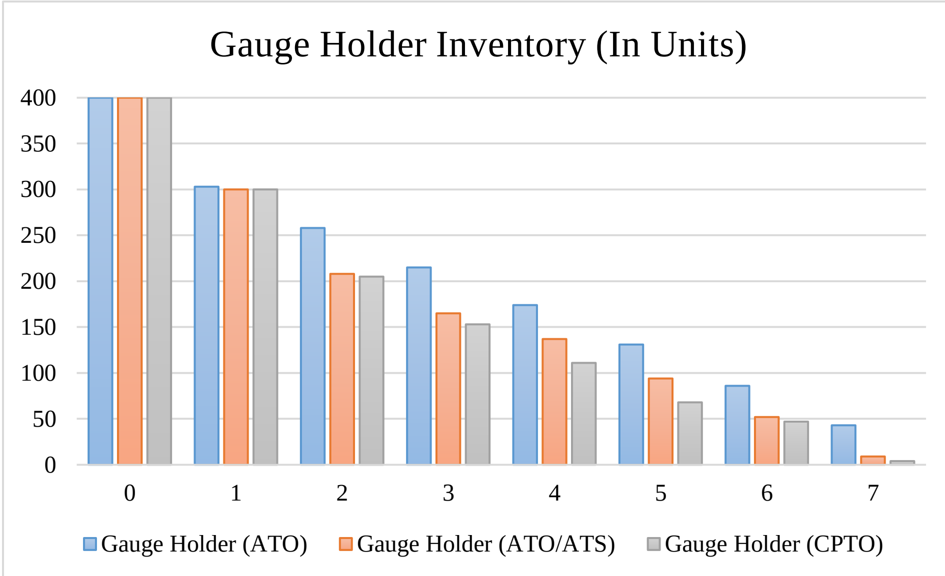


Figure 4.6: Actual Experiment Gauge Holder Inventory Over Time

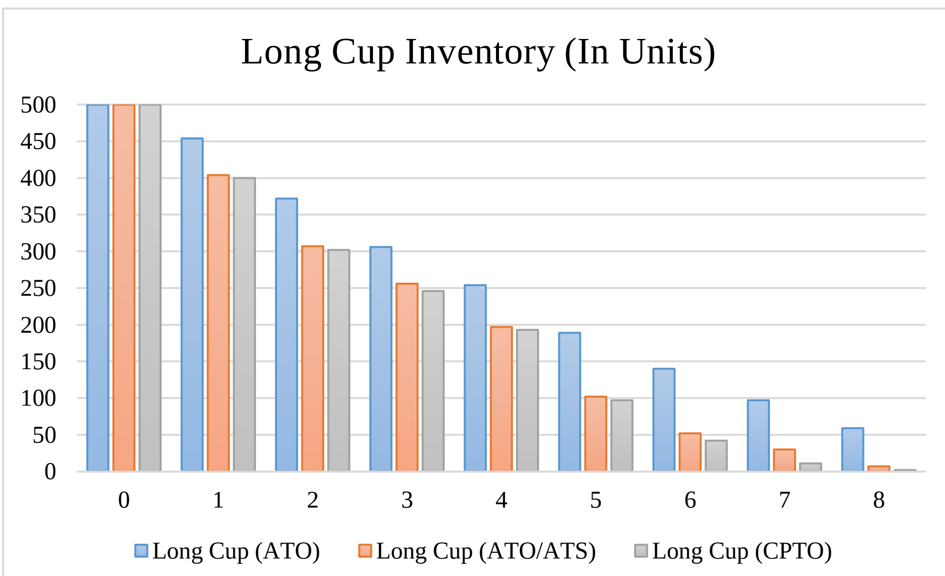


Figure 4.7: Actual Experiment Long Cup Inventory Over Time

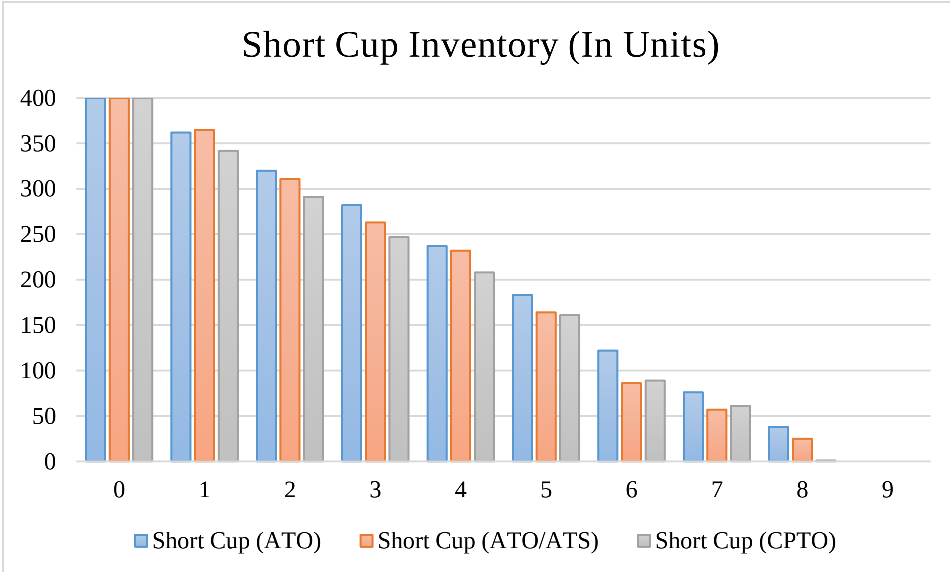


Figure 4.8: Actual Experiment Short Cup Inventory Over Time

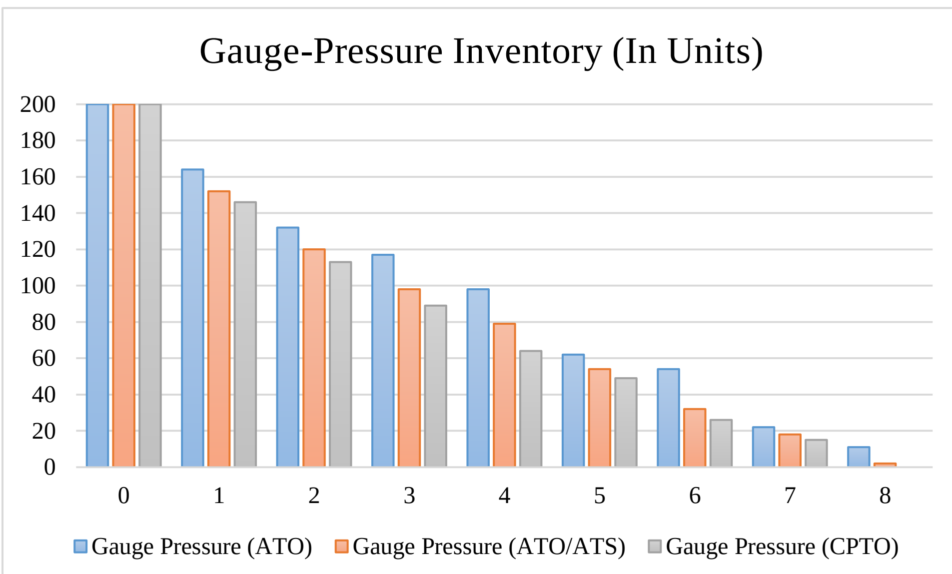


Figure 4.9: Actual Experiment Gauge-Pressure Inventory Over Time

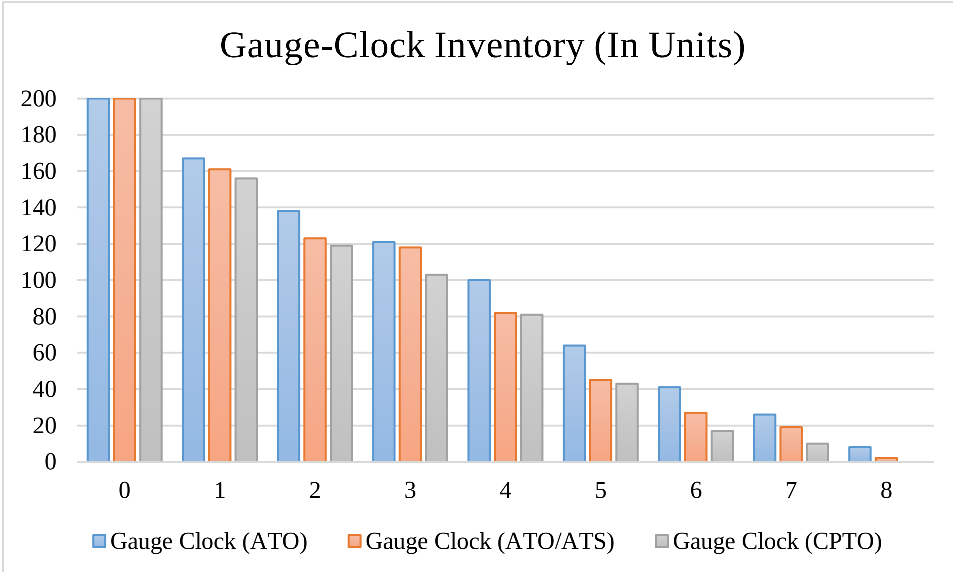


Figure 4.10: Actual Experiment Gauge-Clock Inventory Over Time

4.3.3 Actual Total Assembly Time

Tables 4.7 and 4.8 show assembly times, using different assembly policies for different variants of the desk set. Two assembly stations are considered—the robotic and manual assembly stations. After observing the average time it took for individual variants to be assembled, the results were multiplied with the overall demand quantities to find the total assembly time for the assembly policy.

Table 4.7: Actual Experiment Assembly Time for ATO Assembly Policy

	Variants Assembly Times, in Seconds				
Station	**V1**	**V2**	**V3**	**V4**	**V5**
Robotic	16	16	8	24	24
Manual	7	7	10	-	-
Total	23	23	18	24	24
Demand	100	90	92	83	35
Assembly Time *Demand	2300	2070	1656	1992	840
Total Assembly Time for All Variants	8858				

Table 4.8: Actual Experiment Assembly Times for ATS/ATO Policy

	Variants Assembly Times, in Seconds				
Station	**V1**	**V2**	**V3**	**V4**	**V5**
Robotic	8	8	NA	16	16
Manual	9	9	12	6	6
Customization	NA	NA	NA	NA	NA
Total	17	17	12	22	22
Demand	100	90	92	83	35
Assembly Time *Demand	1700	1530	1104	1826	770
Total Assembly Time for All Variants	6930				

The assembly time for the third scenario depended on customer demand, since the platforms were developed according to customers' orders. Tables 4.9–4.12 show the assembly times for each demand scenario. A summation of the four demand scenarios are presented in Table 4.13 and Figure 4.11.

Table 4.9: Actual Experiment CPTO Assembly Times for Demand 1

	Assembly Time (In Seconds)				
Station	**V1**	**V2**	**V3**	**V4**	**V5**
Robotic	8	8	NA	16	16
Manual	9	9	12	6	6
Customization	NA	NA	NA	NA	NA
Total	17	17	12	22	22
Demand	20	20	20	20	20
Assembly Time *Demand	340	340	240	440	440
Total Assembly Time for All Variants	1800				

Table 4.10: Actual Experiment CPTO Assembly Times for Demand 2

	Assembly Time (In Seconds)				
Station	**V1**	**V2**	**V3**	**V4**	**V5**
Robotic	8	8	0	0	0
Manual	8	8	11	14	14
Customization	0	0	0	2	2
Total	16	16	11	14	14
Demand	40	30	15	10	5
Assembly Time *Demand	640	480	165	140	70
Total Assembly Time for All Variants	1495				

Table 4.11: Actual Experiment CPTO Assembly Times for Demand 3

	Assembly Time (In Seconds)				
Station	**V1**	**V2**	**V3**	**V4**	**V5**
Robotic	0	0	0	8	NA
Manual	11	11	14	8	NA
Customization	0	0	2	0	NA
Total	11	11	14	16	NA
Demand	25	25	7	43	0
Assembly Time *Demand	275	275	98	688	0
Total Assembly Time for All Variants	1336				

Table 4.12: Actual Experiment CPTO Assembly Times for Demand 4

	Assembly Time (In Seconds)				
Station	**V1**	**V2**	**V3**	**V4**	**V5**
Robotic	8	8	0	0	0
Manual	8	8	11	14	14
Customization	0	0	0	2	2
Total	16	16	11	14	14
Demand	15	15	50	10	10
Assembly Time *Demand	240	240	550	140	140
Total Assembly Time for All Variants	1310				

Table 4.13: Actual Experiment CPTO Total Assembly Times Summary

Manufacturing Strategy (Assembly Policy)	Assembly Time (In Seconds)
ATO	8858
ATS/ATO (Small Platform)	6930
CPTO (Larger Platforms)	5941

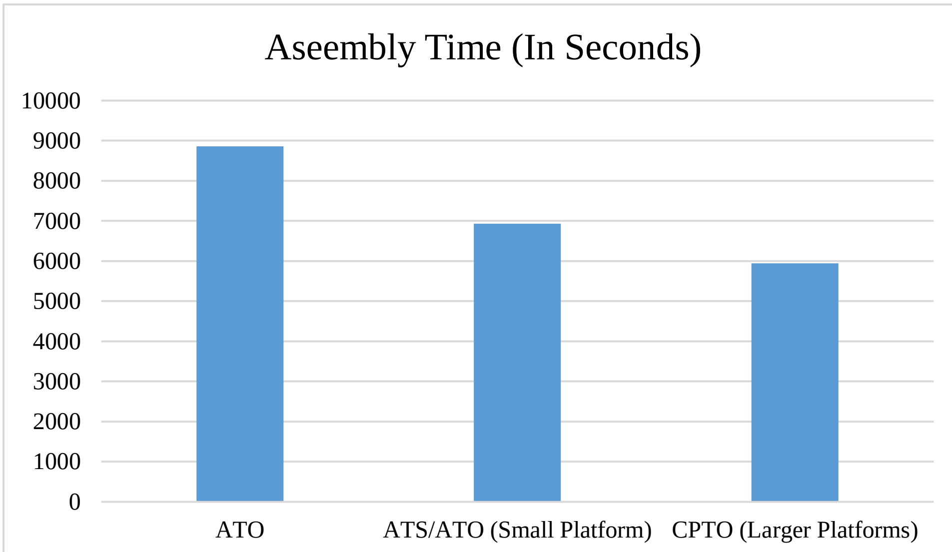


Figure 4.11: Actual Experiment Total Assembly Time Summary

4.3.4 Actual Assembly Cost

Actual assembly costs is calculated using the Boothroyd and Dewhurst (DFA) tool shown in Appendix C. The same approach implemented in the calculating the assembly costs using the simulation model is followed in this section to validate the result obtained previously. The labour rate for the manual station was assumed to be $12.00/hour, while the machine rate for the robotic station was assumed to be $18.00/hour. The assembly times were taken from the previous section and were 3 seconds for manual assembly, 2 seconds for manual disassembly, and 8 seconds for robotic assembly. The summaries of the results of the three manufacturing strategy scenarios are shown in Table 4.14 and Figure 4.12.

Table 4.14: Actual **Total** Assembly Costs

Manufacturing Strategy (Assembly Policy)	Assembly Cost ($)
ATO	1200
ATS/ATO (Small Platform)	910
CPTO (Larger Platforms)	740

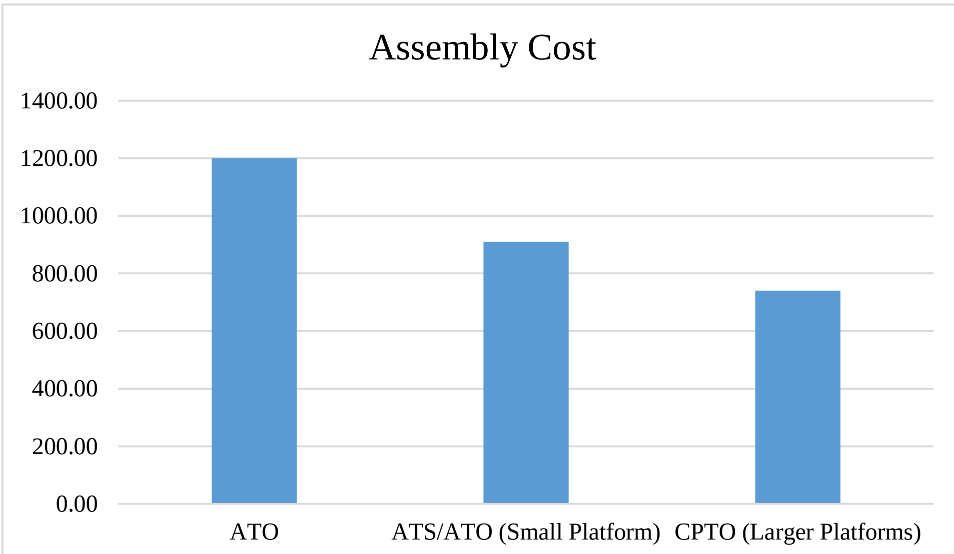


Figure 4.12: Actual Assembly Cost Comparison

4.4 Discussion, Validation, and Comparison between Simulation Model and Actual Experiments Results

The results derived from the discrete-event simulation model and the actual experiment for the lead times, and inventory units are shown in Tables 4.15 and 4.16 as well as Figures 4.13 and 4.14. The ATO approach resulted in the highest lead times and WIP units in the simulation model and the actual experiment, while the CPTO approach resulted in the fewest lead times and WIP inventory units. In addition, the hybrid ATS/ATO approach resulted in having a middle value between the ATO and CPTO manufacturing strategies. The lead times percentage difference between ATO and CPTO in the simulation model is 30.91% while the actual experiment is 30.79%. On the other hand, the WIP inventory unit percentage difference results are from 7% to 24% depending on the demand scenario and variants requirements.

Table 4.15: Comparison and Results of Actual and Simulated Lead Times

	Manufacturing Strategy (Assembly Policy)/Lead Time (In Seconds)					
	ATO	**ATO**	**Hybrid ATS/ATO**	**Hybrid ATS/ATO**	**CPTO**	**CPTO**
	Simulation	**Actual**	**Simulation**	**Actual**	**Simulation**	**Actual**
Demand 1	6891	7380	6062	6400	6062	6400
Demand 2	7328	7855	6512	6970	5019	5345
Demand 3	6971	7391	6113	6658	4873	5178
Demand 4	7097	7590	5789	6040	4759	5230
Overall Lead Time (In Seconds)	28287	30216	24476	26068	20713	22153

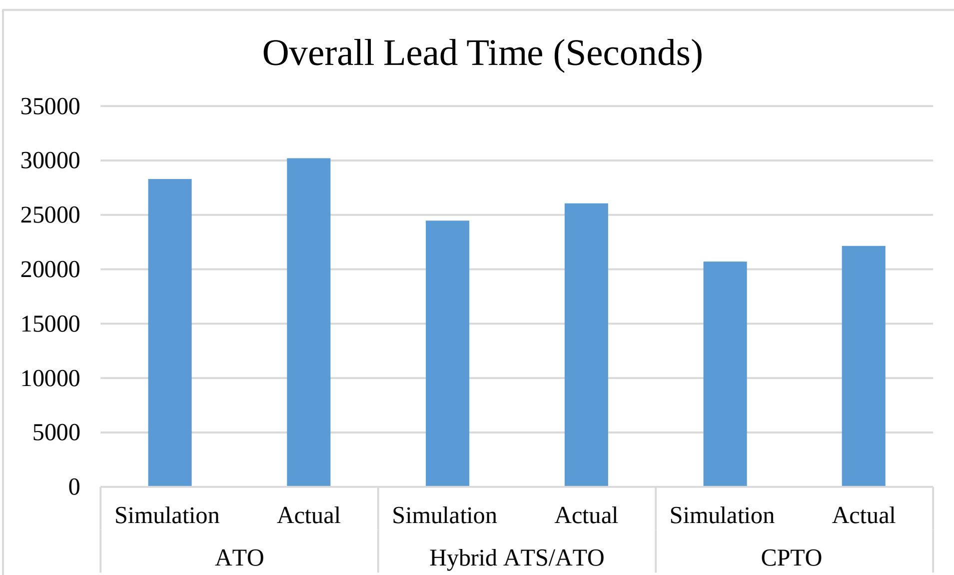


Figure 4.13: Overall Lead Times Comparison

Table 4.16: Comparison and Results of Actual and Simulated WIP Inventories

Time (In Hours)	WIP (ATO) Simulation	WIP (ATO) Actual	WIP (ATO/ATS) Simulation	WIP (ATO/ATS) Actual	WIP CPTO Simulation	WIP CPTO Actual
0	2000	2000	2000	2000	2000	2000
1	1748	1750	1637	1682	1595	1644
2	1425	1477	1333	1281	1287	1232
3	1207	1255	1151	1054	1092	984
4	968	1034	936	824	883	740
5	679	757	667	515	631	472
6	491	528	479	262	454	232
7	240	306	224	133	195	101
8	116	116	102	64	91	33
9	0	0	0	0	0	0

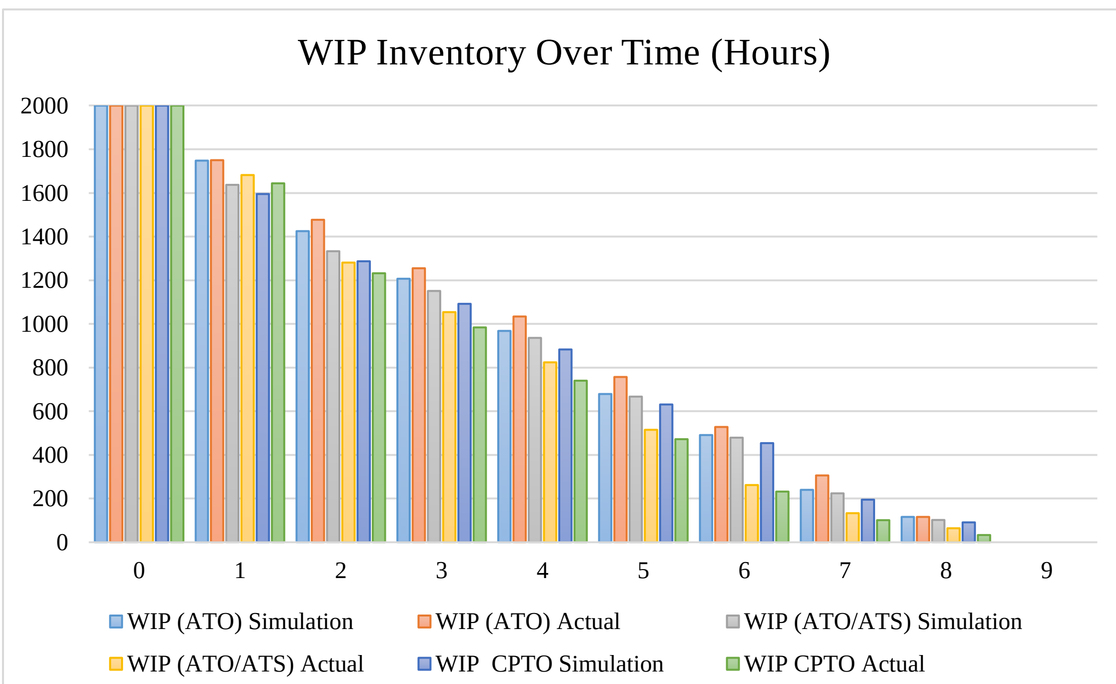


Figure 4.14: WIP Comparison

It should be noted from the results that the lead times and inventory units between the simulation model and the actual experiment were slightly different but had the same trends for a specific manufacturing strategy. A reason for the differences between the two is that they might have been caused by human error and the iFactory's capabilities. During the experiment, two persons were involved in recording the times, observing the inventory counts, and assembling the gauges in the manual station. Having more than one job takes the observers' attention. Another possible source of error is that the iFactory is capable of handling only 25 products per run. There are only 25 available fixtures to place the base on in the IMSC, while each run in the simulation model represents the actual demand of 100 products of the desk set variants. Thus, for each run in the simulation model, four runs in the iFactory were required. Averaging these four runs caused the differences between the simulated and iFactory results. Implementing the experiment on a reconfigurable and flexible system that is capable of handling more than 100 products would reduce/eliminate these discrepancies.

However, the assembly times and assembly costs were 100% the same for both the simulation model and the actual experiment, as shown in Tables 4.17 and 4.18 and Figures 4.15 and 4.16. This is due to the fact that the observations during the data collection from the actual experiments were the input for the simulation model. To be more specific, assembly times were observed in this case study from two stations in the iFactory: the robotic and manual stations. The assembly times did not change from one variant to another, because they required the same assembly procedures and steps. Moreover, when constructing the simulation model in FlexSim, the process times were constant. This also applies to the assembly costs implemented using the Boothroyd and Dewhurst (DFA) tool.

Assembly costs for the same operations with the same complexities have the same costs. Labour and machines costs did not change either, as the insertion and the alignment difficulties were the same.

Table 4.17: Comparison and Results of Actual and Simulated Assembly Times

Manufacturing Strategy (Assembly Policy)	Simulated Assembly Time (In Seconds)	Actual Assembly Time
ATO	8858	8858
ATS/ATO (Small Platform)	6930	6930
CPTO (Larger Platforms)	5941	5941

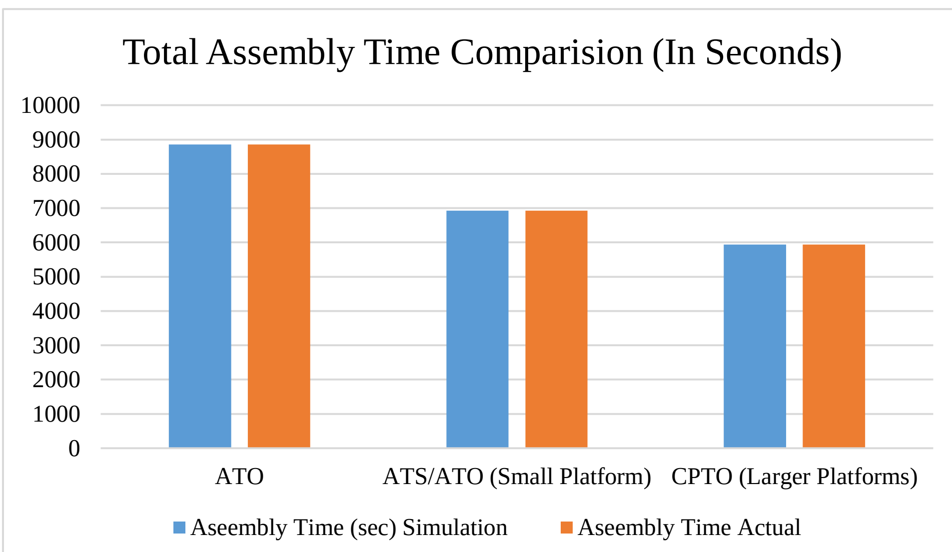


Figure 4.15: Total Assembly Times Comparison

Table 4.18: Comparison and Results of Actual and Simulated Assembly Costs

Manufacturing Strategy (Assembly Policy)	Simulated Assembly Cost ($)	Actual Assembly Cost ($)
ATO	1200	1200
ATS/ATO (Small Platform)	910	910
CPTO (Larger Platforms)	740	740

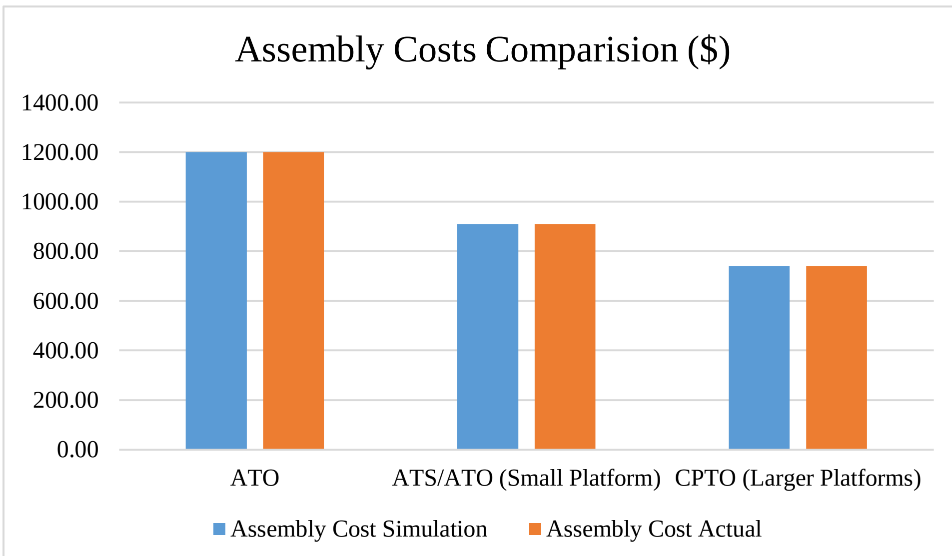


Figure 4.16: Assembly Costs Comparison

4.5 Conclusion

In this chapter, the customize platform to order (CPTO) approach is implemented in a physical experiment using the iFactory and discrete event simulation model and compared with other manufacturing strategies such as ATO and hybrid ATS/ATO using digital and physical simulation. The results indicate that the CPTO provides manufacturers with the ability to reduce total assembly time and costs, lead time, and inventory costs.

CHAPTER 5: DISCUSSION AND CONCLUSION

5.1 Research Significance

This research has introduced a new term/ manufacturing strategy , CPTO, which is concerned with forming platform components using demand data inspired by recent research by (Hanafy & ElMaraghy, 2015) and (Ben-Arieh, et al., 2009). This manufacturing strategy has been compared to existing manufacturing methods, such as the hybrid ATS/ATO method, which forms a platform according to similarities in the core components, and the ATO method, which does not have a platform. The results and recommendations of this study will help manufacturers configure their products platforms and assembly strategy, which will in turn result in reductions in production and inventory costs. Moreover, it will assist manufacturers with meeting customer demands and needs and with being responsive to market changes. In addition, the CPTO manufacturing strategy will help manufacturers better manage their product varieties and variant assemblies in terms of shortening their lead times and meeting customers' due dates. It also thus increases the competitive edges and efficiency of manufacturers. Furthermore, the strategy will increase the profitability of manufacturers by minimizing the number of units they need to hold in inventory. Finally, this research has a unique contribution which is proving the previously indicated effect of platform customization for the first time through digital and physical simulation.

After comparing the results with the actual experiment, one can say that the CPTO method provides benefits to manufacturers. Forming a product platform according to customer demands and implementing the customize-to-order manufacturing strategy reduces lead times. Doing so also reduces inventory costs. This proves the research thesis hypothesis.

5.2 Applicability of Proposed Product Platform Configuration Approach

The researched Product Platform configuration Methodology is applicable to a product family with an assembly and disassembly processes that do not involve permanent joining applications such as welding, soldering, crimping, and adhesive joining. These applications may results in damaging the products during disassembly of parts. It is also recommended when customization time of product variants done by disassembly does not exceed the assembly process time to form a variant and must be done manually (Hanafy & ElMaraghy, 2015, (Ben-Arieh, et al., 2009). The CPTO manufacturing strategy is applicable to both modular and flexible product platforms. The obtained savings in products assembly lead time and inventory cost, as with any simulation study, are specific to the case study. Similar effects of applying the platform customization to other products and assembly systems would be obtained using similar simulations.

5.3 Conclusion

Customer demands and needs are changing over time. Today, product variety is essential to satisfy customers and help manufacturers gain more market shares. As a result, manufacturers are shifting from mass production to mass customization. The product platform approach, a mass customization approach, has been implemented by many manufacturers in order to satisfy customers' changing needs and requirements. Moreover, keeping inventory is becoming more and more important to companies so that they may remain competitive despite market changes. However, both offering product variety and keeping inventory come with costs. Managers have to deal with these issues very carefully, since holding high or low numbers of completed product variants and inventory can be a problem for both the productivity and the profitability of a company.

This research focused on developing a discrete-event simulation model in FlexSim. The results were validated with an actual experiment in the Intelligent Manufacturing Systems Centre (IMSC). The outcome of this research shows that a product platform customized according to customers' demands in this case study minimizes lead times by 30 % when compared with not having a product platform. Also, inventory costs decreases with customize platform to order CPTO approach which results in 7-24% reduction compared with ATO approach. Assembly times result in percentage difference between ATO and CPTO of 27% .Moreover, when implementing the CPTO approach assembly cost of the studied family of products (desk sets) decreases by 19%. Therefore, it is recommended to adapt and customize the configuration of assembled product platforms in accordance with demand for product variants in highest demand in a given production period.

5.4 Future Work

Future work may include applying the customize-to-order approach to an industrial application with complex assembly procedures such as laptop assembly. Expanding the customize platform to order CPTO strategy to include a variable customer demand wherein different forecasting methods are adopted, collecting data for industrial products and manufacturing systems may also be considered. Finally, future work may explore similarity in manufacturing process among product variants as a form of a platform instead of common product components.

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Appendix A: Actual Lead Time Calculations for Scenario A, B, and C

1. Scenario A: Actual Lead Time: (ATO), No Platform

Steps	Operation Sequence	V1	V2	V3	V4	V5
1	Assemble Gauge Holder and Base	4				
2	Place Base	2				
3	Process AS/RS	7				
4	Transportation from AS/RS to Quality Control Station	4				
5	Quality Control Station	1				
6	Transportation from Quality Control Station to Robot Assembly Station	5				
7	Robotic Assembly Station	16	16	8	24	24
8	Transportation from Robotic Assembly Station to AS/RS	10				
9	Transportation from AS/RS to Manual Station	12	12	12	NA	NA
10	Manual Assembly	3	3	6	NA	NA
11	Transportation from Manual Station to AS/RS	11	11	11	NA	NA
12	AS/RS Storage Processing	7				
	Lead Time (t_L)	82	82	77	64	64

2. Scenario B: Actual Lead Time: Hybrid (ATO/ATS), Small Platform

2.1 Actual Lead Times for Variant 1 and Variant 2

Steps	Operation	Process Time, in seconds	Automated/Manual
1	Assemble Gauge Holder, Base, and Long Cup	6	Manual
2	Place Platform (Base, Gauge Holder, and Long Cup) Together	2	Manual
3	Process AS/RS	7	Automated
4	Transportation from AS/RS to Quality Control Station	4	Automated
5	Quality Control Station	1	Automated
6	Transportation from Quality Control Station to Robot Assembly Station	5	Automated
7	Robotic Assembly Station	8	Automated
8	Transportation from Robotic Assembly Station to manual station	22	Automated
9	Manual Assembly	3	Manual
10	Transportation from Manual Station to AS/RS	11	Automated
11	Process AS/RS Storage	7	Automated
	Lead Time (t_L)	76	

2.2 Actual Lead Times for Variant 3

Steps	Operation	Process time, in seconds	Automated/Manual
1	Assemble Gauge Holder, Base, and Long Cup	6	Manual
2	Place Platform (Base, Gauge Holder, and Long Cup) Together	2	Manual
3	Process AS/RS	7	Automated
4	Transportation from AS/RS to Quality Control Station	4	Automated
5	Quality Control Station	1	Automated
6	Transportation from Quality Control Station to Manual Assembly Station	8	Automated
7	Manual Assembly	6	Automated
8	Transporting from Manual Assembly Station to AS/RS	11	Automated
9	Process AS/RS Storage	7	Automated
Lead Time (t_L)		52	

2.3 Actual Lead Times for Variant 4 and 5

Steps	Operation	Process Time (sec)	Automated/Manual
1	Assemble Gauge Holder, Base, and Long Cup	6	Manual
2	Place Platform (Base, Gauge Holder, and Long Cup) Together	2	Manual
3	Process AS/RS	7	Automated
4	Transportation from AS/RS to Quality Control Station	4	Automated
5	Quality Control Station	1	Automated
6	Transportation from Quality Control Station to Robot Assembly Station	5	Automated
7	Robotic Assembly Station	16	Automated
8	Transportation from Robotic Assembly Station to AS/RS	10	Automated
9	Process AS/RS Storage	7	Automated
Lead		58	

3. Scenario C: Actual Lead Time: CPTO, Larger Platforms

3.1 Actual Lead Times for Platform 1 (Base, Gauge Holder, and Long Cup) for Demand Scenario 1.

<table>
<tr><th></th><th></th><th>V1 & 2</th><th></th><th></th><th>V3</th><th></th><th></th><th>V4 & 5</th></tr>
<tr><th>Steps</th><th>Operation</th><th>Process Time (sec)</th><th>Steps</th><th>Operation</th><th>Process Time (sec)</th><th>Steps</th><th>Operation</th><th>Process Time (sec)</th></tr>
<tr><td>1</td><td>Assemble Gauge Holder, Base, Gauge, and Long Cup</td><td colspan="7">6</td></tr>
<tr><td>2</td><td>Place Platform (Base, Gauge Holder, and Long Cup)</td><td colspan="7">2</td></tr>
<tr><td>3</td><td>AS/RS Processing</td><td colspan="7">7</td></tr>
<tr><td>4</td><td>Transportation from AS/RS to Quality Control Station</td><td colspan="7">4</td></tr>
<tr><td>5</td><td>Quality Control Station</td><td colspan="7">1</td></tr>
<tr><td>6</td><td>Transportation from Quality Control Station to Robot Assembly Station</td><td>5</td><td>6</td><td>Transportation from Quality Control Station to Manual Assembly Station</td><td>8</td><td>6</td><td>Transporting from quality control station to Robotic Assembly Station</td><td>5</td></tr>
<tr><td>7</td><td>Robotic Assembly Station</td><td>8</td><td>7</td><td>Manual Assembly</td><td>6</td><td>7</td><td>Robotic Assembly Station</td><td>16</td></tr>
</table>

8	Transporting from Robotic Assembly Station to Manual Station	22	**8**	Transporting from Manual Assembly Station to AS/RS	11	**8**	Transporting from Robotic Assembly Station to AS/RS	10
9	Assemble Manually	3	**9**	AS/RS Storage Processing	7	**9**	AS/RS Storage Processing	7
10	Transportation from Manual Station to AS/RS	11	Lead Time (tL)		52	Lead Time (tL)		58
11	Process AS/RS Storage	7						
Lead Time (tL)		76						

3.2 Actual Lead Times for Platform 2 (Base, Gauge Holder, Gauge and Long Cup) for Demand Scenario 2

Variant 1 & 2			Variant 3			Variant 4 & 5		
Steps	Operation	Process Time (sec)	Steps	Operation	Process Time (sec)	Steps	Operation	Process Time (sec)
1	Assemble New Platform (Gauge Holder, Gauge, Base, and Long Cup).	8	1	Assemble New Platform (Gauge Holder, Gauge, Base, and Long Cup)	8	1	Assemble New Platform (Gauge Holder, Gauge, Base, and Long Cup	8
2	Place New Platform	2	2	Place New Platform	2	2	Place New Platform	2
3	Process AS/RS	7	3	AS/RS Processing	7	3	AS/RS Processing	7
4	Transportation from AS/RS to Quality Control Station	5	4	Transporting from AS/RS to Quality Control Station	5	4	Transporting from AS/RS to Quality Control Station	5
5	Quality Control Station	1	5	Quality Control Station	1	5	Quality Control Station	1
6	Transportatiom they would have been Quality Control Station to Robot Assembly Station	5	6	Transportation from Quality Control Station to Manual Assembly Station	8	6	Transportation from Quality Control Station to Manual Assembly Station	8
7	Robotic Assembly Station	8	7	Manual Assembly	3	7	Manual Assembly & Customization	8

8	Transportation from Robotic Assembly Station to AS/RS	10	8	Transportation from Manual Assembly Station to AS/RS	11	8	Transporting from Manual Assembly Station to AS/RS	11
9	Process AS/RS Storage	7	9	Process AS/RS Storage	7	9	Process AS/RS Storage	7
Lead Time (tL)		53	Lead Time (tL)		52	Lead Time (tL)		57

3.3 Actual Lead Times for Platform 3 (Base, Gauge Holder, Long Cup, and Short Cup) for Demand Scenario 3

Variant 1 & 2			Variant 3			Variant 4		
Steps	Operation	Process in seconds	Steps	Operation	Process Time, in seconds	Steps	Operation	Process Time, in seconds
1	Assemble New Platform (Base, Gauge-Holder, Long Cup, and Short Cup)	8	1	Assemble New Platform(Base, Gauge-Holder, Long Cup, & Short Cup)	8	1	Assemble New Platform(Base, Gauge-Holder, Long Cup, & Short Cup)	8
2	Place New Platform	2	2	Place New Platform	2	2	Place New Platform	2
3	Process AS/RS	7	3	AS/RS Processing	7	3	AS/RS Processing	7
4	Transportation from AS/RS to Quality Control Station	4	4	in seconds from AS/RS to Quality Control Station	4	4	Transportation from AS/RS to Quality Control Station	4
5	Quality Control Station	1	5	Quality Control Station	1	5	Quality Control Station	1
6	Transportation from Quality Control Station to Manual Assembly Station	8	6	Transportation from Quality Control Station to Manual Assembly Station	8	6	Transportation from Quality Control Station to Robot Assembly Station	5
7	Manual Assembly	3	7	Manual Assembly & Customization	8	7	Robotic Assembly Station	8

8	Transportation from Manual Assembly Station to AS/RS	11	8	Transportation from Manual Assembly Station to AS/RS	11	8	Transportation from Robotic Assembly Station to AS/RS	10
9	AS/RS Storage Processing	7	9	AS/RS Storage Processing	7	9	AS/RS Storage Processing	7
Lead Time (tL)		51	Lead Time (tL)		56	Lead Time (tL)		52

3.4 Actual Lead Times for Platform 4 (Base, Gauge Holder, Long Cup, and Gauge) for Demand Scenario 4

Variant 1 & 2			Variant 3			Variant 4 & 5		
Steps	Operation	Process Time (sec)	Steps	Operation	Process Time (sec)	Steps	Operation	Process Time (sec)
1	A Assemble New Platform (Base, Gauge-Holder, Long Cup, and Short Cup)	8	1	Assemble New Platform (Gauge Holder, Gauge, Base, and Long Cup	8	1	Assemble New Platform (Gauge Holder, Gauge, Base),are Long Cup	8
2	New Place Platform	2	2	Place New Platform	2	2	Place New Platform	2
3	Process AS/RS	7	3	Process AS/RS	7	3	Process AS/RS	7
4	Transportation from AS/RS to Quality Control Station	4	4	Transportation from AS/RS to Quality Control Station	4	4	Transportation from AS/RS to Quality Control Station	4
5	Quality Control Station	1	5	Quality Control Station	1	5	Quality Control Station	1
6	Transportation from Quality Control Station to Robot Assembly Station	5	6	Transportation from Quality Control Station to Manual Assembly Station	8	6	Transportation from Quality Control Station to Manual Assembly Station	8
7	Robotic Assembly Station	8	7	Manual Assembly	3	7	Manual Assembly & Customization	8

8	Transportation from Robotic Assembly Station to AS/RS	10	8	Transportation from Manual Assembly Station to AS/RS	11	8	Transportation from Manual Assembly Station to AS/RS	11
9	Process AS/RS Storage	7	9	Process AS/RS Storage	7	9	Process AS/RS Storage	7
Lead Time (tL)		52	Lead Time (tL)		51	Lead Time (tL)		56

Appendix B: Actual Inventory Unit Observations Over Time for Scenarios A, B, and C

1. Scenario A: Actual Inventory Units for ATO

Time (hr)	Base	Gauge Holder	Long Cup	Short Cup	Gauge(pressure)	Gauge (clock)
0	400	400	500	400	200	200
1	300	303	454	362	164	167
2	257	258	372	320	132	138
3	214	215	306	282	117	121
4	171	174	254	237	98	100
5	128	131	189	183	62	64
6	85	86	140	122	54	41
7	42	43	97	76	22	26
8	0	0	59	38	11	8
9	0	0	0	0	0	0

2. Scenario B: Actual Inventory Units for Hybrid ATO/ATS

Time (hr)	Base	Gauge Holder	Long Cup	Short Cup	Gauge(pressure)	Gauge (clock)
0	400	400	500	400	200	200
1	300	300	404	365	152	161
2	212	208	307	311	120	123
3	154	165	256	263	98	118
4	97	137	197	232	79	82
5	56	94	102	164	54	45
6	13	52	52	86	32	27
7	0	9	30	57	18	19
8	0	0	7	25	2	2
9	0	0	0	0	0	0

3. Scenario C: Actual Inventory Units for CPTO

Time (hr)	Base	Gauge Holder	Long Cup	Short Cup	Gauge(pressure)	Gauge (clock)
0	400	400	500	400	200	200
1	300	300	400	342	146	156
2	202	205	302	291	113	119
3	146	153	246	247	89	103
4	83	111	193	208	64	81
5	54	68	97	161	49	43
6	11	47	42	89	26	17
7	0	4	11	61	15	10
8	0	0	2	1	0	0
9	0	0	0	0	0	0

Appendix C: Actual Assembly Costs for Each Variant using Boothroyd and Dewhurst (DFA) Tool

Labour Rate, ($/hr) = 12

Labour Rate, (¢/sec) = 0.33

Machine Rate, ($/hr) = 18

Machine Rate, (¢/sec) = 0.50

M = Manual Assembly time, R: Robotic Assembly time

1. Scenario A: Assembly Costs for ATO

			V1		V2		V3		V4		V5	
	Part ID	Part Name	M	R	M	R	M	R	M	R	M	R
1	A	Base	3	-	3	-	3	-	3	-	3	-
2	B	Gauge Holder	3	-	3	-	3	-	3	-	3	-
3	C	Gauge (Clock)	3	-	-	-	3	-	-	-	-	-

4	D	Gauge (Pressure)	-	-	3	-	3	-	-	-	-	-
5	E	Long Cup	-	8	-	8	-	8	-	8	-	28
6	F	Short Cup	-	8	-	8	-	-	-	16	-	-
		Total time	9	16	9	16	12	8	6	24	6	28
		Total Cost/ Variant	11.00		11.00		8.00		14.00		16.00	
		Total Cost ($)	1200									

2. Scenario B: Assembly Costs for Hybrid ATO/ATS

	Part ID	Part Name	V1		V2		V3		V4		V5	
			M	R	M	R	M	R	M	R	M	R
1	A	Base	3	-	3	-	3	-	3	-	3	-
2	B	Gauge Holder	3	-	3	-	3	-	3	-	3	-
3	C	Gauge (Clock)	3	-	-	-	3	-	-	-	-	-
4	D	Gauge (Pressure)	-	-	3	-	3	-	-	-	-	-
5	E	Long Cup	-	3	-	3	-	3	-	3	-	19
6	F	Short Cup	-	8	-	8	-	-	-	16	-	-
		Total time	9	11	9	11	12	3	6	19	6	19
		Total Cost/ Variant	8.50		8.50		5.50		11.50		11.50	
		Total Cost ($)	910									

3. Scenario C: Assembly Costs for CPTO

	Part ID	Part Name	V1		V2		V3		V4		V5	
			M	R	M	R	M	R	M	R	M	R
1	A	Base	3	-	3	-	3	-	3	-	3	-
2	B	Gauge Holder	3	-	3	-	3	-	3	-	3	-
3	C	Gauge (Clock)	3	-	-	-	3	-	-	-	-	-
4	D	Gauge (Pressure)	-	-	3	-	3	-	-	-	-	-
5	E	Long Cup	-	3	-	3	-	3	-	3	-	19
6	F	Short Cup	-	3	-	3	-	-	-	9	-	-
		Total time	9	6	9	6	12	3	6	12	6	19
		Total Cost/ Variant	6.00		6.00		5.50		8.00		11.50	
		Total Cost ($)	740									

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2- Jabr, S. Aljorephani, S. Urbanic, R.J. Alsobaihi, A. (2015). Design, Analysis, and Prototyping of a Mechanical Pill Dispensing System. Institute of Industrial Engineers (IIE) Conference, Nashville, TN, USA. May 30 - June 2., pp. 2762.