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2018

Lin, C. (2018). Product configuration design based on customer requirement modelling and optimization method. Master's thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/75895>

<https://doi.org/10.32657/10356/75895>

NANYANG
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**PRODUCT CONFIGURATION DESIGN BASED
ON CUSTOMER REQUIREMENT
MODELLING AND OPTIMIZATION METHOD**

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SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING

2018

Product Configuration Design based on Customer Requirement Modelling and Optimization Method

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A dissertation submitted to
Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Master of Science

2018

Abstract

In the environment of industry 4.0, a smart production system is not a fantasy. Based on Cyber physical system (CPS) and the Internet of things (IoT), it is capable to transform its process flexibly to suit diverse customer requirements and design changes with lower cost in a short period of time, providing digital ‘configure-to-order’ (CTO) services. A product configuration system, which translates the voice of customers to technical specifications, is needed to handle variable and complex product knowledge in order acquisition and fulfilment stage. The purpose of this dissertation is to study and research a methodology to enhance the communication between customers and manufacturers. It aims to find an approach to receive the voice of customers as input to assist product conceptualization and generate a product configuration as output that maximizes the customer satisfaction. In this approach, engineering characteristics (ECs) are defined and selection pools are constructed in the first stage. Secondly, quality function deployment (QFD) is modified and integrated with the Kano’s model to qualitatively and quantitatively analyse the relationship between customer requirements (CRs) and customer satisfaction (CS). Thirdly, a mathematical programming model is applied to maximize overall customer satisfaction levels and recommend an optimal product configuration. Lastly, sensitivity analysis is conducted for customers to revise and determine the final customized product specification. A case study was conducted to demonstrate the procedure and the effectiveness of the proposed product configuration system.

Keywords: Industry 4.0; Product Configuration; Customer Requirement Modelling; QFD; The Kano’s Model; Optimization.

Acknowledgement

I would like to express my gratitude to my supervisor, Dr. Chen Chun-Hsien, for his guidance and patience. He provided me with a lot of constructive advice whenever I struggled to advance. His insightful comments illuminated the path of this research.

I would like to thank my respected senior, Dr. Lee Ching-Hung, for his generosity and enthusiasm. Through this journey, he has mentored me, shared his knowledge and gladly answered any question that I raised. His instruction and inspiration greatly boosted the completion of this dissertation.

I would also like to thank the fellows in Human Factor & Design Lab. Their accompanying smoothed my work and made it much more interesting.

My gratitude is not limited to persons mentioned above but also everyone who has ever given me a hand when I encountered challenges.

Last but not least, I must thank Nanyang Technological University for offering this opportunity that I could learn and gain.

All in all, I wish my juniors have the same experience in the future and good luck.

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Chapter 1 Introduction

1.1 Background

In the first industrial revolution, the invention of steam engine introduced heavy machine to widely replace human in factories. In the second industrial revolution, electricity became a more popular and efficient source of power, leading to an even greater productivity. However, this breakthrough did not bring along flexibility. Heavy machines were capable to produce a large volume, but the output was all the same. In the third industrial revolution, information technology facilitates human to control the manufacturing processes. Since then, the production line started gaining flexibility to produce parts with minor variation.

Now in the fourth industrial revolution, also known as Industry 4.0, people are expecting more. It drives increasingly customer requirements, fast improvements of technology and fierce competition in the market. To overcome this, flexible manufacturing system is used to provide a wide range of products to satisfy different customer expectations without excessive time and cost lost and performance degradation.

The emergence of the Internet-of-things (IoT) enables coordination and integration across the whole manufacturing process, transforming traditional factories to smart factories by cyber-physical system (CPS). A smart factory consists of smart machines, warehousing systems and production facilities. All modules are deeply intertwined,

exhibiting multiple and distinct actions and controls on each other (Kagermann et al., 2013).

The smart factories allow individual customer requirements to be met and make the production even in very low volumes but still profitable. The new way of production, exposing manufacturing companies to a new environment with opportunities and threats. It is important for such companies to make wise decisions in a short response time to succeed in the global market. It is a serious issue about how a company responds in the new environment and how to distribute their resources to optimize production and product transactions within their capability (Porter & Heppelmann, 2014).

Currently, a typical way of customization is to provide selections of subassembly for customers to configure the products by themselves and then place their orders. In this process, manufacturers do not really hear from customers directly, but only receive the orders they place. Yet, customers may not know whether their choices can satisfy their needs, and manufacturers may provide insufficient selections without knowing what customers really need. Instead, manufacturers should recommend the product configuration to customers based on their own voices. However, there is no effective communication channel between manufacturers and customers. In this extremely competitive market, once a manufacturer fails to fulfil the customer requirements fast enough, it will lose its competitive edge and the disadvantage may even snowball in the future.

Another common way of customization is sales interview. In a typical procedure, a customer discusses and negotiates through a sales interview and places an order with assistance of sales office personnel. Sales departments consult and obtain technical advice or feedback from technical departments, to verify the correctness and compatibility of the recommended configuration. If everything goes well, all the information will be passed to the final stage, manufacturing. Throughout the process, an error may happen due to the inefficient communication channel as the product information is increasingly complex and variable. Repeating this procedure in a long run, it will lead to long delays in order acquisition as the sales department has to frequently engage the technical department for the supply of information.

The key to success is to quickly and effectively react to diverse and dynamic customer requirements and bringing the customized products in a shorter time to market. To achieve that, a product configuration system plays an important role, which bridges the gap between customers and manufacturers by selectable predefined attributes within enterprise capability. The implementation of the product configuration system helps to significantly reduce errors in the configurations released by the sales department. It is capable of handling a large volume of information exchanged between frontend and backend departments with greater accuracy and efficiency, recovering a considerable amount of manpower spent on the traditional manual activities in a long run. Furthermore, it serves as a database to store product knowledge and all historical configurations for different user groups, accumulating intangible but valuable asset to the organization for future reference.

There are three main problems to be addressed:

- 1) Lack of research to adopt product configuration system in Industry 4.0;
- 2) Lack of refinement of existing methodologies for mass customization;
- 3) Lack of exploration of new and empirical scenarios.

1.2 Research Objective

The objective of this dissertation is to develop an approach to translate the voice of customers to product configurations that can be reviewed by customers and produced by manufacturers in their processes. The ultimate goal is to construct a process where a customer needs to prioritize or weight his requirements, and then the optimal configuration will be generated within budget automatically. Firstly, the manufacturers need to define the engineering characteristics of the product as well as a set of possible selections. Secondly, the manufacturers must be able to quantify the customer requirements and their satisfaction level against different configuration. Thirdly, an algorithm must be deployed to work out the optimal configuration that maximizes overall customer satisfaction. Lastly, the customers deserve to know the possible minor variation, so they may not necessarily go for the proposed configuration.

In this dissertation, the following outcomes are expected:

- 1) Design a product configuration system to suit Industry 4.0;
- 2) Research, integrate and refine existing methodologies;
- 3) Apply the proposed approach into a real-life scenario.

1.3 Dissertation Structure

This dissertation consists of 5 chapters. Chapter 1 is the overview of this study. Chapter 2 introduces flexible manufacturing system in Industry 4.0, product configuration system in Industry 4.0, quality function deployment (QFD) approach, the Kano's model and integration of the Kano's model into QFD. Chapter 3 illustrates the research framework of this study step by step, from the preparation of the product configuration to the final optimization formulation based on customer input. Chapter 4 is a case study to show how the configuration system could be applied in the real world. It describes a company, which specializes in manufacturing IT devices, facing challenges of diverse customer expectations, and losing sales because of the inflexibility of its production lines. To embrace the revolution in Industry 4.0, the company decides to offer customization service for its laptop products, with a new flexible production line, capable of small batch processing in high mix and low volume. Yet, this process requires an effective product configuration system to quickly recommend the optimal solution to support this 'configure-to-order' service. The configuration system will be tested with a specific target user group to see whether the solution is reasonable. Chapter 5 is the conclusion of this study, including conclusion, the contribution, limitations, and the future work.

Chapter 2 Literature Review

2.1 New Flexible Manufacturing Systems in Industry 4.0

Flexible manufacturing system (FMS) is a manufacturing system in which there is a certain amount of flexibility that allows the system in response to changing requirements in the manufacturing process. The objective of such system is to manufacture customized products in a cost-efficient way, within pre-determined functionality and capacity, with minimum changeover cost, on the identical system at demanded volume and quality (ElMaraghy, 2005).

The increasing demand for customization and decreasing product lifecycles forced the further transformation of the organizational structures of industrial production. For the growing complexity of products and process, collaboration becomes more important especially for small and medium enterprises (SME) which own limited resources. (Brettel et al., 2014) CPS and IoT enable the coordination through the whole manufacturing process, between machines, factories, suppliers, and customers. It allows enterprises to closely integrate globally distributed supply chains. CPS bridge the cyber-world and physical products based on computing and communication core enable real-time monitoring, remote control, flexible optimization and automation (Rajkumar et al., 2010).

2.2 Product Configuration System in industry 4.0

Product configuration system is an effective design methodology that offers tailored products with shorter lead time to market in the mass customization environment. It

bridges the gap between customer requirements (CRs) and product engineering characteristics (ECs) and assists in order acquisition and fulfilment process in ever-rising product variety environments (Forza & Salvador, 2002). Generally, it is based on a configure-to-order (CTO) model that configures predefined engineering characteristics upon the placement of orders, to satisfy diverse CRs. In product configuration system, CRs are utilized as input, and the system would derive the optimized recommended ECs as output.

Many researches have been carried out into the field of product configuration. Zhou et al. (2008) proposed an optimization approach for customer-driven product configuration for assemble-to-order (ATO) manufacturing enterprises. Schuh et al. (2014) refined the product configuration process based on the similarities between product variance to increase the transparency in order processing and better control the quotation process. Wei et al. (2015) presented a product requirement modelling and optimization method based on product configuration design. SML technology was employed to express the product requirement elements in requirement modelling process and utilized in product function and structure model. Zheng et al. (2017) proposed a personalized product configuration process to determining design attributes in a cloud-based adaptable product configuration. The adaptable interfaces enable the efficient changing of optional and personalized modules among different service providers with respect to the dynamic changes of customer requirements (CRs). Tang et al. (2017) developed a new bi-objective optimization model with considering of customer satisfaction index (CSI) and greenhouse gas (GHG) emission of products in product configuration.

2.3 Quality Function Deployment (QFD) Approach

Quality Function Deployment (QFD) was first introduced in Japan by Yoji Akao in 1972. QFD is a customer-driven design methodology that focuses on customer requirements (CRs) and coordination in the product development and manufacturing process. It translates the Voice of Customers (VoC) into design specification and employs in product development stage. Some researches have been done on employing QFD into product and service optimization design.

Yan et al. (2005) proposed a QFD-enabled product conceptualization system consisting of knowledge elicitation module, design knowledge representation and design knowledge organization module that enables effective design knowledge handling in product development process. Lai et al. (2006) conducted QFD optimization in product design process assisted by linear physical programming (LPP) technique to maximize overall satisfaction. The performance of competitors is taken as the highest and lowest limit with respect to the ideal and intolerable customer satisfaction level respectively. Luo et al. (2014) proposed a five-step QFD-based method to optimize the value selection of platform ECs and non-platform ECs within product family to maximize overall customer satisfaction (OCS). Liu et al. (2017) proposed a 2-phase approach based on fuzzy QFD and design structure matrix (DSM) to optimize a customer-collaborative design. A maximum performance model was constructed to maximizing customer satisfaction with the constraints of costs and function of part characteristics (PCs). Wang et al. (2017) combined service QFD, TRIZ (Theory of Inventive Problem Solving) and service blueprint approaches in service design, and a scalable and interoperate ordering model was formed for self-

service restaurants. Salari and Bhuiyan (2018) constructed an optimal model based on QFD and multi-attribute utility theory to make trade-offs between sustainability, quality and cost and CRs simultaneously to get the optimum combined level and optimized design specifications.

QFD is a methodology that can be integrated with other methods, like Kano model and TRIZ. However, it is not suitable for cases where the evaluation of an EC is different for some CRs.

2.4 The Kano's Model

The Kano's model (Kano et al. 1984) is a two-dimensional model applied to better understand CRs and their impact on customer satisfaction. Kano proposed the non-linear relationship between quality attribute performance and overall satisfaction. According to the Kano's model, quality attributes can be classified into six categories related to the different CS level correlation to specific CRs fulfilment levels:

- **One-dimensional (O)**

CS will be positively and linearly dependent to the fulfilment level. The higher the fulfilment level, the greater the CS, and vice versa.

- **Attractive (A)**

Low fulfilment level will not incur dissatisfaction whereas higher fulfilment level will lead to greater CS because the customers do not expect it.

- **Must-be (M)**

Customers will always expect its presence. Therefore, high fulfilment level will not increase satisfaction, but low fulfilment level will result in severe dissatisfaction.

- **Indifferent (I)**

The fulfilment level will not cause any satisfaction or dissatisfaction as customers do not care about it.

- **Reverse (R)**

CS will be negatively and linearly dependent to the fulfilment level. The lower the fulfilment level, the greater the CS, and vice versa.

- **Questionable (Q)**

The customer demonstrated a contradiction in the investigation.

Figure 1 - The Kano Relationship Function (Berger et al. 1993)

The Kano's model is conducted through 3 procedures: Kano investigation, Kano evaluation, and Kano categorization. The Kano questions exams each CR with a pair of questions, in functional form and dysfunctional form, and each answer pair is

aligned with the Kano evaluation table. There are five possible answers: like, must-be, neutral, tolerate and dislike. The final definition of Kano categories for specific CRs are determined by checking the Kano evaluation table, and the highest frequent observations of answer pairs can represent the view of dominant customers.

Table 1 - The Kano Classification Matrix

CRs		Dysfunctional				
		Like	Must-be	Neutral	Live with	Dislike
Functional	Like	Q	A	A	A	O
	Must-be	R	I	I	I	M
	Neutral	R	I	I	I	M
	Live with	R	I	I	I	M
	Dislike	R	R	R	R	Q
A = Attractive		M = Must-be		R = Reverse		
O = One-dimensional		I = Indifferent		Q = Questionable		

Berger et al. (1993) proposed customer satisfaction coefficient that indicates the quantitative values of satisfaction (CS) and dissatisfaction (DS) with respect to CR fulfilment level. T. Wang et al. (2010) proposed a qualitative analysis in the Kano's model by identifying S-CR relationship functions to measure customer satisfaction(CS) at different CR fulfilment level.

Violante and Vezzetti (2017) proposed an assessment matrix that identifies the relationships and classifications requirements between different Kano qualitative and quantitative approaches to assist in selecting the most suitable methodology that response better in customer-driven product and service design.

Kano model is suitable to model customer requirements by assessing their satisfaction. Several Kano qualitative and quantitative approaches were proposed by several researches, but there were limited applications in product customization.

2.5 Integration of the Kano's model into QFD

The Kano's model and QFD are both widely used in customer-oriented design procedure for CR analysis. Many researchers proposed a combination of the Kano's model and QFD.

Lai et al. (2004) integrated quantitative information in the Kano's model into QFD by evaluating the degree of customer satisfaction (CS) and dissatisfaction (DS), and a mathematical programming model was built under cost constraint for an optimal design solution. Ji et al. (2014) proposed an optimization model that integrates the Kano's model into QFD to maximize customer satisfaction (S) with the constraints of cost and technical attributes. In this model, the Kano's model was firstly quantified by constructing the S-CR relationship functions. Then the results were integrated into QFD to construct a mixed integer nonlinear programming model. Finally, the optimal level of CR fulfilment and the value of specific technical attributes for engineer characteristics (ECs) can be determined. He et al. (2017) proposed an importance-frequency Kano (IF-Kano) model and integrated IF-Kano into QFD with a non-linear programming model to maximum share surplus consisting of overall customer satisfaction CS and producer satisfaction. And multi-population adaptive genetic algorithm (MPAGA) is designed to solve the proposed model.

As mentioned above, QFD and Kano model were proposed for quantitative analysis. However, the complexity of EC and the constraints among ECs were seldom emphasized in those studies. Thus, they were not widely used in product configuration system.

2.6 Optimization Methods for Product Configuration

In mathematics, an optimization model consists of three elements, namely decision variables, objective function, and constraints. An example of a well-structured optimization model is provided below.

Description:	<p>maximize revenue, z</p> <p>x is sold at \$2/unit and y is sold at \$3/unit</p> <p>x and y consume 3 and 2 units of material A (10 units available)</p> <p>x and y consume 1 and 3 units of material B (8 units available)</p>
Decision Variables:	x, y
Objective Function:	$\max \quad z = 2x + 3y$
Constraints:	$3x + 2y \leq 10$ $x + 3y \leq 8$ $x, y \geq 0$

There are some existing researches on product configuration by using optimization algorithm. Yet, the formulation of the optimization model varies to each research, which has different focuses and pitfalls.

Lai et al. (2006) developed an optimization algorithm integrated with quantitative quality function deployment (QFD). In the research, it expressed the fulfilment level in term of the cost for any technical attribute by a linear function ($y = ax + b$). It assumed the fulfilment level is linear dependent on the cost. Furthermore, it calculated overall customer satisfaction by the sum of the product of the fulfilment level and the importance weight ($CS = \sum Importance\ Weight * Fulfilment\ Level$). In another word, it also assumed a linear relationship between the overall customer satisfaction and the fulfilment level of each technical attribute.

Yet, the linear dependency is not always true in real life. A study can be done to make a more realistic prediction on the customer satisfaction based on the fulfilment level.

In the optimization framework proposed by Ji et al. (2014), there is only one numerical feature for each engineering characteristic (EC). Therefore, in the same EC, every pair of parts is comparable, and it is possible to rank all parts. A part could be strictly preferable over another, regardless of the customer preference. For an extreme example, if the budget is unlimited, the algorithm will recommend only one configuration, which contains the ‘best’ part from each EC, regardless of the customer preference. However, the definition of the ‘best’ part varies to each individual in reality. The algorithm should be robust to process ECs with multiple features.

Chapter 3 Research Framework

This study proposes a product configuration system that can generate an optimal product configuration to maximize customer satisfaction under budget constraint. This configuration system consists of four phases, namely: 1) Evaluation of Enterprise Capabilities; 2) Investigation of Market Demand; 3) Formulation and Optimization; 4) Review.

In the first phase, engineering characteristics (ECs) are defined and selection pools are constructed based on the information collected from the service provider. Each EC has a selection pool to contain the parts that could be chosen in the configuration. Each part has a normalized EC fulfilment score and configuration constraint with other parts stated by the domain experts. In the second phase, quality function deployment (QFD) is integrated with the Kano's model to qualitatively and quantitatively analyse the relationship between customer requirements (CRs) and customer satisfaction (CS). S-CR relationship functions proposed by Ji et al. (2010) were used in this phase. A customer survey is conducted among the target users with a Kano questionnaire to help the construction of S-CR relationship functions, which is renamed as CS-F (Customer Satisfaction – Fulfilment) Relationship Function in this research. In the third phase, a mathematical programming model is applied to formulate the overall customer satisfaction (OCS) with predefined information from the first two phases, and additional input from the service demander. It will recommend an optimal product configuration that maximizes OCS. In the fourth phase, sensitivity analysis is conducted for the service demander to review and

determine the final customized product specification. The configuration framework is developed as shown in Figure 2.

At the end of this chapter, a further discussion will be provided to elaborate the functions and how it assists the order acquisition and fulfilment process in the environment of Industry 4.0.

3.1 Definition of Engineering Characteristics

In Phase 1, enterprise capabilities are evaluated. The capabilities include the available selection, the score of each selection and the incompatibility constraint. The research process of Phase 1 can be expressed as shown in Figure 3.

Figure 3 - The Research Process of Phase 1: EC Definition

A product typically consists of multiple parts, modules, or subassembly. Engineering characteristics (ECs) of a product refer to the types of parts of it. In this dissertation, the product configuration system focuses on only discrete ECs, i.e. the selection of parts. The technical experts help to define the ECs to be involved in the product configuration, and define the selection pool for each EC, i.e. the set of parts can be chosen for the EC. For an EC, there could be more than one score to evaluate the performance of parts. These scores must be normalized for further analysis. In addition, configuration constraints must be known by the configuration system to avoid recommendation of infeasible solutions.

The ID of EC is written in an alphabet, denoted by j , and **the ID of a part** is written in number, denoted by k . For any product, there are selection pools for each EC as shown in Table 2.

Table 2 - List of ECs and Parts

EC	Part
A	1
	2
	3
	...
B	1
	2
	3
	...
...	...

The term, '**Part jk** ', will be used to represent **the k -th part of EC_j** , where $j \in \{A, B, C, \dots\}$ and $k \in \{1, 2, 3, \dots\}$. **The selection of Part jk** is denoted by X_{jk} .

The following assumption is made for the optimization model:

a) The total number of parts selected for one EC must be exactly one.

Assumption (a) leads to the following assumption:

b) For any part, at most one unit can be selected

Based on Assumption (a) and Assumption (b), X_{jk} will be a binary variable:

$$X_{jk} = \begin{cases} 1 & \text{if Part } jk \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

and Eq. (3.1) must be always true:

$$\sum_k X_{jk} = 1 \quad (3.1)$$

In reality, Assumption (a) and (b) are not always true. For some products, there may be a particular EC which is possible to be absent. In this case, it is recommended to create a virtual part in the selection pool, to indicate the absence of the EC. For instance, given that there are initially 3 parts for selection in EC_A , which is optional

in the product configuration, i.e. it is possible to make no selection. Therefore, an additional virtual part, '**Part A4**', should be added to the selection pool to represent the null selection as shown in Table 3.

Table 3 - Null Selection (Example)

EC	Part	Interpretation
A	1	Select Part A1
	2	Select Part A2
	3	Select Part A3
	4	Select Nothing

On the other hand, for some products, there may be a particular EC which allows multiple or repetitive selections. In this case, virtual parts can be introduced to represent such selection. For instance, given that there are initially 2 parts for selection in EC_b and it is allowed to select up to 2 parts. Therefore, 3 additional virtual parts, '**Part B3**', '**Part B4**' and '**Part B5**', should be added to the selection pool to represent the multiple and repetitive selections as shown in Table 4.

Table 4 - Multiple and Repetitive Selections (Example)

EC	Part	Interpretation
B	1	Select Part B1
	2	Select Part B2
	3	Select Part B1 *2
	4	Select Part B2 *2
	5	Select Part B1 + Part B2

Normally, each part has a score to indicate its performance. There are typically two types of score. One is positive-favour (high score is strictly preferred over low score), and the other is negative-favour (low score is strictly preferred over high score). The scores can be linearly dependent to the technical parameters or manually evaluated. However, for some customer requirements, the contribution of EC depends on various aspects with different weights. In this case, the parts in EC should have more

than one score for the further evaluation. **Score m of Part jk** is denoted by $S_{jk,m}$.

For instance, the parts of EC_A have two scores for evaluation, while those of EC_B have only one score. The data can be stored as shown in Table 5.

Table 5 - List of Scores according to Parts

EC	Part	Score 1	Score 2
A	1	$S_{A1,1}$	$S_{A1,2}$
	2	$S_{A2,1}$	$S_{A2,2}$
	3	$S_{A3,1}$	$S_{A3,2}$
	...	...	...
B	1	$S_{B1,1}$	
	2	$S_{B2,1}$	
	3	$S_{B3,1}$	
	...	...	

For parts representing multiple or repetitive selections, the score can be multiplied if the score is linearly dependent to the technical parameters. Otherwise, re-evaluation is required. An example is shown in Table 6:

Table 6 - Linearly Dependent Score (Example)

EC	Part	Interpretation	Score 1
A	1	Select Part A1	$S_{A1,1}$
	2	Select Part A1 *2	$S_{A2,1} = 2 * S_{A1,1}$

If score 1 of EC_A is positive-favour and linearly dependent to certain technical parameters. $S_{A2,1}$ should be twice of $S_{A1,1}$. If the linear dependency is not true, $S_{A2,1}$ must be re-evaluated.

Before further evaluation, all scores must be normalized with selected upper bound and lower bound. **Normalized Score m of Part jk** is denoted by $S'_{jk,m}$, which can be calculated by:

$$S'_{jk,m} = \frac{S_{jk,m} - S_{j,m}^{\min}}{S_{j,m}^{\max} - S_{j,m}^{\min}} \quad \text{if the score is positive-favour (higher is better), or}$$

$$S'_{jk,m} = \frac{S_{j,m}^{\max} - S_{jk,m}}{S_{j,m}^{\max} - S_{j,m}^{\min}} \quad \text{if the score is negative-favour (lower is better)}$$

where $S_{jk,m}$ is the score m of Part jk , $S_{j,m}^{\min}$ is the selected minimum score m of EC_j for benchmark, and $S_{j,m}^{\max}$ is the selected maximum score m of EC_j for benchmark.

There are three recommended schemes to set the minimum and maximum score for benchmark.

- 1) Use the minimum and maximum score in the selection pool;
- 2) Use the minimum and maximum score available in the market; and
- 3) Hybrid of Scheme (1) and (2).

The final score m of EC_j is denoted by $S'_{j,m}$. It depends on the selection of part in EC_j and can be calculated by Eq. (3.2):

$$S'_{j,m} = \sum_k X_{jk} S'_{jk,m} \quad (3.2)$$

where X_{jk} is the selection of Part jk and $S'_{jk,m}$ is the normalized score m of Part jk .

An example is provided as shown in Table 7.

Table 7 - Selection of Parts (Example)

Part	Score 1	Score 2	Selection	Remark
A1	$S'_{A1,1}$	$S'_{A1,2}$	$X_{A1} = 0$	Not selected
A2	$S'_{A2,1}$	$S'_{A2,2}$	$X_{A2} = 1$	Selected
...	...	...	...	...

In Table 7, Part A2 is selected in EC_A . Therefore, the final score 1 of EC_A , $S'_{A,1}$, is equal to $S'_{A2,1}$ and the final score 2 of EC_A , $S'_{A,2}$, is equal to $S'_{A2,2}$. The calculation follows:

$$S'_{A,1} = X_{A1}S'_{A1,1} + X_{A2}S'_{A2,1} + \dots = 0 * S'_{A1,1} + 1 * S'_{A2,1} + \dots = S'_{A2,1}$$

$$S'_{A,2} = X_{A1}S'_{A1,2} + X_{A2}S'_{A2,2} + \dots = 0 * S'_{A1,2} + 1 * S'_{A2,2} + \dots = S'_{A2,2}$$

In addition, each part has a price. **The price of Part jk** is denoted by P_{jk} . For parts representing multiple or repetitive selections, the price should be the sum of each individual price. An example is shown in Table 8:

Table 8 - Price of Parts (Example)

EC	Part	Interpretation	Price
A	1	Select Part A1	P_{A1}
	2	Select Part A1 *2	$P_{A2} = 2 * P_{A1}$

There are few possible additional constraints that could exist among parts in nature, or demanded by the service demander. They could be formulated as shown below.

If Part jk is required, the following constraint should be added:

$$X_{jk} = 1$$

If Part jk is incompatible with Part pq , the following constraint should be added:

$$X_{jk} + X_{pq} \leq 1$$

If either Part jk or Part pq must be selected, the following constraint should be added:

$$X_{jk} + X_{pq} \geq 1$$

If either Part jk or Part pq must be selected but not both, the following constraint should be added:

$$X_{jk} + X_{pq} = 1$$

If X_{jk} and X_{pq} complement each other, the following constraint should be added:

$$X_{jk} = X_{pq}$$

In conclusion, this section constitutes the first portion of the optimization framework as shown in Figure 4.

$$\begin{array}{c} \text{Final Score of EC} \\ \left(\begin{array}{cccc} S'_{j1,1} & S'_{j2,1} & S'_{j3,2} & \dots \\ S'_{j1,2} & S'_{j2,2} & S'_{j3,2} & \dots \\ S'_{j1,3} & S'_{j2,3} & S'_{j3,3} & \dots \\ \dots & \dots & \dots & \dots \end{array} \right) \left(\begin{array}{c} X_{j1} \\ X_{j2} \\ X_{j3} \\ \dots \end{array} \right) = \left(\begin{array}{c} S'_{j,1} \\ S'_{j,2} \\ S'_{j,3} \\ \dots \end{array} \right) \quad \forall j \\ \text{Normalized Score} \quad \text{Selection of Part} \quad \text{for all } j \end{array}$$

Figure 4 - EC component in Optimization Framework

This portion generates ECs, selection pools, normalized scores and possible configuration constraints for the subsequent process.

3.2 Definition of Customer Requirements

In Phase 2, the market demand is investigated. The investigation consists of identification of customer requirements and the formulation of customer satisfaction. In this phase, traditional QFD is refined and integrated with the Kano's model to form a CS-F relationship function for each CR, which was named as S-CR relationship function proposed by Ji. et al (2010). The research process of Phase 2 can be expressed as shown in Figure 5.

Figure 5 - The Research Process of Phase 2: CR Modelling

3.2.1 Fulfilment of Customer Requirements

Customer requirements of a product refer to the judging criteria when a customer is evaluating it. The marketing experts help to identify the CRs to be involved for the product to fulfill. Then it requires an investigation to be done to classify the CRs into several types. Based on the investigation result, CS could be mathematically expressed by the fulfilment level of each CR and integrated into the optimization model.

The ID of CRs is written in number. Quality function deployment (QFD) is implemented to construct the house of quality (HOQ), which is the main representation to show the relationships between ECs and CRs. A typical HOQ is shown in Figure 6.

		Engineering Characteristics
Customer Requirements	Importance Weights	Strength of Relationship between Customer Requirements and Engineering Characteristics

Figure 6 - Typical HOQ in this dissertation

The strength of relationship has a discrete value scaled from 0 to 9 with interpretations as shown in Figure 7.

Figure 7 - Scale of Strength of Relationship

The strength of relationship between CR_i and EC_j is denoted by $R_{i,j}$, while $R_{i,j} \in \{0,1,2, \dots, 9\}$. An example of HOQ can be written as shown in Table 9.

Table 9 - Filled HOQ

EC \ CR	A	B	C	...
1	$R_{1,A}$	$R_{1,B}$	$R_{1,C}$	...
2	$R_{2,A}$	$R_{2,B}$	$R_{2,C}$	...
3	$R_{3,A}$	$R_{3,B}$	$R_{3,C}$	...
...	...	...	...	...

Then, $R_{i,j}$ needs to be normalized by Eq. (3.3):

$$R'_{i,j} = \frac{R_{i,j}}{\sum_j R_{i,j}} \quad (3.3)$$

(The fraction of the sum of the row in HOQ)

The normalized HOQ can be written as shown in Table 10.

Table 10 - Normalized HOQ

EC \ CR	A	B	...
1	$R'_{1,A}$	$R'_{1,B}$	...
2	$R'_{2,A}$	$R'_{2,B}$	...
...	...	...	...

Eq. (3.4) be always true to validate the normalized HOQ:

$$\sum_j R'_{i,j} = 1 \quad \forall i \quad (3.4)$$

(The sum of each row is equal to 1)

$R'_{i,j}$ can be considered as the contribution of EC_j towards CR_i . The overall score of EC_j depends on its scores. It will require a fractional contribution of each score to calculate the overall score of EC_j . **The fractional contribution of score m of EC_j for CR_i** is denoted by $FC_{i,j,m}$. Eq. (3.5) must be always true:

$$\sum_m FC_{i,j,m} = 1 \quad \forall i, j \quad \text{for } R'_{i,j} \geq 0 \quad (3.5)$$

An example of $FC_{i,j,m}$ can be written in a matrix as shown in Table 11.

Table 11 - Fractional Contribution of EC_A

CR	EC_A	
	Score 1	Score 2
1	$FC_{1,A,1} = 0.8$	$FC_{1,A,2} = 0.2$
2	$FC_{2,A,1} = 0$	$FC_{2,A,2} = 1$

Table 11 shows that the contribution of EC_A towards CR_1 weights 80% on score 1 and 20% on score 2, and the contribution of EC_A towards CR_2 fully depends on score 2, i.e. score 1 of EC_A has no effect to the fulfilment of CR_2 .

The normalized strength of relationship, $R'_{i,j}$ is then modified to $R''_{i,j,m}$, which represents the contribution of score k of EC_j towards the CR_i . $R''_{i,j,m}$ can be calculated by Eq. (3.6):

$$R'_{i,k,m} = FC_{i,j,m} * R'_{i,j} \quad (3.6)$$

Eq. (3.7) must be always true:

$$\sum_m FC_{i,j,m} = 1 \quad \forall i,j \quad \text{for } R'_{i,j} \geq 0 \quad (3.7)$$

The modified normalized HOQ can be written as shown in Table 12.

Table 12 - Modified Normalized HOQ

EC \ CR	A		B	...
	1	2	1	...
1	$R'_{1,A,1}$ $= FC_{1,A,1} * R'_{1,A}$	$R'_{1,A,2}$ $= FC_{1,A,2} * R'_{1,A}$	$R'_{1,B,1}$ $= FC_{1,B,1} * R'_{1,B}$ $= R'_{1,B}$	...
2	$R'_{2,A,1}$ $= FC_{2,A,1} * R'_{2,A}$	$R'_{2,A,2}$ $= FC_{2,A,2} * R'_{2,A}$	$R'_{2,B,1}$ $= FC_{2,B,1} * R'_{2,B}$ $= R'_{2,B}$	...
...	...	...	...	...

If EC_j has only one score, Eq. (3.7) can be simplified to Eq. (3.8):

$$\sum_m FC_{i,j,m} = FC_{i,j,1} = 1 \quad \text{for } m \in \{1\} \quad (3.8)$$

In Table 12, EC_B has only one score. Therefore, $R'_{1,B,1}$ is equal to $R'_{1,B}$ and $R'_{2,B,1}$ is equal to $R'_{2,B}$.

The fulfilment level of CR_i is denoted by F_i . For any product configuration, the scores of ECs can be translated to the fulfilment level of each CR by Eq. (3.9):

$$F_i = \sum_j \sum_m S'_{j,m} R'_{i,j,m} \quad (3.9)$$

In conclusion, this subchapter constitutes the second portion of the optimization framework as shown in Figure 8.

$$\begin{array}{c} \text{Normalized Strength of Relationship} \\ \left(\begin{array}{cccccc} R''_{1,A,1} & R''_{1,A,2} & \dots & R''_{1,B,1} & R''_{1,B,2} & \dots \\ R''_{2,A,1} & R''_{2,A,2} & \dots & R''_{2,B,1} & R''_{2,B,2} & \dots \\ R''_{3,A,1} & R''_{3,A,2} & \dots & R''_{3,B,1} & R''_{3,B,2} & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \end{array} \right) \end{array} \begin{array}{c} \text{Fulfilment Level} \\ \left(\begin{array}{c} S'_{A,1} \\ S'_{A,2} \\ \dots \\ S'_{B,1} \\ S'_{B,2} \\ \dots \end{array} \right) = \left(\begin{array}{c} F_1 \\ F_2 \\ F_3 \\ \dots \end{array} \right) \end{array}$$

Figure 8 - CR Component in Optimization Framework

This portion generates the fulfilment level of CRs as an expression of the selection of part and the normalized strength of relationship in HOQ for the subsequent process.

3.2.2 The Kano's Model

The Kano's model is proposed to formulate the customer satisfaction (CS) of each CR as an expression of the fulfilment level.

In the Kano's model, there are 6 types of CR, namely:

- **One-dimensional (O)**
- **Attractive (A)**
- **Must-be (M)**
- **Indifferent (I)**
- **Reverse (R)**
- **Questionable (Q)**

A Kano questionnaire, proposed by Berger et al. (1993), is required to classify CRs into the 6 Kano categories. The questionnaire examines each CR with a pair of questions, one in functional condition and the other in dysfunctional condition. The questionnaire concerns customers' responses about two extreme cases, nearly 0% and 100% fulfilment of each CR. There are 5 possible answers for each question: like, must-be, neutral, live with and dislike. According to the responses to each pair of questions, the corresponding CR can be classified into one of the 6 Kano categories for each customer by the Kano classification matrix as shown in Table 13.

Table 13 - The Kano Classification Matrix

CRs		Dysfunctional				
		Like	Must-be	Neutral	Live with	Dislike
Functional	Like	Q	A	A	A	O
	Must-be	R	I	I	I	M
	Neutral	R	I	I	I	M
	Live with	R	I	I	I	M
	Dislike	R	R	R	R	Q
A = Attractive		M = Must-be		R = Reverse		
O = One-dimensional		I = Indifferent		Q = Questionable		

Each CR can be classified according to the most frequently appeared category. If the Kano classification of a CR is ‘I’, it will be excluded in the further study as the fulfilment level of this CR does not influence CS.

Since the fulfilment of CR should be described as a positive influence on CS, ‘R’ is not supposed to be the most frequently appeared category for the CR. Otherwise, the functional and dysfunctional definitions should be swapped and reinvestigate the Kano classification.

‘Q’ indicates an irrational perception of the CR. It is not reasonable for one to like or dislike the functional condition and the dysfunctional condition at the same time. It may appear when the respondent is not answering the questionnaire seriously. Therefore, it is not supposed to be the most frequently appeared category for the CRs, either.

Overall, the further analysis will only focus on ‘O’, ‘A’ and ‘M’.

Two important values, the coefficient of satisfaction (CS) and the coefficient of dissatisfaction (DS), must be calculated in order to formulate CS as an expression of the fulfilment of CR. The CS of CR_i , denoted by cs_i , can be calculated by the sum of satisfaction elements (one-dimensional and attractive), divided by all effective responses (excluding ‘R’ and ‘Q’), as shown below by Eq. (3.10):

$$cs_i = \frac{f_O + f_A}{f_A + f_O + f_M + f_I} \quad (3.10)$$

where f_A , f_O , f_M and f_I is the total number of attractive, one-dimensional, must-be and indifferent responses, respectively.

Similarly, the DS of CR_i , denoted by ds_i , can be calculated by the negative sum of dissatisfaction elements (one-dimensional and must-be), divided by all effective responses, as shown below by Eq. (3.11):

$$ds_i = -\frac{f_O + f_M}{f_A + f_O + f_M + f_I} \quad (3.11)$$

ds_i and cs_i quantify the customer satisfaction when CR_i is 0% fulfilled and 100% fulfilled respectively. Therefore, the $CS_i - F_i$ relationship function should pass through $(0, ds_i)$ and $(1, cs_i)$ as shown in Figure 9.

Figure 9 - The CR-F Relationship Function for 'O', 'A' and 'M'

The formulation of customer satisfaction level against the fulfilment level was proposed by Ji, P et al (2010). For one-dimensional CS_i , the $CS_i - F_i$ relationship function can be expressed as a linear function, $CS_i = aF_i + b$. By substituting $(0, ds_i)$ and $(1, cs_i)$, a and b can be expressed by cs_i and ds_i as shown below:

$$a = cs_i - ds_i \quad (3.12)$$

$$b = ds_i \quad (3.13)$$

For attractive CS_i , the $CS_i - F_i$ relationship function can be expressed as an exponential function, $CS_i = ae^{F_i} + b$, by substituting $(0, ds_i)$ and $(1, cs_i)$, a and b can be expressed by cs_i and ds_i as shown below:

$$a = \frac{cs_i - ds_i}{e - 1} \quad (3.14)$$

$$b = -\frac{cs_i - e * ds_i}{e - 1} \quad (3.15)$$

For must-be CS_i , the $CS_i - F_i$ relationship function can be expressed as a linear function, $CS_i = ae^{-F_i} + b$, by substituting $(0, ds_i)$ and $(1, cs_i)$, a and b can be expressed by cs_i and ds_i as shown below:

$$a = \frac{e(cs_i - ds_i)}{e - 1} \quad (3.16)$$

$$b = \frac{e * cs_i - ds_i}{e - 1} \quad (3.17)$$

Generally, $f_i(F_i, a, b)$ denotes the $CS_i - F_i$ relationship function, where a and b depend on the Kano classification of CR_i and the responses in the Kano questionnaire.

This subchapter focuses on the constitution of the third portion in the optimization framework as shown in Figure 10.

$$CR_i - F_i \text{ Function} \begin{pmatrix} f_1(F_1, a_1, b_1) \\ f_2(F_2, a_2, b_2) \\ f_3(F_3, a_3, b_3) \\ \dots \end{pmatrix} = \begin{pmatrix} CS_1 \\ CS_2 \\ CS_3 \\ \dots \end{pmatrix} \text{ Customer Satisfaction of CR}$$

Figure 10 - CS Component in Optimization Framework

This portion generates the CS as an expression of the fulfilment level based on the Kano's model.

3.3 Input from Service Demander

After Phase 1 and Phase 2, the enterprise capabilities have been defined and the market demand has been investigated. The optimization mode would be ready to take input from the service demander to generate an optimal solution for them. The basic input includes the budget and the importance weight for each CR. In addition, the service demander could also request to fix a particular EC in their needs, and the configuration system would optimize the rest of ECs in this condition. The research process of Phase 3 can be expressed as shown in Figure 11.

Figure 11 - The Research Process of Phase 3: Formulation and Optimization

A very important piece of information is budget, denoted by B . The optimization model is subject to the budget constraint as shown below by Eq. (3.18):

$$\sum_j \sum_k P_{jk} X_{jk} \leq B \quad (3.18)$$

where P_{jk} is the price of Part jk and X_{jk} is the selection of Part jk .

Furthermore, the importance weight of each CR, denoted by w_i , is required from the service demander.

It constitutes the last portion in the optimization framework as shown in Figure 12.

$$\text{Importance Weight} \begin{pmatrix} w_1 \\ w_2 \\ w_3 \\ \dots \end{pmatrix} \cdot \begin{pmatrix} CS_1 \\ CS_2 \\ CS_3 \\ \dots \end{pmatrix} = S \quad \begin{matrix} \text{Overall Customer} \\ \text{Satisfaction} \end{matrix}$$

Figure 12 - Overall Satisfaction in Optimization Framework

3.4 Optimization Model Formulation

In Phase 1, the service provider needs to define engineering characteristics (ECs) with prices (P_{jk}) and scores ($S_{jk,m}$) and then normalize the scores into normalized scores ($S'_{jk,m}$). The normalized final score m of EC j ($S'_{j,m}$) depends on the selection of parts (X_{jk}). In Phase 2, the service provider needs to construct an HOQ with the strength of relationship between CRs and ECs ($R_{i,j}$) and normalize them into the normalized strength of relationship ($R'_{i,j}$), in order to express the fulfilment level (F_i) by the final scores of all ECs for all CRs. Meanwhile, a Kano questionnaire must be done to derive an expression of customer satisfaction, $CS_i = f_i(F_i, a_i, b_i)$. In Phase 3, the service demander needs to set a budget (B) and input the importance weight (w_i) for each CS. The total price of the selected parts must be no more than the budget. Overall customer satisfaction (S) can be expressed by the dot product of importance weights and customer satisfaction. The objective of the optimization model is to maximize the overall customer satisfaction under the budget and other constraints.

By integrating all the variables, the optimization model can be formulated as shown below.

Notation:

a_i	<i>Constant a in $CS_i - F_i$ Relationship Function</i>
b_i	<i>Constant b in $CS_i - F_i$ Relationship Function</i>
B	<i>Budget</i>
F_i	<i>Fulfilment Level of CR_i</i>
CS_i	<i>Customer Satisfaction of CR_i</i>

P_{jk}	Price of Part jk
$R'_{i,j,m}$	Normalized Strength of Relationship between CR_i and Score m of EC_j
S	Overall Customer Satisfaction
$S'_{jk,m}$	Normalized Score m of Part jk
$S'_{j,m}$	Normalized Final Score m of EC_j
w_i	Importance Weight of CR_i in Overall Customer Satisfaction
X_{jk}	Selection of Part jk

Decision Variables:

$$X_{jk} = \begin{cases} 1 & \text{if Part } jk \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

Objective Function:

$$\max \quad S \quad \text{Overall Customer Satisfaction}$$

Constraints:

$\sum_j \sum_k P_{jk} X_{jk} \leq B$	Total Price $\leq$ Total Budget Available
$\sum_k X_{jk} = 1 \quad \forall j$	Only one component can be selected for an EC
$\sum_k S'_{jk,m} X_{jk} = S'_{j,m} \quad \forall i$	Calculate Final Score m of EC
$\sum_j \sum_m R'_{i,j,m} S'_{j,m} = F_i \quad \forall i$	Calculate Fulfilment Level of CR
$CS_i = f_i(F_i, a_i, b_i) \quad \forall i$	Calculate Customer Satisfaction of CR
$\sum_i w_i CS_i = S$	Calculate Overall Customer Satisfaction

The expression of one-dimensional CSs follows a linear function, $y = ax + b$. The expression of attractive or must-be CSs follows a smooth nonlinear function, $y = ae^x + b$. Overall, this is a nonlinear optimization model. It cannot be solved by linear programming algorithm. Instead, it can be solved by the **Generalized Reduced**

Gradient (GRG) method developed by Lasdon et al (1974). The GRG method can be considered as a nonlinear extension of the Simplex method, which solves a linear optimization problem by selecting a basis, determining a search direction and performing a line search on each iteration. The GRG method computes or approximates derivatives of the problem functions many times during the course of the optimization. It is robust to process nonlinear objective function and constraints. More importantly, it can be easily accessed and used in Microsoft Excel.

A mathematical optimization framework is developed as shown in Figure 13.

Figure 13 - Mathematical Optimization Framework

3.4 Recommended Product Configuration & Sensitivity Analysis

Figure 14 - The Research Process of Phase 4: Review

A sensitivity analysis will be performed after the optimization. It offers additional flexibility for the service demanders to review the result and adjust the output before they decide to place the orders. It looks for the nearest downgraded configuration and the nearest upgraded configuration based on the current recommended configuration. The research process of Phase 4 can be expressed in Figure 14.

It is assumed that budget does not negatively affect the customer satisfaction. In another word, if more budget is provided, the new optimal configuration will be at least as good as the old one to the same customer.

Based on this assumption, the nearest downgraded configuration is defined as the configuration that provides highest customer satisfaction below the current level, i.e. the best ‘worse’ configuration. By comparing the difference between the nearest downgraded configuration and the current recommended configurator, the customers will know the least value-added EC that he may consider dropping with less budget.

The nearest upgraded configuration is defined as the configuration that provides lowest customer satisfaction above the current level, i.e. the worst ‘better’ configuration. By comparing the difference between the nearest upgraded configuration and the current recommended configurator, the customers will know the most value-added EC that he may consider upgrading with more budget.

3.5 Product Configuration System Design

In summary, the product configuration system consists of backend and frontend operation.

The backend operation is contributed by technical experts and marketing experts to maintain the database of configurable parts for all ECs and the effectiveness of CS-F relationship function. Technical experts need to list down ECs and parts involved in the configuration system, with predefined scores and constraints. Marketing experts need to perform market research to understand the nature of CRs as well as how they could be fulfilled by ECs with technical experts.

The frontend operation engages the service demanders directly. They could indicate their budget, importance weight for CRs (or choose a user profile which contains default importance weight suggested by the experts) and additional requests if any. Once they confirm the information, the optimal solution would be presented to them with the sensitivity analysis. They could make minor adjustments or requested technical support from the service provider before they place the orders. Once the

orders are placed, the service provider would soon manufacture the products based on the ordered configuration and deliver to the service demanders.

Throughout this process, the product configuration system plays a vital role to bridge the communication gap and speed up the customization process, earning a competitive edge for the service provider in Industry 4.0. The product configuration system can be evaluated in two aspects, namely efficiency and effectiveness.

In Industry 4.0, quick response is a key to success. The service provider must be able to respond to the diverse customer expectations in a short time. The product configuration system is designed to speed up the customization process. With the pre-defined database of ECs, the sales personnel do not have to countercheck with the technical experts as frequent as before while engaging the service demanders. Therefore, the efficiency can be measured by the average time from receiving a request for customization to the confirmation of the order and whether it is significantly improved by implementing the system.

While being able to make prompt responses, the effectiveness of the system must be maintained as well. The system must be able to propose a solution that addresses the customer's needs precisely. In the early stage of implementing the system, technical experts should help to monitor the proposed solutions or configurations. In the long run, the effectiveness can be measured by the number of revisions required, the percentage of customers placing the order in the end, and the actual customer satisfaction after their orders are fulfilled.

In the traditional customization process, it is hard to achieve quick response if the sales personnel have to liaise with service demanders and technical experts at the same time. It is also hard to offer effective solutions or customer experience if the customer needs to research and make choices by themselves. As for the existing configuration frameworks, most of them stress a lot on the mathematical operations but the practical interpretation. Overall, the proposed product configuration system has a sophisticated mechanism to perform the optimization of customer satisfaction in a feasible and reasonable range in a short period of time, empowering the service providers to make a quick response to dynamic customer requirements in Industry 4.0.

The next chapter will provide a case study to elaborate on the application of the proposed product configuration system.

Chapter 4 Case Study

4.1 Case Background

DT Company is a leading industrial automation manufacturer, offering efficient and reliable products and solutions to serve global customers. One of their specialty is an automated batch process for small volume, high mix customization. It has a loyal client, Company A, for years.

Company A is a business-to-business (B2B) information technology (IT) company, specializing in the flexible manufacturing of desktop, laptops and other IT devices. Established for years, A had been running smoothly with its standard operation procedure, including sale interview with their clients. ‘configure-to-order’ services, and batch production. However, recently, they have been receiving increasingly frequent customized orders in greater diversity from their client, Company B.

Company B is a laptop retailer, which is supplied mainly by Company A. In their standard collaborative process, individual consumers visited Company B’s outlet, expressed their needs to B’s sales personnel and hoped to get a desirable product. If their needs are beyond the existing products available in shops, B’s sales personnel would inform the procurement team to place the customized order. The procurement team would then engage Company A’s sales personnel for an interview to discuss the cost and the feasibility of the customization. At this point, A’s sales personnel would also seek technical advice from A’s technical personnel to validate the feasibility. Along with this communication chain, information might be misaligned sometimes.

A diagram is developed to help the understanding of this communication chain as shown in Figure 15.

Figure 15 - 'As-is' model of order acquisition process

In the recent years, B noticed that the consumers expectations have gone more diverse. The communication activities between A and B became more frequently, and thus, more severe misalign of information was observed. Both A and B agreed that the current process had consumed a considerable amount of manpower and showed inefficiency when the communication was more intensive. They were keen to find a solution to address this issue.

In addition, Company A also notices that there could be a communication barrier between A' sales personnel and B's procurement team. Neither of them knows how to translate the customer needs to engineering characteristics. For instance, they may want the laptop to be good at graphics processing, but they have no idea which graphics card is capable enough to satisfy the need. Apparently, the best way to recommend the optimal laptop configuration is through a direct communication with A's technical personnel. But it requires much manpower and incurs more workload on the technical personnel.

Therefore, Company A engaged DT Company to streamline the communication process. DT wishes to propose a recommendation system, which takes the customer's evaluation priority or weight as the input, to generate the optimal product configuration under the given budget condition.

4.2 Definition of Engineering Characteristics

4.2.1 Selection Pool

To begin with, DT Company must evaluate the capabilities of Company A on laptop configuration. Currently, Company A allows the customers to customize the laptops in various engineering characteristics (ECs). In a typical customization process, a customer would first decide the primary functional components, including central processing unit (CPU), graphics processing unit (GPU), random-access memory (RAM), hard disk drive (HDD) and solid-state drive (SSD), then the secondary functional components, including display, speaker, battery and fan, and lastly the non-functional components, which is housing, consisting of colour theme and surface finish. The customizable ECs are summarized in Table 14 below.

Table 14 - ECs of Company A's Laptops

EC ID	EC	Category
A	CPU	Primary Functional EC
B	GPU	
C	RAM	
D	HDD	
E	SSD	
F	Display	Secondary Functional EC
G	Speaker	
H	Battery	
J	Fan	
K	Housing	Non-functional EC

An EC is denoted by EC_j , where $j \in \{A, B, C, \dots\}$, e.g. EC_A refers to CPU and EC_B refers to GPU.

A customer can judge the non-functional EC by own aesthetics and the functionality of secondary functional ECs by senses, i.e. evaluate displays by eyes or speakers by ears. However, one can hardly evaluate the primary functional ECs by reading the technical specifications or parameters. Therefore, in the 1st phase, DT Company expects the product configuration system to maximize the customer satisfaction with the optimal solution of primary functional ECs.

To construct the selection pool for primary functional ECs, reference data is obtained from UserBenchmark (<http://www.userbenchmark.com/>), which is a platform that tests and evaluates thousands of PC components with millions of benchmarks and votes.

The evaluation of CPU consists of 3 parameters, namely single-core integer speed, quad-core integer speed and multi-core integer speed. Single-core integer speed is the

most important element of a processor's performance as it determines how quickly the laptop responds to typical tasks such as opening a window and switching between applications. Therefore, it is heavily weighted in business performance. Quad-core integer speed measures the ability of a processor to performance 4 single-core integer operations simultaneously. This processing speed is typically needed in multimedia performance, including gaming and professional design work such as animation and rendering. Multi-core integer speed measures the ability of a processor to perform 32 integer operations simultaneously. This parameter heavily contributes to computation performance like programming, database server and big data analysis. There are different sets of weights for these three parameters to measure the overall performance of CPU in business, multimedia and computation. The configurable CPU components are listed as shown in Table 15.

Table 15 - The List of Parts for EC_A : CPU

EC_A: CPU				
Part ID	Single-core Integer Speed (pts)	Quad-core Integer Speed (pts)	Multi-core Integer Speed (pts)	Price (S\$)
A1	83.1	161	164	53
A2	102	271	277	89
A3	114	300	308	166
A4	111	417	427	274
A5	140	484	733	418
A6	140	539	1091	475
	Score 1	Score 2	Score 3	

GPU and RAM have an overall score to indicate their performance in all contexts. The scores are evaluated based on a set of technical parameters. The configurable GPU and RAM components are listed as shown in Table 16.

Table 16 - The List of Parts for EC_B : GPU and EC_C : RAM

EC_B: GPU				
Part ID	CLim (MHz)	MLim (MHz)	Score	Price (S\$)
B1	1227	1468	19.5	99
B2	1290	1392	38.8	223
B3	1506	1709	72.2	410
B4	1607	1683	98.9	619
B5	2025	2928	126	792
EC_C: RAM				
Part ID	Capacity (GB)		Score	Price (S\$)
C1	1x4		38.3	77
C2	1x8		41.7	124
C3	2x4		76.4	148
C4	2x8		84.7	265

The evaluation of HDD and SSD consists of 2 parameters, namely capacity and sequential read speed. The capacity determines the amount of data can be stored in the device, but this parameter has no impact on the performance in any context. Sequential read speed measures how quickly the data can be read from the device. This parameter has no impact on the storage, but it can speed up the laptop, increasing the overall performance.

In addition, a laptop does not have to possess both HDD or SSD. However, one of the assumptions and constraints for this optimization model is that there must be exactly one part selected for each EC. Therefore, a virtual part, Part D1 and Part E1, is added to HDD and SSD respectively, to represent the absence of the EC. They have zero value for all parameters, including the price. Selecting Part D1 or Part E1 means no HDD or SSD is selected in the optimal product configuration. On the other hand, it is not allowed to select Part D1 and Part E1 at the same time. This constraint can be formulated as:

$$X_{D1} + X_{E1} \leq 1$$

where X_{D1} and X_{E1} denote the selection of Part D1 and Part E1.

The configurable HDD and SSD components are listed as shown in Table 17 and Table 18.

Table 17 - The List of Parts for EC_D : HDD

EC_D: Hard Disk Drive (HDD)			
Part ID	Capacity (TB)	Sequential Read Speed (MB/s)	Price (S\$)
D1	0	0	0
D2	0.5	163	58
D3	1	169	65
D4	2	174	86
D5	4	152	132
D6	8	127	252
Score 1		Score 2	

Table 18 - The List of Parts for EC_E : SSD

EC_E: Solid-state Drive (SSD)			
Part ID	Capacity (GB)	Sequential Read Speed (MB/s)	Price (S\$)
E1	0	0	0
E2	120	498	107
E3	250	497	127
E4	500	496	216
E5	1000	499	603
Score 1		Score 2	

In general, $S_{jk,m}$ denotes the score m of Part jk and P_{jk} denotes the price of Part jk . Particularly, since the parts in GPU and RAM have only one score, m can only be 1 for EC_B and EC_C .

4.2.2 Normalized Score

A new parameter, called ‘normalized score’, denoted by $S'_{jk,m}$, which represents the normalized score m of Part jk , is introduced to each part. To calculate this value, the following formula is used:

$$S'_{jk,m} = \frac{S_{jk,m} - S_{j,m}^{\min}}{S_{j,m}^{\max} - S_{j,m}^{\min}} \quad \text{if the score is positive-preferable (more is better), or}$$

$$S'_{jk,m} = \frac{S_{j,m}^{\max} - S_{jk,m}}{S_{j,m}^{\max} - S_{j,m}^{\min}} \quad \text{if the score is negative-preferable (less is better)}$$

where $S_{jk,m}$ is the score m of Part jk , $S_{j,m}^{\min}$ is the minimum score m of EC_j available in the market in the recent 3 years, and $S_{j,m}^{\max}$ is the maximum score m of EC_j that Company A possesses.

Currently, all scores are positive-preferable. Therefore, only the first normalization equation is needed. The normalized score is calculated for all groups as shown in Table 19 and Table 20.

Table 19 - The List of Parts for EC_A : SSD with Normalized Score

EC_A: CPU						
Part ID	Score			Normalized Score		
	1	2	3	1	2	3
A1	83.1	161	164	0.521	0.243	0.118
A2	102	271	277	0.680	0.463	0.225
A3	114	300	308	0.781	0.521	0.255
A4	111	417	427	0.756	0.756	0.368
A5	140	484	733	1	0.890	0.659
A6	140	539	1091	1	1	1
$S_{A,m}^{min}$	21.2	39.7	40.5			
$S_{A,m}^{max}$	140	539	1091			

For instance, according to the reference data on UserBenchmark, in the recent 3 years, the minimum score 1 can be found in the market is 21.2. Therefore, $S_{A,1}^{min}$ is equal to 21.2. Among all CPUs that Company A can provide, Part A6 has the higher score 1, which is 140. Therefore, $S_{A,1}^{max}$ is equal to 140.

Table 20 - The List of Parts for EC_B , EC_C , EC_D and EC_E with Normalized Score

EC_B: GPU			EC_C: RAM		
Part ID	Score	Normalized Score	Part ID	Score	Normalized Score
B1	19.5	0.126	C1	38.3	0.185
B2	38.8	0.286	C2	41.7	0.244
B3	72.2	0.563	C3	76.4	0.854
B4	98.9	0.784	C4	84.7	1
B5	125	1	$S_{C,m}^{min}$	27.8	
$S_{B,m}^{min}$	4.25		$S_{C,m}^{max}$	84.7	
$S_{B,m}^{max}$	125				

EC_D: HDD				
Part ID	Score		Normalized Score	
	1	2	1	2
D1	0	0	0	0
D2	0.5	163	0.063	0.937
D3	1	169	0.125	0.971
D4	2	174	0.25	1
D5	4	152	0.5	0.874
D6	8	127	1	0.73
$S_{D,m}^{min}$	0	0		
$S_{D,m}^{max}$	8	174		

EC_E: SSD				
Part ID	Score		Normalized Score	
	1	2	1	2
E1	0	0	0	0
E2	122	498	0.125	0.998
E3	250	497	0.25	0.996
E4	500	496	0.5	0.994
E5	1000	499	1	1
$S_{E,m}^{min}$	0	0		
$S_{E,m}^{max}$	1000	499		

Some examples of calculation are provided below:

$$S'_{A3,3} = \frac{S_{A3,3} - S_{A,3}^{min}}{S_{A,3}^{max} - S_{A,3}^{min}} = \frac{308 - 40.5}{1091 - 40.5} = 0.255$$

$$S'_{C3,1} = \frac{S_{C3,1} - S_{C,1}^{min}}{S_{C,1}^{max} - S_{C,1}^{min}} = \frac{76.4 - 27.8}{84.7 - 27.8} = 0.854$$

$$S'_{E4,1} = \frac{S_{E4,1} - S_{E,1}^{min}}{S_{E,1}^{max} - S_{E,1}^{min}} = \frac{500 - 0}{1000 - 0} = 0.5$$

4.3 Definition of Customer Satisfaction for each CR

4.3.1 Customer Requirements

Based on the discussion with Company A, DT Company lists down a set of customer requirements (CRs) that its customers commonly concern below:

- Price
- Business Performance (e.g. surfing, email, office work)
- Multimedia Performance (e.g. 3D gaming, professional design)
- Computation Performance (e.g. programming, big data analysis)
- Display Performance
- Audio Performance
- Battery Life
- Temperature Control

Among all the CRs, the price is used as the budget constraint, with the assumption that the customer always likes to spend all the budget for the best possible product configuration. A house of quality (HOQ) is generated to summarize the strength of relationships between the rest of CRs and ECs as shown in Table 21.

Table 21 - HOQ

<div> <div>CR</div> <div>EC</div> </div>		CPU	GPU	RAM	HDD	SSD	Display	Speaker	Battery	Fan	Housing
		A	B	C	D	E	F	G	H	J	K
Business Performance	1	9	2	1	2	5					
Multimedia Performance	2	5	9	1	3	3					
Computation Performance	3	8	4	1	3	5					
Storage	4				8	1					
Display	5						9				
Audio	6							9			
Battery Life	7								9		
Temperature Control	8									9

A CR is denoted by CR_i , where $i \in \{1, 2, 3, \dots\}$, e.g. CR_1 refers to business performance and CR_2 refers to multimedia performance. The strength of relationship is denoted by $R_{i,j}$, representing the strength of relationship between CR_i and EC_j , e.g. $R_{3,B} = 4$ and $R_{4,E} = 1$.

For business performance, multimedia performance and computation performance, the strength of relationship is estimated based on a set of formulae suggested by UserBenchmark as shown in Table 22.

Table 22 - Suggested Evaluation Criteria

CR	Evaluation
Business Performance	50% CPU + 10% GPU + 10% HDD + 30% SSD
Multimedia Performance	25% CPU + 50% GPU + 10% HDD + 15% SSD
Computation Performance	40% CPU + 20% GPU + 15% HDD + 25% SSD

The formulae in Table 22 does not include RAM. It is because most of RAM parts in the market is sufficient to support the laptop activities. Upgrade of RAM has only a minor increase in the overall performance. Therefore, $R_{1,C}$, $R_{1,C}$ and $R_{1,C}$ are all set to 1 in the HOQ.

Furthermore, as the maximum capacity of HDD that Company A can provide is 8 TB whereas that of SDD is 1 TB. Therefore, $R_{4,D}$ is 8 times of $R_{4,E}$.

The HOQ shows that primary functional ECs (CPU, GPU, RAM, HDD and SSD) are highly associated with business performance, multimedia performance, computation performance and storage. These CRs are considered as critical factors for the customers to evaluate the laptop configuration. Therefore, in the 1st phase, Company A expects the product configurator to maximize the customer satisfaction by fulfilling these critical CRs. Other CRs are excluded at this stage.

Furthermore, the normalized strength of relationship, denoted by $R'_{i,j}$, is calculated by Eq. (3.3):

$$R'_{i,j} = \frac{R_{i,j}}{\sum_j R_{i,j}} \quad (3.3)$$

(The fraction of the sum of the row in HOQ)

The normalized HOQ is generated, with critical CRs and primary functional ECs, as shown in Table 23.

Table 23 - Normalized HOQ

<div style="display: flex; align-items: center; justify-content: center;"> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">CR</div> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">EC</div> </div>		CPU	GPU	RAM	HDD	SSD
		A	B	C	D	E
Business Performance	1	0.47	0.11	0.05	0.11	0.26
Multimedia Performance	2	0.24	0.43	0.05	0.14	0.14
Computation Performance	3	0.38	0.19	0.05	0.14	0.24
Storage	4				0.89	0.11

An example of calculation is provided below:

$$R'_{1,A} = \frac{R_{1,A}}{\sum_j R_{1,j}} = \frac{9}{9 + 2 + 1 + 2 + 5} = \frac{9}{19} = 0.47$$

Eq. (3.4) must always hold:

$$\sum_j R'_{i,j} = 1 \quad \forall i \quad (3.4)$$

(The sum of each row is equal to 1)

The next step is to integrate the score breakdown into the HOQ. Since GPU and RAM are evaluated with a general score, their normalized strength of relationship remains unchanged.

For CPU, the contribution towards each CR can be broken down as shown in Table 24.

Table 24 - Fractional Contribution of EC_A

CR	EC_A		
	Score 1 (Single-Core Integer Speed)	Score 2 (Quad-Core Integer Speed)	Score 3 (Multi-Core Integer Speed)
Business Performance	0.8	0.1	0.1
Multimedia Performance	0.3	0.6	0.1
Computation Performance	0.1	0.1	0.8
Storage	-	-	-

For HDD and SSD, the contribution towards each CR can be broken down as shown in Table 25. The capacity has no contribution to the performance and the sequential read speed has no contribution to the storage.

Table 25 - Fractional Contribution of EC_D and EC_E

CR	EC_D		EC_E	
	Score 1 (Capacity)	Score 2 (Sequential Read Speed)	Score 1 (Capacity)	Score 2 (Sequential Read Speed)
Business Performance	0	1	0	1
Multimedia Performance	0	1	0	1
Computation Performance	0	1	0	1
Storage	1	0	1	0

The fractional contribution of score m of EC_j for CR_i is denoted by $FC_{i,j,m}$. Eq. (3.5)

must always hold:

$$\sum_m FC_{i,j,m} = 1 \quad \forall i, j \quad \text{for } R'_{i,j} \geq 0 \quad (3.5)$$

(The sum of fraction contribution of any EC towards each CR is 1.)

The normalized strength of relationship, $R'_{i,j}$ is then modified to $R''_{i,j,m}$, which represents the contribution of score k of EC_j towards the CR_i . $R''_{i,j,m}$ can be calculated by Eq. (3.6):

$$R'_{i,k,m} = FC_{i,j,m} * R'_{i,j} \quad (3.6)$$

Eq. (4.1) should always hold for countercheck:

$$\sum_m R''_{i,j,m} = R'_{i,j} \quad \forall i, j \quad (4.1)$$

The HOQ is revised as shown in Table 26.

Table 26 - Modified Normalized HOQ

<div style="display: flex; align-items: center; justify-content: center;"> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">CR</div> <div style="writing-mode: vertical-rl; transform: rotate(180deg);">EC</div> </div>		CPU			GPU	RAM	HDD		SSD	
		A1	A2	A3	B	C	D1	D2	E1	E2
Business Performance	CR ₁	0.379	0.047	0.047	0.11	0.05		0.11		0.26
Multimedia Performance	CR ₂	0.071	0.143	0.024	0.43	0.05		0.14		0.14
Computation Performance	CR ₃	0.038	0.038	0.305	0.19	0.05		0.14		0.24
Storage	CR ₄						0.89		0.11	

Some examples of calculation are provided below:

$$R''_{1,A,1} = FC_{1,A,1} * R'_{1,A} = 0.8 * 0.47 = 0.379$$

$$R''_{2,A,2} = FC_{2,A,2} * R'_{2,A} = 0.6 * 0.24 = 0.143$$

$$R''_{3,A,3} = FC_{3,A,3} * R'_{3,A} = 0.8 * 0.38 = 0.305$$

$$R''_{4,D,1} = FC_{4,D,1} * R'_{4,D} = 1 * 0.89 = 0.89$$

$$R''_{2,E,1} = FC_{2,E,1} * R'_{1,E} = 0 * 0.14 = 0$$

4.3.2 Application of the Kano's Model on Customer Requirements

A Kano questionnaire is developed to investigate the Kano categorization, the coefficient of satisfaction and dissatisfaction for the four critical CRs. For each CR, a pair of question is asked, one in functional form and another in dysfunctional form. The questionnaire concerns customers' responses about two extreme cases, nearly 0% and 100% fulfilment of each CR. For instance, the pair of questions regarding business performance in the Kano questionnaire is shown in Table 27. The full questionnaire could be found in Appendix A.

Table 27 - Kano Survey Question (Example)

If the laptop is very good at basic office work and surfing, how do you feel?	☐ I like it that way.
	☐ It must be that way.
	☐ I am neutral.
	☐ I can live with it that way.
	☐ I dislike it that way.
If the laptop is very bad at basic office work and surfing, how do you feel?	☐ I like it that way.
	☐ It must be that way.
	☐ I am neutral.
	☐ I can live with it that way.
	☐ I dislike it that way.

In order to formulate the customer satisfaction (CS) as an expression of the fulfilment level of each CR, DT Company conducted the survey among the target users of Company A's products. The survey received 120 responses. Referring to Table 13, the responses are summarized and translated to Kano classification as shown in Table 28. For instance, 61 respondents perceive business performance as a must-be attribute. Therefore, the Kano classification of business performance is 'M' for must-be.

Table 28 - Kano Survey Result

CR	O	A	M	I	R	Q	Total	KC	CS	DS
Business Performance	13	20	61	26	0	0	120	M	0.275	-0.675
Multimedia Performance	44	25	12	29	0	0	120	O	0.658	-0.467
Computation Performance	27	41	14	38	0	0	120	A	0.567	-0.342
Storage	31	25	35	28	0	1	120	M	0.47	-0.555
O: One-dimensional			A: Attractive			M: Must-be				

According to the result, customer satisfaction is formulated by the equations corresponding to the Kano classification for each customer requirement as shown in Table 29.

Table 29 - Formulation of CRs

CR	KC	a	b	$f(x)$	$S = af(x) + b$
Business Performance	M	1.503	0.828	$-e^x$	$S = -1.503e^x + 0.828$
Multimedia Performance	O	1.125	-0.467	x	$S = 1.125x - 0.467$
Computation Performance	A	0.529	-0.87	e^x	$S = 0.529e^x - 0.87$
Storage	M	1.622	1.067	$-e^x$	$S = -1.622e^x + 1.067$

Based on Table 29, the customer satisfaction curves can be plotted as shown in Figure 16. The x-axis is the fulfilment level of the CR and the y-axis is the corresponding satisfaction level.

Figure 16 - CS-F Relationship Functions

4.4 Optimization Modelling

The definition of ECs is built based on Company A's capabilities. CRs and CS-F relationship functions are built based on the market research and survey. They support the backend operation of the product configuration system. Once they are ready, the system would be ready to take customer input to recommend the optimal solution.

Company B approaches Company A to order 100 units of laptops for their customers. The expected budget is around \$1000 per unit, out of which, \$750 is allocated to the primary functional ECs (CPU, GPU, RAM, HDD and SSD). The importance weight for each CR is given as shown in Table 30.

Table 30 - Customer Profile

Target User	Office Clerks, White-Collars
Total Budget Allocated	750

Customer Requirement	Importance Weight
Business Performance	0.5
Multimedia Performance	0.15
Computation Performance	0.25
Storage	0.1

Based on the profile of the target user, the optimization model can be formulated below.

Decision Variables:

$$X_{jk} = \begin{cases} 1 & \text{if Part } jk \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

Objective Function:

$$\max \quad S$$

Constraints:

< Total price must be no more than \$750. >

$$53 X_{A1} + 89 X_{A2} + 166 X_{A3} + \dots + 216 X_{E4} + 603 X_{E5} \leq 750$$

< Exactly one part must be chosen from each group. >

$$X_{A1} + X_{A2} + X_{A3} + X_{A4} + X_{A5} + X_{A6} = 1$$

$$X_{B1} + X_{B2} + X_{B3} + X_{B4} + X_{B5} = 1$$

$$X_{C1} + X_{C2} + X_{C3} + X_{C4} = 1$$

$$X_{D1} + X_{D2} + X_{D3} + X_{D4} + X_{D5} + X_{D6} = 1$$

$$X_{E1} + X_{E2} + X_{E3} + X_{E4} + X_{E5} = 1$$

< Calculation of overall normalized score m of EC_j , $S'_{j,m}$ >

$$0.521 X_{A1,1} + 0.680 X_{A2,1} + 0.781 X_{A3,1} + 0.756 X_{A4,1} + X_{A5,1} + X_{A6,1} = S'_{A,1}$$

$$0.243 X_{A1,2} + 0.463 X_{A2,2} + 0.521 X_{A3,2} + 0.756 X_{A4,2} + 0.89 X_{A5,2} + X_{A6,2} = S'_{A,2}$$

$$0.118 X_{A1,3} + 0.225 X_{A2,3} + 0.255 X_{A3,3} + 0.368 X_{A4,3} + 0.659 X_{A5,3} + X_{A6,3} = S'_{A,3}$$

$$0.126 X_{B1} + 0.286 X_{B2} + 0.563 X_{B3} + 0.784 X_{B4} + X_{B5} = S'_{B,1}$$

$$0.185 X_{C1} + 0.244 X_{C2} + 0.854 X_{C3} + X_{C4} = S'_{C,1}$$

$$0.063 X_{D2} + 0.125 X_{D3} + 0.25 X_{D4} + 0.5 X_{D5} + X_{D6} = S'_{D,1}$$

$$0.937 X_{D2} + 0.971 X_{D3} + X_{D4} + 0.874 X_{D5} + 0.73 X_{D6} = S'_{D,2}$$

$$0.125 X_{E2} + 0.25 X_{E3} + 0.5 X_{E4} + X_{E5} = S'_{E,1}$$

$$0.998 X_{E2} + 0.996 X_{E3} + 0.994 X_{E4} + X_{E5} = S'_{E,2}$$

< Calculation of fulfilment level of CR_i , F_i >

$$0.379 S'_{A,1} + 0.047 S'_{A,2} + 0.047 S'_{A,3} + 0.11 S'_{B,1} + 0.05 S'_{C,1} + 0.11 S'_{D,2} + 0.26 S'_{E,2} = F_1$$

$$0.071 S'_{A,1} + 0.143 S'_{A,2} + 0.024 S'_{A,3} + 0.43 S'_{B,1} + 0.05 S'_{C,1} + 0.14 S'_{D,2} + 0.14 S'_{E,2} = F_2$$

$$0.038 S'_{A,1} + 0.038 S'_{A,2} + 0.305 S'_{A,3} + 0.19 S'_{B,1} + 0.05 S'_{C,1} + 0.14 S'_{D,2} + 0.24 S'_{E,2} = F_3$$

$$0.89 S_D + 0.11 S_E = F_4$$

< Calculation of customer satisfaction level of CR_i , CS_i >

$$-1.503 e^{-F_1} + 0.828 = CS_1$$

$$1.125 F_2 - 0.467 = CS_2$$

$$0.529 e^{-F_3} - 0.87 = CS_3$$

$$-1.622 e^{-F_4} + 1.067 = CS_4$$

< Calculation of overall customer satisfaction level, S >

$$0.55 CS_1 + 0.15 CS_2 + 0.2 CS_3 + 0.1 CS_4 = S$$

< Incompatibility Constraint(s) >

$$X_{D1} + X_{E1} \leq 1$$

4.5 Recommended Configuration

After solving the optimization model by GRG Nonlinear Algorithm, the optimal product configuration is obtained as shown in Table 31, with the fulfilment level and customer satisfaction level as shown in Table 32.

Table 31 - Recommended Configuration

EC	Selection	m	Normalized Score $m, S'_{j,m}$	Price (\$)
CPU	A3	1	0.781	166
		2	0.521	
		3	0.254	
GPU	B2	1	0.286	223
RAM	C3	1	0.854	148
HDD	D4	1	0.25	86
		2	1	
SSD	E3	1	0.25	127
		2	0.996	
			Total	750

Table 32 - Optimal F and CS

CR	Fulfilment Level, F_i	Customer Satisfaction	Importance Weight
Business Performance	0.775	0.13561	0.5
Multimedia Performance	0.585	0.19121	0.15
Computation Performance	0.602	0.09524	0.25
Storage	0.25	-0.19587	0.1
Overall Customer Satisfaction			0.10072

With a budget of \$750, the system recommends a configuration that costs \$750, providing an overall customer satisfaction of 0.10072. The rank of fulfilment level is the same as the rank of importance weight. It suggests that the optimization model is at least reasonable to a certain extent.

The summarized product parameters are listed as shown in Table 33.

Table 33 - Recommended Technical Parameters

EC	Selection	Technical Parameter		
CPU	A3	Single-Core Integer Speed (pts)	Quad-Core Integer Speed (pts)	Multi-Core Integer Speed (pts)
		114	300	308
GPU	B2	CLim (MHz)	MLim (MHz)	
		1290	1392	
RAM	C3	Capacity (GB)		
		2x4		
HDD	D4	Capacity (TB)	Sequential Read Speed (MB/s)	
		2	174	
SSD	E3	Capacity (GB)	Sequential Read Speed (MB/s)	
		250	497	

4.6 Sensitivity Analysis

The sensitivity analysis presents the nearest downgraded configuration and the nearest upgraded configuration as shown in Table 34.

Table 34 - The Sensitivity Analysis

EC	Selection	The Nearest Downgraded Configuration	The Nearest Upgraded Configuration
CPU	A3	A3	A5[#]
GPU	B2	B2	<i>B1[*]</i>
RAM	C3	C3	<i>C1[*]</i>
HDD	D4	D4	<i>D2[*]</i>
SSD	E3	<i>E2[*]</i>	<i>E2[*]</i>
CS	0.10072	<i>0.09930[*]</i>	0.10981[#]
Total Price	750	<i>730[*]</i>	759[#]

Italic^{}*: Decrease from the recommended configuration

Bold[#]: Increase from the recommended configuration

The nearest downgraded configuration makes an effect on SSD. It shows that SSD is the least value-added EC for the current configuration. Therefore, it should be the

first one to be dropped if Company B wants to cut down the budget. It tallies with the fact that storage has the smallest weight in the overall customer satisfaction.

The nearest upgraded configuration makes effect on CPU by downgrading all other ECs. It shows that CPU is the most value-added EC for the current configuration. Therefore, it should be the first one to be enhanced if Company B is willing to provide more budget. It tallies with the fact that business performance, which greatly relies on CPU, has the highest weight in the overall customer satisfaction.

After review, Company B decided to order the recommended optimal configuration.

4.7 Further Discussion

The relationship between the maximum overall customer satisfaction and the total budget allocated is analysed as shown in Figure 17.

Figure 17 - Overall Satisfaction against Budget

The x-axis is the total budget allocated, from \$300 to \$2400 with an interval of \$100, and the y-axis is the maximum overall customer satisfaction level. Based on

Company A's selection pool, the minimum possible price is \$294, and the maximum possible price is \$2,387. Therefore, when the budget is less than \$294, this optimization model has no solution. Once the budget is \$2,387, further increase of budget will not increase the overall customer satisfaction level anymore. As expected, the overall customer satisfaction level is a non-decreasing function. Yet, it increases slower and slower, and eventually becomes constant once all ECs are optimal.

The selection of part for each EC is also plotted against the total budget allocated as shown in Figure 18.

Figure 18 - Selection of Parts against Budget

The x-axis is the total budget allocated, from \$300 to \$2400 with an interval of \$100, and the y-axis is the selected part ID. Generally, the parts in each EC are ranked from worst to best, with minor exceptions when an EC has multiple scores. According to the graph, it can be observed that only CPU is non-decreasing. The observation tallies with the condition where business performance is the most important CR and in which CPU is the biggest contributor.

Except for CPU, all other ECs have dropped at few budget conditions. It implies that there is something else worthier, but too expensive to buy, before the dropping. Therefore, when the budget is sufficient, the EC will be downgraded to save the cost of upgrading another EC. In another word, downgrading an EC must occur together with upgrading another EC. Otherwise, downgrading will only result in lower overall customer satisfaction level, which must not be the optimal solution for the budget condition.

In addition, it can be observed that Part C2 (RAM) has never been chosen in any budget condition. It is because Part C2 has a low score per unit price. Referring to Table 35, the normalized score of Part C2 is 0.06 higher than Part C1, with a price of

\$47 higher. However, the normalized score of Part C3 is 0.61 higher than Part C2, with a price of \$24 higher. It is almost 20 times worthier to upgrade RAM to Part C3, than to Part C2. Therefore, if upgrading RAM to Part C2 is the optimal move in the budget condition, compared to the last one, then it will be probably upgraded to Part C3 immediately, unless the budget is capped.

Table 35 - Normalized EC_C

EC_C			
Part ID	Score	Normalized Score	Price (S\$)
C1	38.3	0.185	77
C2	41.7	0.244	124
C3	76.4	0.854	148
C4	84.7	1	265

Lastly, in Figure 18, it can be seen that CPU is the first EC which reaches optimal state, followed by GPU, HDD, RAM and lastly SSD. It is a reasonable sequence of optimization for office clerks and white-collars.

4.8 Product Configuration System Design

In the first phase of the case study, DT Company defined ECs with the technical experts from Company A. The ECs included CPU, GPU, RAM, HDD and SSD. The secondary functional ECs and non-functional ECs would be taken into consideration in the future.

In the second phase, DT Company also identified CRs with the marketing experts from Company A. The critical CRs, associated with primary functional ECs, included business performance, multimedia performance, computation performance and

storage. Particularly, CPU, HDD and SSD had different metrics to evaluate its contribution towards CRs. Their contribution was broken down into smaller elements in the HOQ. Then DT Company conducted a market research to analyse and formulate CS for each CR as an expression of the fulfilment level. At this point, the backend process had been completed.

In the third phase, DT Company used a customer profile given by Company B to test the product configuration system. The customer profile included expected budget, importance weight of each CR and special requests. It generated an optimal configuration within the budget.

In the fourth phase, Company B reviewed the sensitivity analysis. The analysis provided the nearest downgraded configuration and the nearest upgraded configuration for Company B to consider. After the review, Company B decided to order the recommended optimal. Finally, the order would be sent to Company A for manufacturing.

Throughout this process, the product configuration system plays a vital role to bridge the communication gap between Company A and B and speed up the customization process, earning a competitive edge for both parties in Industry 4.0.

The 'to-be' process model is developed and shown in Figure 19.

Figure 19 - 'to-be' model of order acquisition process

Chapter 5 Conclusion

5.1 Summary

In Industry 4.0, personal customization is getting more popular and demanded. One of the basic concerns in the traditional customization process is that the customer's direct access to the selection of parts could lead to inefficiency, causing the configuration process to be incomplete or incorrect, especially if the product variety is great. The objective of this dissertation is to develop an approach to automate this configuration process by taking the voice of customers as an input.

This research proposes an optimization framework which can be applied in various 'configure-to-order' contexts. Phase 1, Evaluation of Enterprise Capabilities, takes input from technical experts to define ECs, their selection pool, and the scores of parts. Phase 2, Investigation of market demand, takes input from marketing experts to define CRs, and a marking investigation to formulate CS as an expression of the fulfilment level of CR. Phase 3, Formulation and Optimization, takes the customer input as well as the output from Phase 1 and 2, to optimize and recommend the optimal solutions. Phase 4, Review, provides more minor variation based on the output from Phase 3 for the service demanders as well as providers to review.

The case study demonstrates a series of procedures to apply the optimization framework for laptop configuration. In addition, sensitivity analysis helps the customers to understand the possible minor variation based on the recommended configuration. Further discussion is made to elaborate on the effectiveness of the

framework. It shows that the result is closely and reasonably related to the customer input.

5.2 Contribution

In summary, there are three main areas which the dissertation could contribute to:

- 1) It fits a product configuration system in the context of Industry 4.0, with a sophisticated mechanism to perform the optimization of customer satisfaction in a feasible and reasonable range in a short period of time, empowering the service providers to make a quick response to dynamic customer requirements;
- 2) It studies a product configuration system with the integration of QFD, the Kano's model and mathematical programming; QFD is modified to suit a more complex relationship between CRs and ECs
- 3) It elaborates how the product configuration system could be adopted in the order acquisition and fulfilment process for SME in the context of laptop configuration. It could be adopted for other modular and personalized products, e.g. automotive, digital cameras.

For academic contribution, one of the breakthroughs in this dissertation is the modification of QFD approach. In traditional QFD approach, only the strength of relationship between CRs and ECs is considered and defined. However, an EC could be broken down into smaller elements, whose weight could vary in different CRs. In this dissertation, the strength of relationship is between CRs and ECs is first defined and normalized, then substituted by the smaller elements. It reflects the role of EC in each CR better than before. In this way, the optimization model is robust to evaluate

more than one feature for each EC and solve a more practical problem. In the case study, if the algorithm only considered the storage capacity for HDD and SSD, HDD will be almost strictly preferable over SSD due to the large size and SSD will be considered only when there is no room to improve the storage capacity in HDD, i.e. the choice of HDD is optimal. Yet, the proposed configuration consists of SSD while the choice of HDD is not optimal, because SSD surpasses HDD by its read speed instead of the storage capacity.

For empirical contribution, there are many researches on quantitative analysis like the Kano's model or QFD approach that can be applied by companies. However, they are not widely applied in the context of a flexible manufacturing system. This dissertation integrates mathematical approaches into the traditional design process, presenting a customization framework in a bigger scale, from the product database definition, to customer satisfaction quantification, to optimization modelling and sensitivity analysis.

5.3 Limitations

In this dissertation, the Kano's model is not modified. However, there are few areas that the Kano's model shows ineffectiveness.

Firstly, the Kano questionnaire is used in the proposed method to classify the CRs (Kano et al. 1984). For a certain CR, if the proportion of 'O', 'A', 'M' and 'I' is 20%, 20%, 20% and 40%, 'I' will be the most frequently appeared category and this CR will be classified as 'indifferent'. Apparently, more than half of the population

concerns about the CR. Classifying this CR as ‘indifferent’ is not reasonable. On the other hand, the CS-F relationship function, which was named S-CR relationship function proposed by Ji et al. (2010), is used in the proposed method to quantify the customer satisfaction as an expression of the fulfilment level of ECs. However, the selection of CS-F relationship function is solely based on the most frequently appeared category. It does consider enough when there is exactly or nearly a tie between two categories. Overall, the Kano’s model can be better defined to quantify the customer satisfaction.

Secondly, in the case study, storage is considered as a ‘must-be’ CR. By definition, the satisfaction level of a ‘must-be’ CR should reach a plateau at a certain fulfilment level. Yet, the CR-F relationship function does not exhibit obvious demolishing gradient even at nearly 100% of fulfilment based on the expression, $y = -ae^{-x} + b$ with $x \in [0,1]$. It implies that there is a considerable amount of improvement on customer satisfaction for the capacity of HDD increased from 4 TB to 8 TB. In the market nowadays, there are rarely laptops with storage more than 2 TB. Apparently, 4 TB is more than enough for an individual non-professional user. Increasing to 8 TB should not boost too much satisfaction level.

Another limitation of this optimization framework is that the weight of each CR is not robust enough to represent the actual customer psychology. In some cases, the weights can lead to an extreme configuration. Related to the previous limitation, if the weight of storage is a bit higher, it is very easy for the product configuration

system to upgrade HDD as a priority, especially given that HDD is much cheaper than other ECs. In reality, there is no need to have that much capacity.

However, some limitations mentioned above could be addressed case by case. In the case study, only HDD exhibits the limitations. Yet, unlike CPU and GPU, by looking at the numbers, customers may not be able to tell whether the single-core integer speed is fast or slow, but they do understand the capacity of HDD and know the amount of capacity they need. This EC can be directly set by the customers, instead of being optimized by the product configuration system.

5.4 Future Work

In this dissertation, all ECs are discrete. In the future, continuous ECs can be included and analysed. The complexity of the optimization model could be further increased to address the potential problems in the real world. For instance, in the optimization framework, incompatibility constraint between two parts is introduced. However, things can be much more complicated in reality. There could be conditional incompatibility, e.g. a part is incompatible with a combination of other parts. It requires more sophisticated formulation to construct the optimization model. Naturally, if the model is more complex, the user will need to do more preparation work, which could make the system more user-unfriendly. More research and study can be done to find the balance in this trade-off.

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Appendix A

Customer Survey on Personal Laptop

Part 1: Basic information

1. What is your gender?

- ☐ Male
- ☐ Female

2. What is your age?

- ☐ 16 and below
- ☐ 16-25
- ☐ 26-35
- ☐ 36-45
- ☐ 46 and above

3. What is your major usage of laptop?

- ☐ Basic Office Work (MS Word, MS PPT, Email)
- ☐ Design Work (2D/3D Design, Animation, Rendering)
- ☐ Gaming
- ☐ Professional (Computation, Programming)
- ☐ Others

Part 2: Kano questionnaire

The objective of following questions is to test your satisfaction level when presence or absence of the described attributes when you are choosing a ‘personal

laptop'. All questions have the same set of options with explanations provided below. Please understand them before proceeding to the questions.

For Basic Office Performance

Basic office work and website surfing (e.g. MS Word, MS PPT, email, web browsing, video playback)

1-1 If the laptop is **very good** at basic office work and surfing, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

1-2 If the laptop is **very bad** at basic office work and surfing, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

For Multimedia Performance

Graphic processing (e.g. gaming, rendering, 2D/3D design, video editing).

2-1 If the laptop is **very good** at graphic processing, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.

- I am neutral.
- I can live with it that way.
- I dislike it that way.

2-2 If the laptop is **very bad** at basic office work and surfing, how do you feel?

- I like it that way.
- It must be that way.
- I am neutral.
- I can live with it that way.
- I dislike it that way.

For Computation Performance

Computation (e.g. programming, database, algorithm, data analysis)

3-1 If the laptop is **very good** at computation, how do you feel?

- I like it that way.
- It must be that way.
- I am neutral.
- I can live with it that way.
- I dislike it that way.

3-2 If the laptop is **very bad** at computation, how do you feel?

- I like it that way.
- It must be that way.
- I am neutral.
- I can live with it that way.
- I dislike it that way.

For Storage

4-1 If the laptop has **very large** storage (> 4TB), how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

4-2 If the laptop has **very small** storage (< 128GB), how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

For Display Screen

5-1 If the laptop has a **very good** at display screen, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

5-2 If the laptop has a **very bad** at display screen, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.

- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

For Audio System

6-1 If the laptop has a **very good** at audio system, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

6-2 If the laptop has a **very bad** at audio system, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

For Battery Life

7-1 If the laptop has **very long** battery life (> 8 hrs), how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.

- ☐ I dislike it that way.

7-2 If the laptop has **very short** battery life (< 1 hrs), how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

For Cooling System

8-1 If the laptop has **very good** cooling system, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.

8-2 If the laptop has **very bad** cooling system, how do you feel?

- ☐ I like it that way.
- ☐ It must be that way.
- ☐ I am neutral.
- ☐ I can live with it that way.
- ☐ I dislike it that way.