Design of A Therapeutic Light Device Using Kano's Model and A Decision-making Method Based on HOQ

by

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Abstract

In this research, a therapeutic light device is developed based on customer requirements. The quality function deployment (QFD) is initially used to transfer customer requirements to design parameters. However, several inherent shortcomings of QFD method are identified based on the design evaluation and the customer feedback of the initially proposed model. In the process of improving the initial model, the correlation information is used in ranking technical measurement and components. A decision-making method is proposed to generate an optimal model for the selection of appropriate components. Kano's model is applied to enhance the customer's requirement of "good looking". The result shows that the improved model satisfies the customer with good overall performance.

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Dedicated to my loving parents and lover

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List of Abbreviations

QFD	Quality Function Deployment
HOQ	House of Quality
CFD	Concurrent Function Deployment
HOV	House of Value
CA	Conjoint analysis
KE	Kansei Engineering
CR	Customer Requirements
TQM	Total Quality Management
OPP	Overall product performance
GS	Greedy Search
GA	Genetic Algorithm
SA	Simulated Annealing

Chapter 1

Introduction

1.1 Problem overview

Sunnex Biotechnologies is a Winnipeg-based company involved in manufacturing and marketing of products to regulate human circadian rhythms for the past 16 years. Its low intensity light technology used in Lo-LIGHT lamps avoids the user discomfort and potential risk of retinal damage inherent in high intensity bright light and blue-light therapy lamps. The Lo-LIGHT technology can alleviate seasonal affective disorder and treat sleep disorders. Harvard has used Lo-LIGHT lamps in studies for NASA's Advanced Capabilities Division to improve the alertness and performance of night shift workers on earth, as well as to regulate the circadian rhythms of astronauts on extended missions [1].

Fig.1- 1 Green LIGHT system for counteracting night work fatigue

The limitation of current Lo-LIGHT lamps is their large size as shown in Fig.1- 1. It is necessary to have a small and portable lamp. It can be adapted into many work environments in which high intensity lamps are not practical. The lamp can incorporate an alternate light source that emits the required intensity of a narrow range of wavelengths within the spectral range specified by the patented light technology utilized in Lo-LIGHT lamps. The lamp can be used in a variety of work and home environments.

1.2 Objectives

The objective of this research is to design a therapeutic light device to meet customer's requirements with portable and flexible features. Dimension and mass are used to measure portability by comparing with other similar portable products; a foldable structure is required to satisfy flexibility in order to adapt to various work environments. An attractive appearance is desired in terms of "good looking" in order to increase the chance of success in the market. An effective product development is required to meet these needs. This research will focus on the conceptual design to decide the product generic characteristic and product flexibility in the adaption and expansion of existing design methods.

1.3 Methods

This research presents a customer-oriented development method for a therapeutic light device from the conceptual design to details design. Quality function deployment (QFD) is used based on the review of conceptual design methods. QFD can efficiently transform customer requirements to appropriate technical requirements [2]. QFD is implemented through house of quality (HOQ) to support each phase of QFD [3]. In some cases, HOQ needs to be reformed and extended to fit a specific design situation.

The initial model proposed in this research appears several drawbacks and disadvantages according to evaluations and the customer feedback. In order to enhance the QFD method for the product improvement, a supportive decision-making method is proposed considering overall design requirements to generate a better product concept. Kano's model is used for identifying customers' preference in shapes, colors and forms of the product to satisfy the customer requirement of "good looking".

1.4 Thesis outline

In Chapter 2, two product development methods, QFD and CFD, are reviewed and compared. The concept generation methods are discussed. In order to improve appearance of a design, we review three methods: conjoint analysis, Kansei engineering and Kano's model.

In Chapter 3, a conceptual design process is presented using HOQ for designing a therapeutic light device. Difficulties and disadvantages of the HOQ method are discussed. Several areas of potential improvement are identified based on the evaluation and customer feedback of the proposed model.

In Chapter 4, two improvement methods are applied to enhance the product design: a supportive decision-making method is proposed to generate an optimal product concept; Kano's model is applied to further improve the perceived quality of the model.

In Chapter 5, the conclusion is presented and future work is discussed.

Chapter 2

Literature review

2.1 Conceptual design methods

Conceptual design can be decomposed into three activities: requirement analysis, product concept generation, and concept selection [4]. For the requirement analysis, the two dominant methods quality function employment (QFD) and concurrent function employment (CFD) can be used [5, 6]. For concept selection activities, Pugh's concept selection and AHP method are commonly used [7, 8]. However, there are no dominant methods used for the concept generation [9].

2.1.1 QFD method

Quality function deployment (QFD) is "an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production" [2]. QFD method, in products planning and developing processes, enables designers to identify customer's needs to make a proposed design evaluated for meeting those needs. QFD is originally from Japan developed in the late 1960s. In the 1980s, QFD had been spread to the US and later to various industries in many countries.

There are two main QFD models. The first one is a four-phase model [10], also known as the ASI (American Supplier Institute) model. The second one is Akao's Matrix Model. The Four-Phase Model is a blueprint for product development with basic stages, while the Matrix Model is also proposed for Total Quality Management (TQM) including a lot of activities such as reliability, cost analysis, value engineering, planning, and manufacturing quality control that are implicit or optional in the Four-Phase Model. These two models are different more in terms of style rather than content. The simpler Four-Phase Model is more widely applied and used. A general idea of Four-Phase Model is shown in Fig.2- 1.

This model divides a product development process into four steps using four matrices. Customer requirements for a product are collected in the first phase, which is called WHATs. Those needs are transformed into technical measurements, called HOWs. This step is the fundamental of whole processes and the matrix is called House of Quality (HOQ). HOQ links customer requirements to technical characteristics to meet customers' requirements, which is also named Product Planning or Customer Requirement Planning. In the second step, prioritized technical measures are transformed into part characteristics, named Part Deployment. Main part characteristics are transformed into process parameters in the third phase, named Process Planning. The forth step is to transform process parameters into the final product.

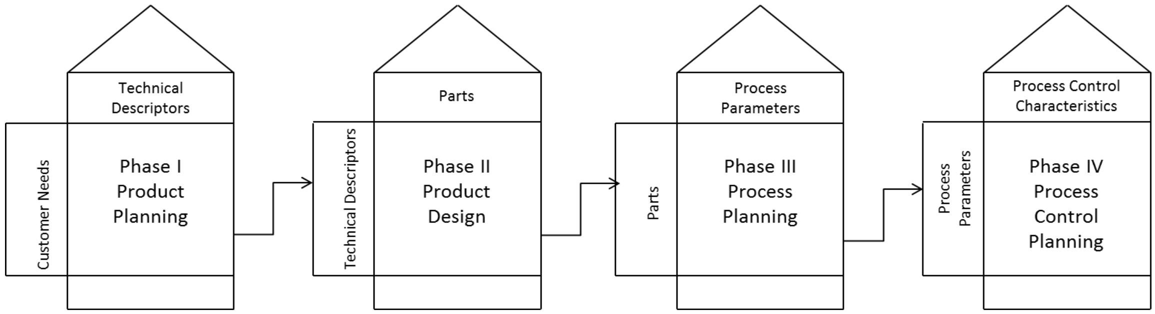


Fig.2- 1 Four-Phase Model of QFD [10]

Although whole QFD processes contain four phases, most organizations just use the phase I of QFD for developing their customized HOQ. There is a lack of details in literature to explain how to design following QFD phases. HOQ is a fundamental and strategic factor in QFD process, because customer requirements for the product are identified and transformed into technical measures for the voice of customers to designers.

2.1.2 QFD VS. CFD

Concurrent function deployment (CFD) is a methodology that allows designers and manufacturing engineers to communicate early working in parallel during various stages of a product development process [11]. The main tool to facilitate this early communication is “House of values” (HOV), which is a similar concept of HOQ. However, HOV is an extent of HOQ since the term “value” does not only mean “quality”. It ranges from quality characteristics to other characteristics, such as X-ability, tools and technology, cost, etc. The comparison of QFD and CFD is listed in Table 2- 1.

Table 2- 1 Comparison of CFD and QFD

QFD	CFD
A phase-based process	Concurrent process
Work with pieces of product	Work with the whole product
Focus on design activities	Work in conjunction with company mission deployment principles
A problem-solving process	Handle all life cycle values of the product
QFD deals with pieces of product or pieces of requirements	CFD optimizes the system with consistency of purpose as target goals

2.1.3 Method selection of CFD and QFD

From Table 2-1, it can be seen that CFD is a systematic design strategy which is more suitable for the cooperative design among various divisions of a big work group. CFD is more suitable for improving an existing design since it requires massive precise and quantitative design information. Considering the whole product life value in CFD process is difficult due to limited design information at the early stage of product development, particularly for the new product development.

On the other hand, the motivation of QFD is designing a product that embeds customer requirements. QFD allows locating those aspects of a product that could contribute most to the quality perceived by customers. QFD divides a product development process into four phases, which gives an advantage of great flexibility for users according to a specific design situation. Development teams are able to select one or more QFD phases combined with other methods according to their design characteristics. QFD is simple and intuitive. As a useful tool to support the QFD method, HOQ can be easily adapted to a specific design requirement. Therefore, in this research, the QFD method is used to develop a therapeutic lighting device.

2.2 Concept generation

Concepts generation is an innovative process [12, 13]. It involves activities in deciding values of the engineering characteristics, deciding resources allocation, and optimizing quality under constraints [14]. QFD does not provide means for concept generation. The users are expected to use their judgement and QFD data to decide design parameters. A tool for the concept generation is the morphological analysis which addresses each requirement through several alternative functional solutions [15]. Designers need to decide a best combination of alternative solutions for each requirement to generate a best product concept. Wei proposed a product concept generation method based on QFD and rough set theory [16]. Experts' initial evaluation information is characterized by rough numbers in the form of intervals, which are capable of accommodating uncertainties and vagueness. Yang suggested that a good way of improving the concept quality is through increasing their quantity [17]. He examined concept generations via brainstorming, morphology charts and sketching. Then, statistically significant correlations can be found between the quantity of brainstormed ideas and design outcome. Cheng et al proposed a one-step QFD method based on 3D morphological charts for generating variant product concepts [18]. Customer's requirements are incorporated in developing morphological charts through a holistic approach, namely one-step QFD. The charts driven by the deployment results produce design concepts of high feasibility through query by function, specification, and module of product. In order to facilitate cooperation of a design team, Sonalkar et al developed a visual representation to characterize moment-to-moment concept generation [19]. The research presented the development of a visual notation called Interaction Dynamics Notation for representing moment-to-moment concept generation through interpersonal interactions.

Although various methods have been proposed, there is a lack of decision-making methods for generating optimal product concepts considering overall product performance (OPP) as well as cost simultaneously. The determination of the product specifications in the product-planning phase significantly affects the product quality and therefore its competitiveness [14]. Improper decisions of these specifications may result in high cost due to subsequent redesign or even the poor market performance. In this research, a decision-making model is proposed based on HOQ to support concept generation with an objective of maximizing OPP. The method considers priorities of components according to identified customer requirement to generate an optimal concrete product concept and specifications. By using the proposed method, efforts on the concept evaluation and selection can be reduced since the solution of the model is already optimized by the proposed decision-making model.

2.3 Appearance improvement

For the perceived product quality, emotion design can make products more attractive to customers [20]. Emotion design involves marketing techniques to product design activities, which makes a design process not only from engineering point of view but also from esthetic viewpoint. Three methods commonly used in the emotion design are conjoint analysis (CA), Kansei Engineering (KE) and Kano’s model.

2.3.1 Conjoint analysis (CA)

CA was firstly proposed by Luce and Tukey as “Simultaneous Conjoint Measurement” [21]. It was known as a new mathematical psychological measurement. In the early 70’s, this idea was brought to the marketing field. Conjoint analysis became an approach for the market analysis [22, 23]. CA is used to weight different conceptual products for identifying what product attributes are preferred by customers and how much the customers are willing to pay for it. There is a basic assumption in the conjoint analysis. The assumption is that opinions of a product can be broken down into some attributes separately [24], which means a combination of different attributes, such as color, weight, shape, price, etc., has a joint influence on customers’ purchase decisions [25]. Generally, description cards are used to gather customer preference data as shown in Fig.2- 2.

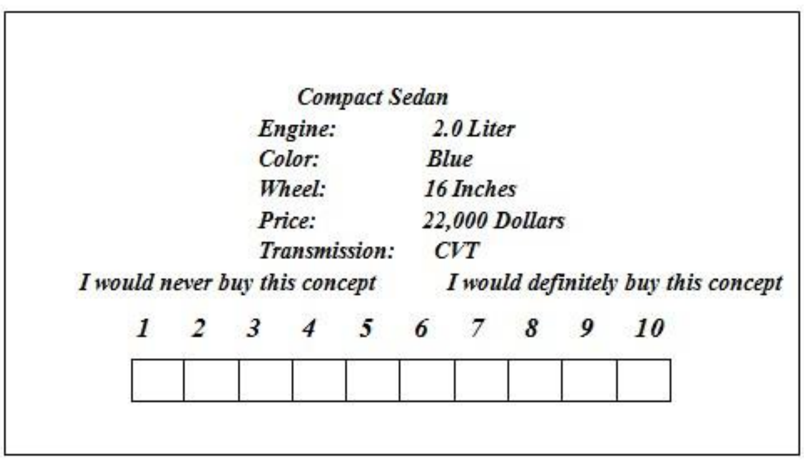


Fig.2- 2 Example of conjoint analysis description card [26]

2.3.2 Kansei engineering (KE)

KE is a product development method which aims to meet customer preferences by translating customer's demands, feelings and impressions into concepts to make design solutions and parameters [27]. The term "Kansei" is a Japanese word which means a customer's psychological feeling and image regarding an object. KE detects lots of emotions of people and divides a product into many aspects, and then links these aspects to detected emotions using statistic methods. KE can be applied to decide customer requirements and their importance, to conduct benchmarking and to connect the customer requirements mathematically for the design features of a product [28-30]. In recent years, KE has been researched and performed by many researchers, and this method has been classified into six types as shown in Table 2- 2.

Table 2- 2 Types of Kansei Engineering [31]

Type	Description
I	Category classification: Identifying the design elements of product, translated from consumers' feelings and image.
II	Kansei engineering system: A computer-based system with interference and Kansei databases
III	Hybrid Kansei Engineering system: the combined computer system or forward Kansei, which is from user's impressions to design specifications and vice versa.
IV	Kansei Engineering modeling: Mathematical modelling with an interference engine and databases
V	Virtual Kansei Engineering: An integration of virtual reality technology and Kansei Engineering in a computer system
VI	Collaborative Kansei Engineering designing: Group work design system utilizing intelligent software and databases over the internet

2.3.3 Kano's model

Professor Kano developed a theory to explain the different relationship between product criterion and customer satisfaction, namely Kano's model [32]. According to the theory, customer preferences can be classified into three basic categories: must-be, one-dimensional, and attractive group.

i. The must-be: When a performance is low, customers become dissatisfied. However, customer satisfaction will not go above neutral with a high performance for the must-be category.

ii. One-dimensional: Customer satisfaction has a linear relationship with the degree of a performance. The better performance results in better customer satisfaction and vice versa.

iii. The attractive: customer satisfaction grows super linearly with the growth of a performance. But, the corresponding decreasing relationship of a performance and customer satisfaction will not be observed.

For identifying Kano categories of must-be, one-dimensional and attractive qualities, the simplest way is to conduct a Kano questionnaire [32]. Customers are requested to choose one of following three feeling responses. Researchers can then organize each criterion into proper category.

i. Satisfied

ii. It should be that way

iii. I can live with it

2.3.4 Method selection of CA, KE and Kano's model

The disadvantage of CA is its complexity both for respondents and designers due to too many combinations of design elements. Respondents and designers resort to simplification strategies. Moreover, poorly designed solutions may over-value preference variables and under-value concrete variables.

KE may introduce more unnecessary difficulties to product design, since it over emphasizes on customers' subjective feelings by complicatedly dividing customers' preference into many different emotions and generating relationships of design elements and emotions. Normally, an engineering design should emphasize more on engineering aspect than emotion aspect. In most cases, one or two type of perceived emotions considered in a product development should be enough for a successful product. Considering the simplicity and effective results in observing customers' preference for a product, in this research, Kano's model is chosen to infer the optimal forms and shapes.

Chapter 3

Conceptual design using HOQ

3.1 House of quality (HOQ)

HOQ is an essential tool for each phase of QFD. A HOQ consists of five parts used for phase I of the QFD method in this research, as shown in Fig.3- 1.

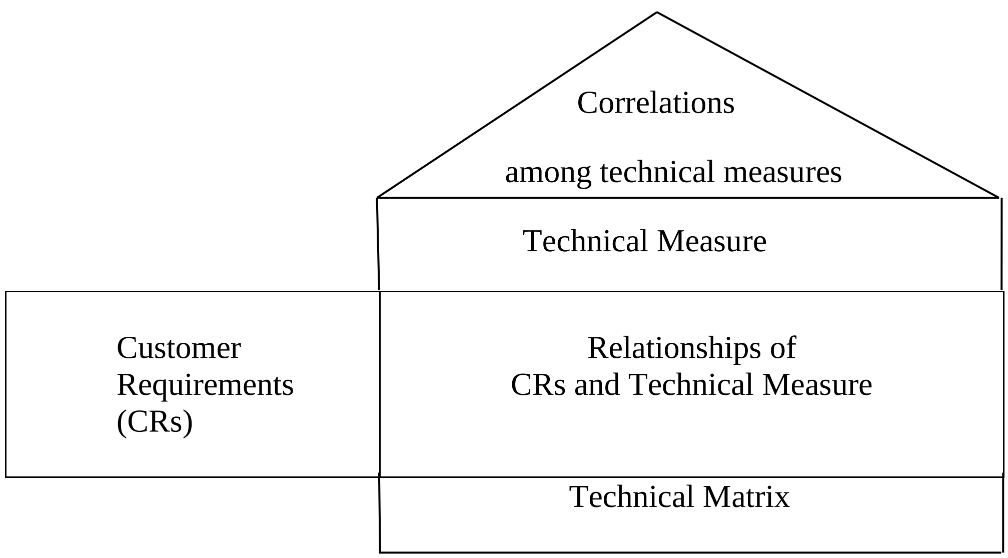


Fig.3- 1 House of Quality: Brief structure [33]

3.1.1 Customer requirements (CRs)-"Voice of customers"

As an initial input of the HOQ, a list of gathered CRs is presented in the CRs section as shown in Fig 3-1. The survey results are collected based on the customer interview. Since the HOQ method is a customer oriented product development method, identifying CRs is significantly important. One problem is that gathered customer requirements are too general to use. Designers need to understand these needs and interpret them into more specific requirements which are more easily to associate with technical measures. In this situation, an Affinity diagram, the method of organizing qualitative information into natural and logical groups, can be used [3]. By using the Affinity diagram, designers are able to organize gathered primary CRs and to transform them into more specific CRs based on designers' understanding of gathered needs as shown in Table 3-1.

Normally, CRs are not equally important. CRs have different important levels which can be rated using the customer survey. In this research, a 5-scale rating method is used to rate CRs based on the customer suggestions as presented in Table 3- 1.

Table 3- 1 Affinity diagram: customer requirements with importance rates

Primary Needs	Secondary Needs	No.	Tertiary needs	Imp. rates
Functional	Good to eyes	1	Soft light	3
	Convenient to use	2	Long lasting ability per charge	4
		3	Quickly charge	4
	Comfortable light	4	Uniform light emitting	3
Portable		5	Small size	5
		6	Light weight	5
Flexible		7	Foldable structure for stand	3
Good looking		8	Good form	4
		9	Good color	3

3.1.2 Technical measures-“Voice of the Engineering”

Measure is used to describe how well a customer requirement presented in Fig. 3-1can be satisfied using engineering methods. Therefore, measures should be determined associating to CRs. For example, if small is a CR, dimension is an appropriate measure for this CR. Improvement direction of measures is also to be determined. Symbols ↑,↓are used for indicating the increase and decrease improvement, respectively. Measures are established in this section from the engineering point of view as described in Table 3- 2.

Table 3- 2 Measure descriptions

No.	Measure	Associated CR	Description	Unit	Improvement direction
1	Light intensity	Soft light	300 Lux is public acknowledged and recommended number for the indoor lighting intensity.	Lux	Closer to 300 Lux
2	Battery capacity	Long lasting ability	As the only source of energy, battery capacity significantly determines lasting ability per charge.	mAh	↑
3	Charge power	Quickly charge	Charge power affects the completion time of charge.	w	↑
4	Dots density of light guide	Uniformity	Light generated from a light source is reflected and uniformed through light guide dots.	Unit /cm^2	↑
5	Product dimension	Small size	Total dimension of the product.	cm^3	↓
6	Product mass	Light weight	Total mass of the product.	g	↓
7	Stand-support mechanism	Fordable structure	The stand-support mechanism supports product stand on desk.		Steady and foldable

3.1.3 Relationships of CRs and measures

A measure is determined according to CRs. One measure may have relationships with more than one CR. The degree of these relationships may have different degree levels. Relationships of CRs and measure are rated by the design team and industrial partner based on the knowledge and experience. Four relationship levels are used: no relationship, weak, moderate, and strong relationship. A scale of (0, 1, 4, 9) is used for these four relationship levels, respectively [34]. The rating result is shown in Table 3- 3. The measure No. and need No. are based on Table 3-1 and Table 3-2.

Table 3- 3 Relationship rates of CRs and Measures

Measure No. vs. Need No.	Rate	Scale
No. 1 vs. No.1	Strong	9
No. 1 vs. No.2	Medium	4
No. 2 vs. No.2	Strong	9
No. 2 vs. No.3	Strong	9
No. 2 vs. No.5	Medium	4
No. 2 vs. No.6	Medium	4
No. 3 vs. No.3	Strong	9
No. 4 vs. No.4	Strong	9
No. 5 vs. No.5	Strong	9
No. 6 vs. No.6	Strong	9
No. 7 vs. No. 7	Strong	9

3.1.4 Technical correlations

Correlation information is shown in the roof of the HOQ as shown in Fig. 3-1. Such information reflects the relationships among technical measures. Conflictions among measures often appear in a design, which should be considered. In this research, five correlation levels are identified from the technical viewpoint: strong negative impact, moderate negative impact, no impact, moderate positive impact, and strong positive impact. The result is shown in Table 3- 4.

Table 3- 4 Technical correlation rates

Measure vs. Measure	Rate
No. 2 vs. No. 5	moderate negative
No. 2 vs. No. 6	moderate negative
No. 5 vs. No. 6	moderate positive

3.1.5 Technical matrix

(a) Importance weights of technical measures

Weights of technical measures can be calculated based on CRs importance ratings and relationships ratings of CRs and measures according to the additive weighting Formula 3-1. Result is shown in Table 3- 5.

Importance weight of a measure (3-1)

$$= \sum_{CRs} [\text{Importance rates of CR} \times \text{Relationship rates of CRs and measure}]$$

Table 3- 5 Importance weights of measures

	Light Intensity	Battery capacity	charge power	Dots density	Product dimension	Product mass	Stand-support mechanism
weight	43	112	36	27	45	45	27
Rank	4	1	5	6	2	2	6

For example, the “light intensity” is associated to CR “Soft light” and “Long lasting ability” with 3 and 4 importance rates as shown in Table 3-1, respectively. The relationship of “light intensity” and “Soft light” is rated 9; relationship of “Light intensity” and “Long lasting ability” is rated 4 as shown in Table 3-3. According to Formula 3-1, the weight of the “light intensity” can therefore be calculated as $3\times9+4\times4=43$.

(b) Benchmarking and setting performance target for technical measure

Three competitors’ products are reviewed as shown in Fig.3- 2. Three most important specifications are selected as technical data for benchmarking as shown in Table 3- 6. Setting performance target for technical measure is based on benchmarking and technical feasibilities as shown in Table 3- 7.

SAD Lifemax [35] Apollo Health [36] Philips Golite BLU [37]

Fig.3- 2 Three competitors' products

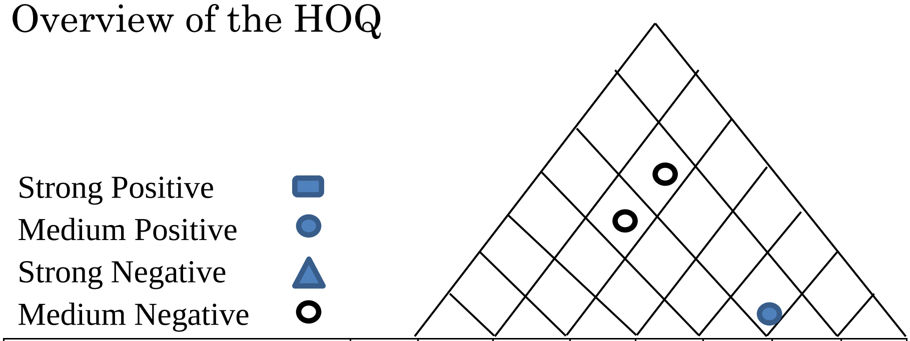
Table 3- 6 Benchmarking of three technical measurements

	Dimension (cm)	Mass (g)	Battery Capacity (mAh)
Lifemax	20.5x12.3x4.5	306	(Plug-in)
Apollo Health	14x14x2.5	400	850
Golite BLU	15x15x3	300	800

Table 3- 7 Performance target for each measurement

	Light Intensity	Battery capacity	Charge power	Dots density of light guide	Product dimension	Product mass
Target value	300 Lux	850 mAh	5 w	100	490 cm^3	300 g

3.1.6 Overview of the HOQ



Measures / CRs	Importance rates of CRs	Light Intensity	Battery capacity	Charge power	Dots density	Product dimension	Product mass	Stand mechanism
Direction of Improvement			↑	↑	↑	↓	↓	
Soft light	3	9						
Long lasting ability	4	4	9					
Quickly charge	4		9	9				
Uniform light emitting	3				9			
Small size	5		4			9		
Light weight	5		4				9	
Fordable structure	3							9
Good form	4							
Good color	3							
Target Value		300	850	5	100	490	300	
Importance weights of measures		43	112	36	27	45	45	27
Relative importance (%)		13	33	11	8	13.5	13.5	8

Fig.3- 3 House of quality

Tables 3-1 to 3-7 can be integrated into a HOQ as shown in Fig.3- 3. The generated HOQ clearly shows how CRs can be met from the engineering viewpoint through identifying relationships of CRs and technical measures, importance levels of CRs, and product development planning information. Based on information in the HOQ, designers are expected to generate a concrete product concept and specifications. However, the customer requirements of "good form" and "good color" are difficult to be described by any engineering measure due to the high subjective nature. In addition, although "stand-support mechanism" is used to indicate "foldable structure", such descriptive information cannot be considered using technical measures. Therefore, efforts on potential improvements can be made to use descriptive information. Following research aims to generate a concrete product concept and specification.

3.2 Concept generation

In the phase II of QFD, components need to be identified to generate a concrete design concept and specifications. Similar to the Phase I, this phase also uses HOQ as an essential tool to establish the relationships of components and technical measures.

3.2.1 Components

Components are classified into two categories according to their sources. Group 1 is purchased components, namely outsourced group. Group 2 is the to-be-made components depending on outsourced components. Four components in group 2 are top body, under body, bracket and button. Outsourced components in group 1 are listed in Table 3- 8.

Table 3- 8 Outsourced components

Component	Description	Attributes	Picture
Rechargeable Battery	A higher battery capacity results in longer lasting time with a larger weight and size.	Dimension, Weight, Capacity	
Battery charger	It controls input voltage and current while charging and protecting battery from being overcharged, discharged and short circuit.	Dimension, Charge power	
Miniature LED	Lighting source	Number of LED used	
Light guide	It uniforms light source through dots emission. More dots density achieves a more uniform performance.	Dots denstiy	
LED driver	Boost output voltage to drive miniature LED.	Dimension	

Each component has one or several attributes which may affect one or several technical measures. Normally, the better performance of a component achieves better technical performance; and therefore it satisfies customer requirements better. However, a better component may also have the higher cost. Therefore, evaluating each attribute of components is significantly important. For each component, there are several candidates with various parameters of attributes and costs. Designers have to make decisions among candidates in this situation. Table 3- 9 shows attributes and cost information of five outsourced components.

Table 3- 9 Components' candidates

Component	Attributes	Unit	No.1	No.2	No.3	No.4
Rechargeable Battery	Dimension	cm^3	11.35	10.5	8.75	16.5
	Mass	g	65	59	48	78
	Capacity	mAh	1350	1100	850	1600
	Cost	dollar	8	6.5	5	8.5
Battery charger	Dimension	cm^3	9.75	10.45	11.05	
	Charge power	watt	3.5	5	3.5	
	Cost	dollar	7.5	8	6.5	
Miniature LED	Number of LED used	unit	6	4		
	COST	dollar	6	4		
Light guide	Dots densitiy	unit/cm2	64	100	144	
	Cost	dollar	5	5.5	6.5	
LED driver	Dimension	cm^3	4.5	5.25		
	Mass	g	38	46		
	Cost	dollar	7.5	7		

3.2.2 Building of HOQ 2 for phase II

The aim of QFD phase II is to decide components and links of components and technical measures. In phase II of the QFD method, components associating to technical measures are established considering attributes of components. The process of building HOQ 2 for phase II is similar to the phase I. The CRs section is replaced by a technical measure section, and the technical measure section is replaced by a component section. All components are independent each other; therefore, a roof section showing the correlation information is unnecessary. The overview of the HOQ 2 for phase II is established and illustrated in Fig.3- 4.

Measure \ Component	Outsourced components Group 1						To-be-made components Group 2			
	Imp. Rates	Battery	Battery charger	Miniature LED	Light guide	LED driver	Bracket	Top body	Under body	Button
Light intensity	43			9						
Battery capacity	112	9								
Charge power	36		9							
Dots density	27				9					
Product dimension	45	1	1			1				
Product mass	45	1				1				
Stand-support mechanism	27									
Importance weights of components		1098	369	387	243	90				
Relative importance (%)		50	17	18	11	4				

Fig.3- 4 HOQ 2 for phase II: Technical matric vs. component

The processes of building the two HOQs (Fig. 3-3 and Fig. 3-4) illustrate how to transfer customer requirements through technical matric to product components. Using information in each section of HOQs, several concrete concepts and specifications can be generated. However, as shown in HOQ 2 in Fig. 3-4, four to-be-made components in group 2 are not associated to any measure, since they are directly related to the customer requirements of “good form” and “good color” which cannot be described by any technical measures.

3.2.3 Generation of concepts with established HOQs

Choosing a proper component among candidates has to be conducted for generating a design concept and specifications. This process involves decision-making, which is complicated in the design process since different design data are to be considered. Normally, a number of concepts need to be developed, and these concepts can be further evaluated and then selected.

Difficulty in the concept generation with HOQs

Each attribute of components complexly associates with one or more measures, and will finally affects customer requirements. For example, in this research, five components form 144 different combinations. Each combination is a design concept with its specifications. Information has to be combined including relationships of CRs and measures, relationships of measures and components, measure correlations and attributes of components to generate concepts. Although HOQ is useful in transforming CRs to product components, it is incapable in suggesting optimal combinations in the concept generation phase.

QFD method does not provide a rule to guide designers for selecting candidates of components. To simplify the problem, the highest priority is given to the customer requirement of “portability” when choosing candidates, since this need is the most important. As a result, the selection among candidates becomes easier (without considering overall product performance). Candidates with the smallest dimension and the least mass are selected. For components without attributes of dimension and mass, candidates with the lowest cost are selected. The selected components are shown in Table 3- 10. The selection is based on the attributes information shown in Table 3-9. The combination of candidates has the best portable performance based on adopted selection principle. For the to-be-made components, top body, under body, bracket and button can be designed. The candidate No. refers to Table 3-9.

Table 3- 10 Candidates selection

Components	Rechargeable Battery	Battery charger	Miniature LED	Light Guide	LED driver
Selected No.	3	1	2	1	1

3.2.4 Details design of to-be-made components

(a) Product body part

The product body consists of a top body part and a under body part. Detail design aims to properly fix each internal component to either top part or under part. Therefore, details design for the two parts form basis of internal components. Design drawings are shown in Fig.3- 5.

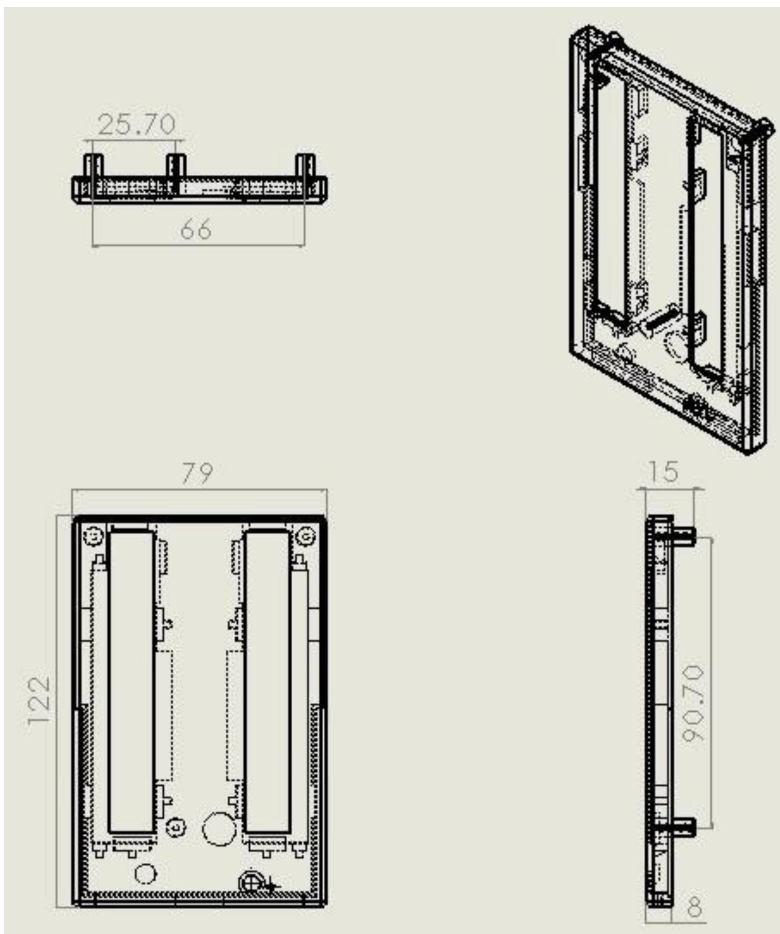


Fig.3- 5 Drawing of top body

(b) Bracket

Bracket supports the product standing on a desk. Spin and stop mechanism should be designed properly. The spin mechanism is shown in Fig.3- 6. The designed structure gives the flexibility in terms of standing angle. It leverages the elasticity property of the material and boosts the friction force to make the bracket stop at any pre-defined angle by grooves.

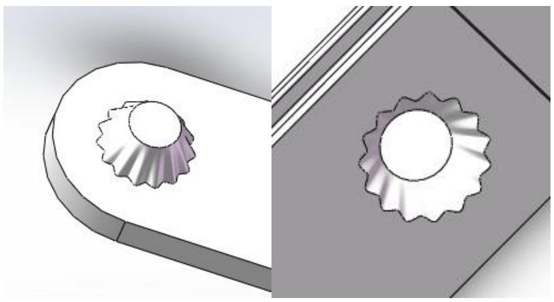


Fig.3- 6 Spin mechanism of bracket

(c) Switch button

Circle switch button is generated as shown in Fig.3- 7

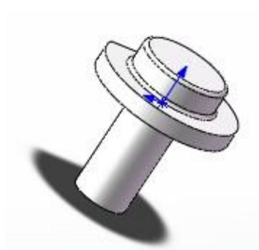


Fig.3- 7 Switch button

3.2.5 Result and Comparison

The proposed model is generated based on the selected outsourced components and designed parts. The design information in HOQs is partially considered in the development process due to the incapable of concept generation in the QFD method. The three measures of the proposed model are shown in Table 3- 11 to compare with competitors' products. The appearance of the model is also shown in Fig.3- 8.

Table 3- 11 Comparison with competitors' products

	Dimension (cm)	Mass (g)	Battery Capacity (mAh)
Lifemax	20.5x12.3x4.5	306	Plug-in
Golite BLU	14x14x2.5	400	850
Apollo Health	15x15x3	300	800
Sunnex (ours)	12.2X7.9X2.5	237	850

SAD Lifemax [35]   Philips Golite BLU [36]   Apollo Health [37]   Sunnex (our design)

Fig.3- 8 Pictures of the four designs

From Table 3-11and Fig. 3-8, the comparison with competitors shows that the generated model has smaller dimension and less mass. Although the generated product concept is more potable than competitors, other customer requirements, such as the soft light and stand-support mechanism, are to be improved.

3.2.6 Areas for improvement of the initial model

Since the adopted principle of generating the concept gives a high priority to portable and low cost, potential issues appear in other aspects. Based on the concept evaluation and the customer feedback, several issues are observed as follows.

(a) Bracket cannot support the device standing steadily because the elasticity of the material used cannot provide enough the friction force.

(b) The device achieves 248 Lux light intensity, which has a certain space to improve according to the ideal value, 300 Lux.

(c) The battery enables the device working for 3.5 hours; and the charge time for the battery is 2 hours. The higher battery capacity and charge power may achieve better performance.

(d) The customer complains the awkward appearance.

3.3 Summary of QFD method

3.3.1 Weakness in the concept generation using HOQ

The concept generation involves a lot of decision-making efforts as shown in Section 3.2.3. Each decision significantly affects the final result. However, making reasonable decisions is difficult due to complex relationships among technical data. Although HOQ is a useful tool in transforming “voice of customer” to “voice of engineer”, it seems incapable in suggesting optimal combinations in concept generation phase. Therefore, it is required to have a supportive decision-making method to combine the overall product performance as well as cost to provide quantitative results when facing complicated decision-making situations.

3.3.2 Weakness in considering descriptive information

Although the proposed design is better in terms of the portable requirement, the work seems to be not attractive compared to competitors' products. This disadvantage exposes the drawback of the QFD method for the incapability of transforming subjective customer requirements, such as "good looking". Additionally, some descriptive information, such as "foldable structure" and "stand-support mechanism", is also difficult to be considered during the design process. Therefore, methods to improve the design in this area are necessary.

3.3.3 Inefficient use of correlation information

Although the roof of the HOQ contains the correlation information, conventional applications of HOQ oversimplifies such data. It is seldom effectively used in determining priorities of measures. However, the measure often appears to be incompatible with each other, which should be considered. A measure may either have positive or negative effects on others. High priority should be given to the measure which has a high positive effect on others. In Section 4.1.1, correlations information is to be effectively used to modify priorities of measures.

Chapter 4

Design Improvement

4.1 Supportive decision-making method for the concept generation

4.1.1 Correlation information among measures

Based on the review of previous work in applying the correlation information to decide priorities of measures, one commonly used method considers the linear multiplication between the correlation value and measures. For instance, Chan and Wu used this approach in their Quality Function Deployment framework [38]. Khoo and Ho's modification method with a linear multiplication was used in a HOQ construction process [39]. Additionally, the same method was also applied by Liu to modify priorities of measures [40]. This research adopts the same approach to modify the initial importance weights of measures as expressed in Formula 4-1.

Modified weight of a measure

$$= \sum \text{(Initial weight of the measure} \times \text{Correlation value of the measure and other measures)} \quad (4\text{-}1)$$

To compute the final weights of measures, a Q matrix representing the correlations information is built. For example, the element of Q in the i^{th} row and the k^{th} column represents the correlation of the i^{th} measure and the k^{th} measure in the HOQ. The diagonal value of Q matrix is 1. The Q is symmetrical. In this research, rating scales (-3, -1, 0, 1, 3) are used for representing strong negative, moderate negative, no relationship, moderate positive, and strong positive, respectively [5, 41]. The values in following Q matrix are from the roof of the HOQ in Fig. 3-3.

The moderate negative correlation of battery capacity and product dimension

The moderate negative correlation of battery capacity and product mass

$$Q=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & \underline{-1} & \underline{-1} & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & \underline{1} & 0 \\ 0 & -1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (4\text{-}2)$$

The moderate positive correlation of product dimension and product mass

The initial weights of measures, shown in the technical matrix of HOQ in Fig. 3-3, can be expressed in the form of matrix as following P matrix.

$$P = [p]^T = [43, 112, 36, 27, 45, 45, 27]^T \quad (4\text{-}3)$$

where,

43 is the initial weight of light intensity.

112 is the initial weight of battery capacity.

36 is the initial weight of charge power.

27 is the initial weight of dots density of light guide.

45 is the initial weight of product dimension and mass.

27 is the initial weight of stand-support mechanism.

As a result, the modified weights matrix P' integrating correlations information can be obtained from Formula 4-4. The comparison of initial weights and modified weights is shown in Table 4- 1.

$$P' = Q \cdot P = [43, 22, 36, 27, 90, 90, 27]^T \quad (4\text{-}4)$$

Table 4- 1 Modified weights of measures

	Light intensity	Battery capacity	Charge power	Dots density	Product dimension	Product mass	Stand mechanism
Measure No.	1	2	3	4	5	6	7
Initial weights	43	112	36	27	45	45	27
Modified weights	43	22	36	27	90	90	27

From Table 4-1, it can be seen that the weight of battery capacity is significantly reduced from 112 to 22 when applying the moderate negative impact on product dimension and product mass. On the other hand, product dimension and product mass has moderate positive impact on each other, which leads an increase from 45 to 90. There is no change for the light intensity, power of charger, dots density, and stand-support mechanism because they have on impact on other measures. As a result, the product dimension and product mass are equally most important measures, followed by light intensity, power of charger, dots density, stand-support mechanism, and battery capacity. The modified weights are more reasonable because the correlation information among measures is considered.

4.1.2 Proposed decision-making model

To generate an effective decision-making model, the model objective needs to be specified. Generally, customers care about both the overall product performance (OPP) and its price when they make a purchase decision. A good value-for-money product is desired in the market. Therefore, the overall product performance and cost of a product are crucial factors for a product’s commercial success. In this situation, the proposed decision-making model aims to maximize OPP within a limited cost to increase the product competitiveness.

4.1.3 Overview of the decision-making model

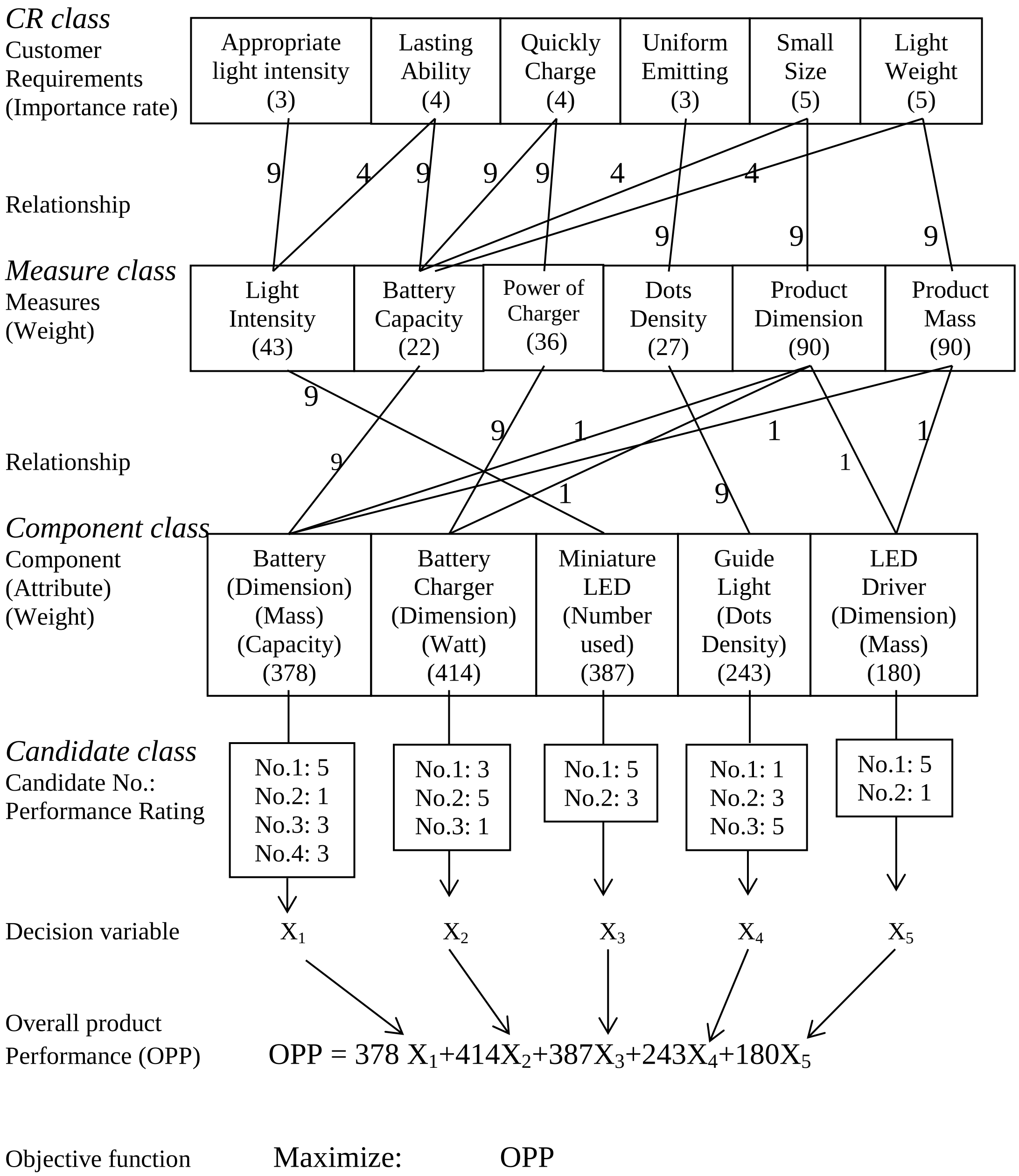


Fig. 4- 1 Decision-making tree

The proposed decision-making tree, shown in Fig. 4- 1, consists of four classes based on their information: customer requirement (CR) class, measure class, component class and candidate class. CR class and measure class are the substitute for HOQ 1 (Fig. 3-3); and measure class and component class are the substitute for HOQ 2 (Fig. 3-4), as explained in Fig. 4- 2.

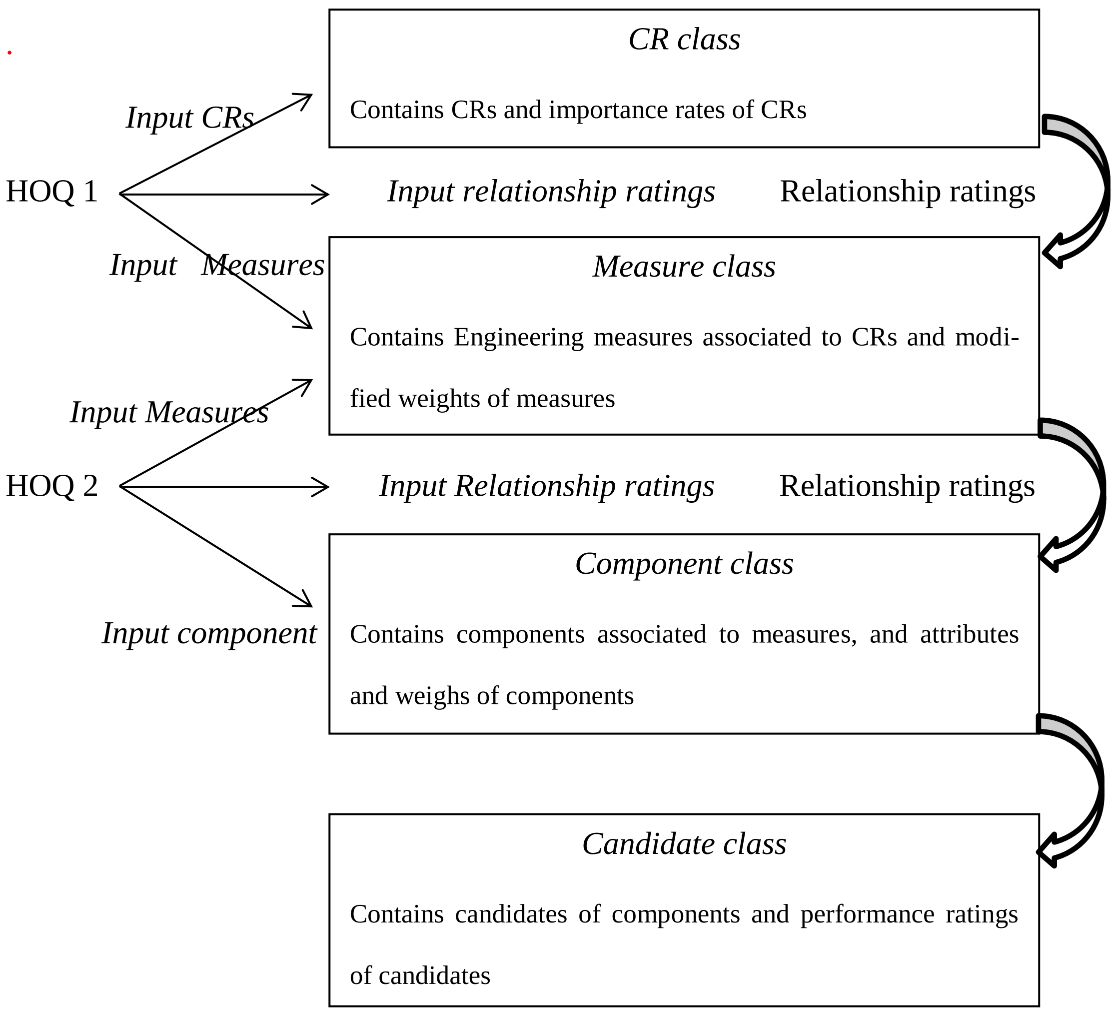


Fig. 4- 2 Input data from the HOQs

Design information of two HOQs used in CR class, measure class, and component class as supportive data for the proposed decision-making method.

HOQ 1 (Fig. 3-3) defines the customer requirements: “appropriate light intensity” and “lasting ability”, and corresponding importance rates, 3 and 4, respectively. These information shows in the CR class.

HOQ 1 also shows the measure “light intensity” which is associated to the two customer requirements with rated relationships of 9, and 4, respectively as shown in Fig. 3-3. These information shows in the measure class. (Weights of measures to impact on others are discussed in Section 4.1.1)

HOQ 2 (Fig. 3-4) defines the component miniature LED associated to the measure “light intensity” with relationship rating 9. The component class also contains attributes of components, which is not shown in HOQ 2. The candidate class contains the candidates’ performance ratings of components.

Design information for customer requirements, engineering measures, and components in the two HOQs is integrated with information of attributes of the components, candidates of the components, relationships of CRs and measures, relationships of measures and components, and the performance of each candidate to develop the proposed decision–making model. The overall product performance is the addition of multiplication of each selected candidate’s performance and its weights. The final objective is to maximize the OPP. The proposed decision-making model considers the overall product development factors, including CRs, measures, relationships, components, weights, and candidates, to suggest an optimal product concept with the quantitative solution.

4.1.4 Performance rating for candidates of components

Rating each candidate's performance is based on evaluating its attributes. For a candidate with several attributes, designers need to consider each attributes' performance and each attribute's weight to give an overall rating to a candidate. For example, battery has three attributes which affect three measures: dimension, mass and capacity with weights 90, 90, and 198, respectively. Designers consider three aspects and three weights to give an overall rating to each candidate of battery based on specifications of candidates. Several methods can be used to evaluate components according to different characteristics of the components. In this research, candidates of battery, battery charger, and LED driver are rated based on the technical data and specifications. Candidates of miniature LED and light guide are rated based on the test. In this research, a scale (1, 3, 5) is used to represent "acceptable", "good", and "excellent" performance level. The results of performance ratings of candidates for five components are shown in Table 4- 2 to 4-6.

(a) Battery

Table 4- 2 Candidates rating for battery

Attribute / Candidate	Dimension (cm^3) (90)	Mass (g) (90)	Capacity (mAh) (198)	Rates
No. 1	11.35	65	1350	5
No. 2	10.5	59	1100	1
No. 3	8.75	48	850	3
No. 4	16.5	78	1600	3

(b) Battery charger

Table 4- 3 Candidates rating for battery charger

Attribute (Imp.) / Candidate	Dimension (cm^3) (90)	Power of charger (w) (324)	Rates
No. 1	9.75	3.5	3
No. 2	10.45	5	5
No. 3	11.05	3.5	1

(c) Miniature LED and light guide

Setting up a test to evaluate candidates of the miniature LED and light guide is required in this research, since technical data of these two types of components cannot give an intuitive sense of their performance. The test platform used is shown in Fig. 4- 3.

(i) Test for Miniature LED

Measurement: Light intensity (300 Lux is the ideal value)

Distance: 1.5 feet (1 to 2 feet is recommended distance)

Tool: Lux metre

(ii) *Test for light guide*

Measurement: Light Uniformity (uncomfortable, acceptable, comfortable)

Distance: 1.5 feet

Fig. 4- 3 The test platform

(iii) Results

Table 4- 4 Candidates rating for miniature LED

Attributes / Candidate	Unit (Num.)	Result (Lux)	Rate
No. 1	6	312	5
No. 2	4	248	3

Table 4- 5 Candidates rating for light guide

Attributes / Candidate	Dots density (unit/cm^2)	Result	Rate
No. 1	64	Uncomfortable	1
No. 2	100	Acceptable	3
No. 3	144	Comfortable	5

(c) LED driver

Table 4- 6 Candidates rating for LED driver

Candidate \ Attribute (Imp.)	Dimension (cm^3) (90)	Mass (g) (90)	Rate
No.1	4.5	38	5
No.2	5.25	46	1

4.1.5 Formulation of the problem

(a) Decision variables:

Decision variables: x^1_1, x^2_1, x^3_1, x^4_1, x^1_2, x^2_2, x^3_2, x^1_3, x^2_3, x^1_4, x^2_4, x^3_4, x^1_5, and x^2_5.

x^1_1, x^2_1, x^3_1, and x^4_1 represent battery candidate No. 1, No. 2, No. 3, and No. 4, respectively.

x^1_2, x^2_2, and x^3_2 represent battery charger candidate No. 1, No. 2, and No. 3, respectively.

x^1_3 and x^2_3 represent miniature LED candidate No. 1 and No. 2, respectively.

x^1_4, x^2_4, and x^3_4 represent light guide candidate No. 1, No. 2, and No. 3, respectively.

x^1_5 and x^2_5 represent LED driver candidate No. 1 and No. 2, respectively.

(b)Objective function:

The objective function is to maximize overall product performance (OPP), as defined in Formula 4-5. OPP is the addition of multiplication of each selected candidate's performance and the corresponding component weights.

Overall product performance (OPP) = $\sum_{i=1}^{i_n} \sum_{j=1}^{j_i} p_i q_i^j \, x_i^j$ (4-5)

Where,

p_i is the modified weight of the i^{th} component.

q_i^j is the performance rating of the j^{th} candidate of the i^{th} component.

i_n is the total number of components.

j_i is the total number of candidate of the i^{th} component.

Therefore, the problem can be formulated as:

$$OPP = 378\,(5x^1{}_1 + x^2{}_1 + 3x^3{}_1 + 3x^4{}_1) + 414(3x^1{}_2 + 5x^2{}_2 + x^3{}_2) + 387(5x^1{}_3 + 3x^2{}_3) + 243(x^1{}_4 + 3x^2{}_4 + 5x^3{}_4) + 180(5x^1{}_5 + x^2{}_5) \quad (4\text{-}6)$$

where,

378 is the weight of the component battery; and values 5, 1, 3 and 3 are four candidates' performance ratings of the battery.

414 is the weight of the component battery; and values 3, 5 and 1 are three candidates' performance ratings of the battery charger.

387 is the weight of the component miniature LED; and values 5, and 3 are two candidates' performance ratings of the miniature LED.

243 is the weight of the component light guide; and values 1, 3, and 5 are three candidates' performance ratings of the light guide.

180 is the weight of the component LED driver; and values 5, and 1 are two candidates' performance ratings of the LED driver.

Objective function: Maximize OPP

(c)Constraints:

Since the high cost reduces customer satisfaction [42], the manufacturer controls cost of a product according to the financial strategy and product positioning in the market. Total cost is the summation of the cost of each selected candidate. The constraint of cost limitation can be formulated as Formula 4-7. Additionally, all variables are binary variables. Therefore, each variable equals either 0 or 1 as defined in Formula 4-8. 0 represents "not selected" and "1" represents "selected". For each component, there is one and only one candidate selected as defined in Formula 4-9.

Total cost = $\sum_{i=1}^{i_n} \sum_{j=1}^{j_i} c_i^j x_i^j \leq C$ (4-7)

$x_i^j \in [0, 1]$, $i = 1, 2, \ldots, i_n$, $j = 1, 2, \ldots, j_i$ (4-8)

$\sum_{j=1}^{j_i} x_i = 1$, $i = 1, 2, \ldots, i_n$ (4-9)

Where,

c_i^j is the cost of the j^{th} candidate of the i^{th} component.

C is the limited total cost.

Therefore, the problem is subject to:

$5x^1_1 + 6.5x^2_1 + 8.5x^3_1 + 8.5x^4_1 + 7.5x^1_2 + 8x^2_2 + 6.5x^3_2 + 6x^1_3 + 4x^2_3 + 5x^1_4 + 5.5x^2_4 +$

$6.5x^3_4 + 7.5x^1_5 + 7x^2_5 \leq 33$ (4-10)

$x^1_1, x^2_1, x^3_1, x^4_1, x^1_2, x^2_2, x^3_2, x^1_3, x^2_3, x^1_4, x^2_4, x^3_4, x^1_5, x^2_5 \in \{0,1\}$, (4-11)

$x^1_1 + x^2_1 + x^3_1 + x^4_1 = 1$, (4-12)

$x^1_2 + x^2_2 + x^3_2 = 1$, (4-13)

$x^1_3 + x^2_3 = 1$, (4-14)

$x^1_4 + x^2_4 + x^3_4 = 1$, (4-15)

$x^1_5 + x^2_5 = 1$ (4-16)

In this research, the price is based on Philips Golite BLU which has an average retail price of 100 dollars. Considering other costs and the expected profit, the estimated cost of five outsourced components should not exceed one third of the benchmarking price 100 dollars. Therefore, upper bound of the total cost, 33 dollars, is defined as the constraint of the objective. Constraint 4-10 defines that the total cost of components does not exceed 33 dollars. All coefficients in Formula 4-10 are the cost of corresponding candidates. Formula 4-11 indicates that all decision variables are binary variables which are either 0 or 1. Formulae 4-12 to 4-16 indicate that there is one and only one candidate of each component can be selected.

4.1.6 Interpretation of the model

As a binary linear programming (BIP) problem, the formulated model is recognized as a discrete combinational problem. In this research, due to the small size of the problem, the total combinations of variables are 144, which can be calculated using exhaustive method to obtain the optimal solution. However, a feature of the problem is that the complexity of the problem increases significantly with the increase of the problem size. For example, if a product has n components, and each component has 5 candidates, the total problem size is 5^n. If the problem size becomes 2n, the complexity of the problem increases to 5^{2n}, which may be impossible to solve using an exhaustive method. For a cost-effective solution, a near optimal search is acceptable in most cases. In order to adapt the method to a large size problem, a meta-heuristic algorithm is applied to efficiently solve the problem in this research.

4.2 Methods of searching the optimal solution

4.2.1 Meta-heuristic methods

Combinatorial optimization is to find an optimal solution from a finite set of solutions [43]. Three meta-heuristics methods have primarily been applied to solve combinatorial problem: Greedy search, Genetic algorithms, and Simulated Annealing [44].

Greedy search (GS) is an algorithm that follows the problem solving heuristic of making the locally optimal choice at each stage. In many problems, a greedy strategy does not produce an optimal solution, but nonetheless a greedy heuristic may yield locally optimal solution that is close to optimal solution in a reasonable time. Generally, GS has five components: (1) a candidate set, from which a solution is created, (2) a selection function, which chooses the best candidate to be added to the solution, (3) a feasibility function, which is used to decide if a candidate can be used as a solution, (4) an objective function, that assigns a value to a solution, and (5) a solution function, which represents when a complete solution has been discovered [45].

Genetic Algorithm (GA) is inspired from the natural evolution. The properties of one solution are generally represented in a form of binary string. Based on the estimating result of a fitness function, the existing solutions are selected to breed a new generation of solutions. In other words, randomly initial solutions will evolve to a better region after several iterations. The iteration process follows the roles of evolution theory such as inheritance, mutation, selection, and crossover. This method is useful to solve the optimization problem with the complex fitness landscape [46].

Simulated Annealing (SA) is a random-search technique which can locate a near optimal solution. It mimics the annealing process of mental cooling and reaching the minimum energy crystalline structure [47]. The goal of SA is to find an accentually good solution in the statistic aspect. It is more efficient than the exhaustive search for the best possible solution.

4.2.2 Summary of meta-heuristic methods

The greedy search may fail to find the optimal solution, and may even produce the unique worst possible solution. It can make commitments to certain choices too early which prevent from finding the best overall solution later [48].

There are several limitations of the genetic algorithm. Finding the optimal solution to complex high dimensional and multimodal problems often requires very expensive fitness function evaluations. One single function evaluation may require significant computational cost. Moreover, GA cannot reduce the complexity of the problem. When, the number of elements exposed to mutation is large, an exponential increase may appear in search space size [49].

Simulated annealing (SA) is more suitable for the combinational problem of locating the near optimum of a given function in a large search space. It is often used when the search space is discrete. SA may be more efficient than an exhaustive enumeration if the goal is merely to find an acceptably good solution in a relative short time, rather than the best possible solution. SA can avoid trapping at local minima and exploring the whole space to find the near optimal solution. Therefore, in this research, SA is applied to solve the formulated problem.

4.3 Simulated annealing

4.3.1 Overview of simulated annealing algorithm

SA is an analogy to the cooling process of heated metals, which allows the system to probabilistically select different points in the function both in and out of different local minima [50]. In order to jump the local minima, there is still likelihood that the system would accept a worse solution. However, such likelihood would be reduced with the accepting worst solution. A flow chart of SA is shown in Fig. 4- 4.

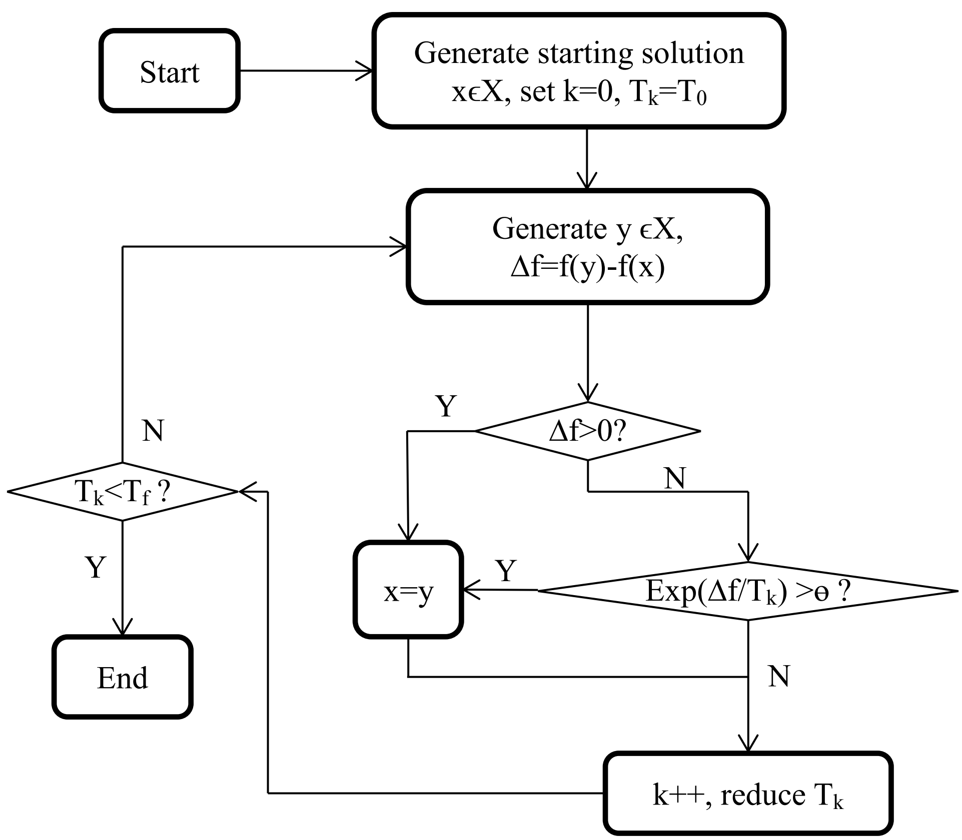


Fig. 4- 4 Flow chart of the SA for maximization problem [48]

Metropolis Principle is used to decide the probability of solution changing [51]:

$$P = \begin{cases} 1 & \text{if } E(x_{new}) > E(x_{old}) \\ \text{Exp}\left(\frac{E(Xnew)-E(Xold)}{T}\right) & \text{if } E(x_{new}) \leq E(x_{old}) \end{cases} \tag{4-17}$$

where,

x,y—current solution and new solution,

X—collection of whole solutions,

T_0—initial temperature,

T_k—temperature of k^{th} iteration,

T_f—final temperature,

a—cooling rate,

θ—random decimal between 0 and 1,

k—counters.

4.3.2 Apply SA to solve the problem

Following steps are used to solve the problem using SA:

Step1. Encoding and initialization

The feasible initial solution is a matrix indicating the selection of candidates of five components, noted as $X_0 = (x_1, x_2, x_3, x_4, x_5)$. If x_1 represents battery, battery has four candidates, noted as $x_1 = (x_1^1, x_1^2, x_1^3, x_1^4)$. When $x_1 = [1, 0, 0, 0]$, it means the first candidate of battery is selected. A feasible initial solution can be generated randomly, noted as X_k, then $X_k = X_0$. A higher initial temperature can improve the ability of finding an optimal solution; however the corresponding computational cost will increase accordingly. In this research, the initial temperature is set to T_0 = 1000 based on the suggestion by Johnson as shown in Formula 4-18 [52].

$$T_0 = \frac{\Delta\tilde{f}}{In(x_0^{-1})} \tag{4-18}$$

Step 2. Generating a new solution

This step is to generate a new solution, noted as X_n, to compare its fitness function with the fitness function with the current solution X_k. X_n is generated according to the neighbourhood function. The fitness function is defined by Formula 4-6. The objective is to find the maximum fitness value. Constraints defined by Formulae 4-10 to 4-16 are applied in the new solution search.

Step 3. Selection

This step selects a new solution X_k between the solution X_n and previous solution X_k'. Metropolis Principle is applied to decide the solution X_k defined in Formula 4-17. If the new solution is better than current solution, the system will take the new solution $X_k = X_n$; otherwise, there is still a probability to let $X_k = X_n$. However, with temperature cooling down, such probability will decrease. SA can find the near optimal solution by avoiding the system to trapping a local optimal solution.

Step 4. Cooling down

Annealing temperature, T should not be decreased too fast to allow the system to have sufficient time to achieve equilibrium [50]. Therefore, the annealing scheduling should be set properly. In this research, the annealing schedule is decided based on Formula 4-19 [53].

$T_t/T_0 = 1/(1+t)$, (4-19)

Where, t=1,2,…

t=4 is used, then cooling rate a=0.8.

Step 5. Termination

In this research, a termination condition is managed by setting final temperate $T_f = 0.1$. Every time after cooling down of the temperature, system decides if the search reaches the termination conditions. If $T_k > T_f$, the search will go back to Step 2 for next iteration. If $T_k < T_f$, the search will be ended.

4.3.3 Result

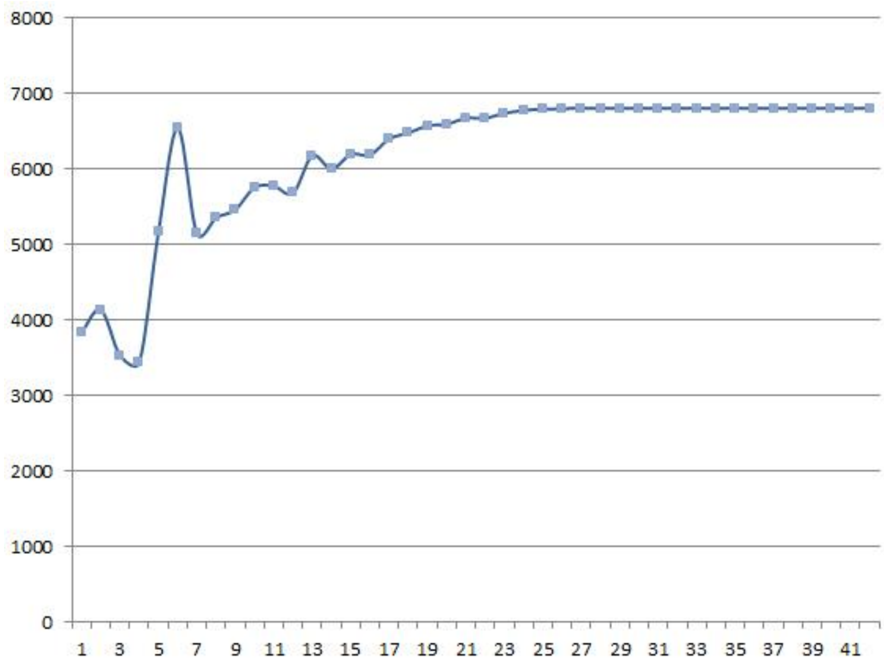


Fig. 4- 5 The process of solution improving

In Fig. 4-5, the convergence curve of the SA search process shows that the system reaches a stable solution after 25 iterations. According to the SA result, the near optimal solution has the total cost of 31.5 dollars and OPP value of 6804. This solution and specifications are shown in Table 4- 7.

Since the small size of the problem, the best solution can be obtained using exhaustive method. To verify the SA effectiveness, the optimal solution is obtained using Excel Solver to compare with the near optimal solution obtained from SA. Additionally, the OPP of the initial design is also calculated to compare with the SA solution, as shown in Table 4- 8.

Table 4- 7 The optimal combination and specifications from SA

Variable	Component	Selected candidate No.	Attributes	Unit	Value
X_1	Battery	1	Dimension	cm^3	11.35
			Mass	g	65
			Capacity	mAh	1350
X_2	Battery charger	2	Dimension	cm^3	10.45
			Charge power	w	5
X_3	Miniature LED	1	Num. of LED	unit	6
X_4	Light guide	2	Dots density	$unit/cm^2$	100
X_5	LED driver	2	Dimension	cm^3	5.25
			Mass	g	46

Table 4- 8 Solution comparisons

	Selected candidate No. of the initial design	Selected candidate No. of the SA solution	Optimal solution
Battery	3	1	1
Battery charger	1	2	2
Miniature LED	2	1	1
Light guide	1	2	2
LED driver	1	2	1
Total cost	32.5	31.5	32
OPP value	4680	6804	7524

From Table 4-8, it can be seen that the proposed decision-making model with the SA algorithm improves OPP from 4680 to 6804 compared with the initial model. Although, the SA solution is not the optimal solution, such result is near optimal. The only difference between SA solution and the optimal solution is the selection of LED driver. SA suggests selecting the candidate No. 2, while the optimal solution selects No. 1. When comparing the efficiency, SA appears better performance than the Solver. SA runs 30 iterations to obtain the near optimal solution, while the Solver runs 144 iterations. SA can provide a near optimal solution to maximize OPP with only about one fifth of the calculation effort of the Solver. The following work aims to identify the product form and color to improve the appearance of the product to satisfy the customer's need for "good looking".

4.4 Appearance improvement

4.4.1 Morphological analysis

Morphological analysis is widely used in product design, manufacturing and architectural design [54, 55]. Using morphological analysis, acceptable solutions can be obtained by using a morphological table [56].

Procedures of the morphological analysis are as follows:

(1) Identify the functional requirement of the target product

(2) List the acceptable solutions for each function in a morphological table

(3) Combine the suitable solutions for each function to build the product

Based on the review of three similar products and the requirements of industrial partner, there are four elements, called as first class factors, to decide the aesthetic aspect of the design: (A) body, (B) screen, (C) support part, and (D) color. There is a sub-class for the body: (a) edge, (b) length-width ratio and (c) button. There is a sub-class for the support part: (a) support arm and (b) stand-support mechanism. Each element has various design forms as shown in Fig. 4- 6.

(A)Body

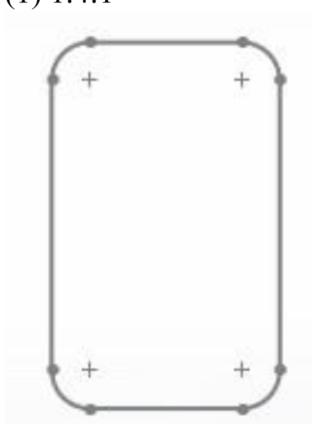
(a) Edge

(1) Small radius (2-4 mm)

(2) Big radius (5-8mm)

(b) Length-Width ratio

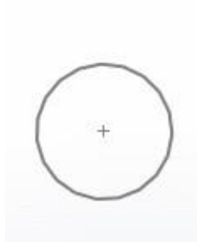
(1) 1.4:1



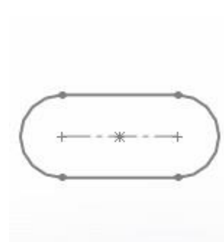
(2) 1.8:1

(c) Button

(1) Circle

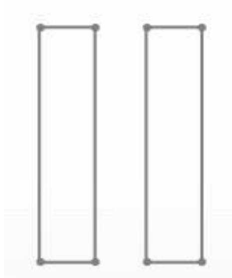


(2) Column

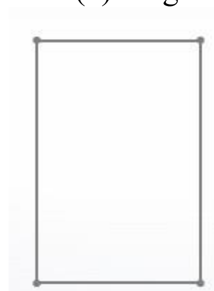


(B) Screen

(1) Double



(2) Single

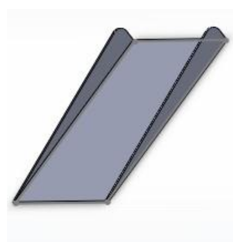


(C) Support part

(a) Support arm

(1) Frame style

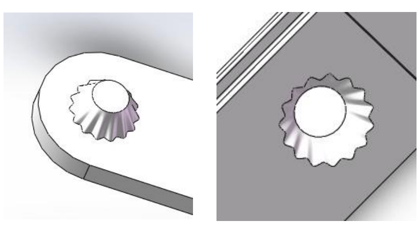
(2) Plain Cover



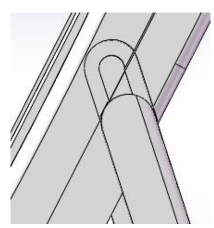
(3) Stick

(b) Stand-support mechanism

(1) Groove style



(2) Slide style



(D) Color

(1) White (2) Black (3) Silver

Fig. 4- 6 Morphological Table

4.4.2 Stand-support mechanism

Although the groove style mechanism cannot support the device stably based on the evaluation of the first model as mentioned in Section 3.2.6, using more rigid materials may solve the problem. Alternatively, a slide style can support the device in a good steady manner; however, it only provides one pre-defined stand angle as shown in (C b 2) of the Fig. 4-6. Therefore, Kano's model is used.

4.4.3 Kano's model

Kano's model is applied to determine the product forms and colors shown in Morphological Table in Fig. 4-6. In this research, a five-category of Kano's model is used. It uses five levels of the customer satisfaction for an attribute including: must-be, one-dimensional, attractive, indifferent, and reverse as shown in Fig. 4- 7.

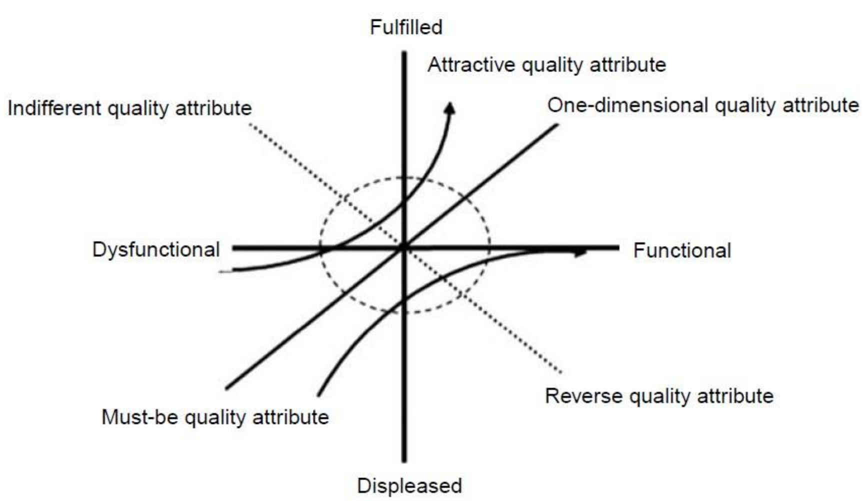


Fig. 4- 7 Five-category of Kano's Model [57]

(i) Must-be: If an attribute of the product is absent, the customer will be extremely dissatisfied. On the other hand, customer satisfaction only increases a little if the product has this attribute. The customer regards the must-be attribute as prerequisite.

(ii) One-dimensional: the customer satisfaction is proportional to the level of fulfillment, the higher level of fulfillment, the higher customers' satisfaction and vice versa.

(iii) Attractive: attractive attribute leads to more than the proportional satisfaction. It has a great influence on customer satisfaction with the given attribute.

(iv) Indifferent: customers are not sensitive to an attribute presented or not.

(v) Reverse: customers dissatisfy to an attribute presented in a product.

The industrial partner is requested to answer two questions. "How do you feel if that feature is presented in the product?" (Functional form of the question) and "How do you feel if that feature is not presented in the product?" (Dysfunctional form of the question) [57, 58]. Five answers are described as "like"; "must-be"; "no feeling"; "give up"; and "do not like". The perceptions are then evaluated into quality dimensions on basis of the respondents perceived the functional and dysfunctional form of an attribute as shown in Table 4- 9.

For example, if the answer is, "I like it that way" and "I can live with it that way" regards "How do you feel about a groove style ?" and "How do you feel without the groove style ?", respectively. The combined answers yield category I according to Table 4-9. In this research, according the response of the industrial partner, the result of Kano's model is shown in Table 4- 10.

Table 4- 9 Five levels of Kano's classification

		Dysfunctional question (Negative)				
		Like	Must-be	Neutral	Live with	dislike
Functional Question (Positive)	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; Q: Questionable; I: indifferent)

Table 4- 10 Results of Kano's model

Attribute / No.	Edge	Length/ width	Button	screen	Support arm	Stand-support mechanism	Color
(1)	M	I	M	M	A	I	O
(2)	A	M	A	O	R	M	O
(3)					M		A

(A: attractive; M: must-be: R: reverse; O; one-dimensional; Q: Questionable; I: indifferent)

Based on the results of Kano's model, designers can know which form is more desirable for the customer. The designers can then select forms of each attribute according to the sequence: A, O, M, I, and R, to generate a complete product concept. The selected forms are Aa(2) for edge, Ab(2) for Length/width, Ac(2) for button, B(1) for screen, Ca(1) for support arm, Cb(2) for stand-support mechanism, and D(3) for color.

4.5 Details design of to-be-made components

Based on the new specifications of internal components and the new forms of the product, details design can be implemented for parts of top body, under body, button and bracket. Design drawing of the top body is shown in Fig. 4- 8.

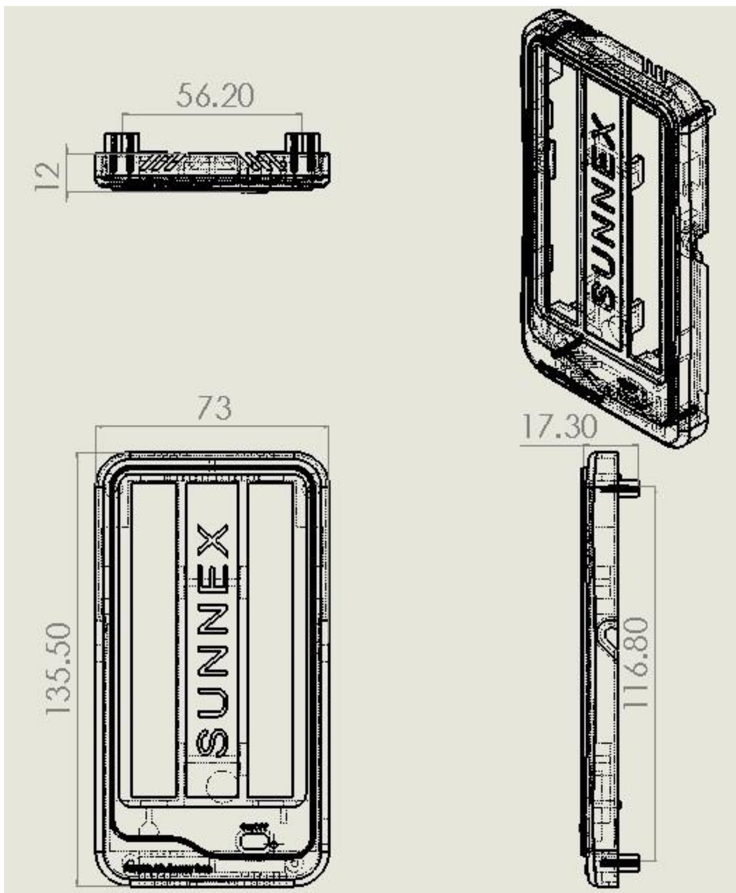


Fig. 4- 8 Design drawing

4.6 Result

The initial design is improved using the proposed method and Kano's model. The method, based on HOQs, uses the overall design information to provide an optimal concept with a high OPP. The Kano's model enhances the appearance of the design to satisfy the customer requirement for "good looking". The comparison of the improved model with the initial model and competitors' models is shown in Table 4- 11 and Fig. 4-9.

Table 4- 11 Improved model compared with the first model and competitors' models

	Dimension (cm)	Mass (g)	Battery Capacity (mAh)
Lifemax	20.5x12.3x4.5	306	Plug-in
Apollo Health	14x14x2.5	400	850
Golite BLU	15x15x3	300	800
First model	12.2x7.9x2.5	215	850
Improved model	13.5x7.3x2.5	287	1350

SAD Lifemax [35]

Apollo Health [36]

Philips Golite BLU [37]

Initial model

Improved model

Fig. 4- 9 Five product models

Table 4- 12 New specifications compared to the initial model

	Initial model	Improved model
Light intensity (Ideal value: 300)	248 Lux	312 Lux
Battery capacity	850 mAh	1350 mAh
Power of charger	3.5 W	5W
Dots density	64	100

Additionally, other specifications are improved as well based on the evaluation shown in Table 4- 12. Although, the improved model is slightly longer and heavier than the initial model, the overall performance has been improved. The improved specifications satisfy the customers' needs better, which improves the initial model in several aspects mentioned in Section 3.2.6. For the light intensity, 312 Lux is closer to the ideal value (300 lux) than 248 lux, which will make users feel more comfortable. A larger battery capacity makes the device work longer from 3.5 to 5 hours (satisfy customer's requirement "long lasting ability"); a higher power of charger charges the battery quicker from 2 hours to 1.5 hours (satisfy customer's requirement "quickly charge"); and a denser dots of the light guide makes the light more uniform (satisfy customer's requirement of "uniform emitting"). Additionally, the slide style stand-support mechanism can support the product steadily with foldable structure, which makes the product more flexible to use in a various environments.

When comparing with three portable competitors' products, the improved model has the smallest dimension, the lightest weight, and the largest battery capacity, which means a better performance of portability and flexibility. According to the evaluation and the customer feedback in terms of uniformity, light intensity, charge time, and foldable structure, the improved model appears features of high competitiveness. More importantly, the customer satisfies the appearance of the improved design.

Chapter 5

Conclusion and further work

5.1 Summary

This paper presents a new product development process through designing a therapeutic light device. The process illustrates how to transfer the customer requirements through engineering measures to necessary components using HOQ. Although HOQ turns out being a useful tool in this transfer process, several shortcomings still exposes based on the evaluations and the customer feedback on the first proposed model.

In the analysis of the proposed model for the improvement, it is found that correlation information in the roof of the HOQ is not effectively used in deciding priorities of the measures, which leads to the significant change of battery capacity importance compared to other measures.

Although HOQ can manage design information in a good manner, designers may have troubles in generating a concrete product concept when facing complicated design information. The conventional way in this step is based on designers' knowledge and experience. As a result, the performance of the product is remarkably affected by designers' knowledge and experience, as demonstrated in the development of the initial model.

For the descriptive information such as "good looking", HOQ appears to be incapable to take such information to the design activity because of the highly subjective nature, as shown in the awkward appearance of the first model. Since the customer's requirement of "good looking" is a common requirement of consumer products, marketing techniques are desired to combine with engineering method to develop a competitive product.

To improve the initial model, the correlation information is applied to modify the weights of measures by using matrix multiplication of Q matric and initial weighs. The modified weights of measures shows that the importance of battery capacity is significantly reduced and the importance of product dimension and mass are increased moderately. The modified weights of measures finally affect the final product concept and specifications by applying proposed decision-making model. The proposed method combines information in HOQs together to generate a reasonable product concept by suggesting an optimal combination of components with the objective of maximizing OPP. By applying the proposed model, the overall product performance can be properly considered rather than partial aspects of a design. Moreover, because the result of the model has been optimized, efforts on evaluating and selecting dozens of concepts can be reduced. Kano's model is an effective tool for identifying customers' preference on shapes, forms and colors of a concept. The applied methods result in a remarkable enhancement for the final design not only in terms of specifications but also perceived quality of the design.

5.2 Research contribution

This research identifies several drawbacks of using HOQ to develop a therapeutic light device. Rethinking the development processes of the first proposed model, three main shortcomings are identified: inefficient use of design information, incapable of concept generation, and implicit perceived design quality. These shortcomings may widely exist in other new product development processes. To improve the first model, three contributions are made as follows:

(1) The correlation information is used among engineering measures quantitatively to modify priorities of measures. This process can provide a more reasonable ranking for measures without oversimplifying or overweighting a measure.

(2) A decision-making model is proposed to generate an optimal concept considering overall design requirements with objective of maximizing OPP. This process can help designers the concept generation with decreasing efforts on concept evaluations and selections.

(3) Kano's model is applied to identify customer preference in shapes, forms and colors of a design to improve the perceived design quality. This process can satisfy a common customer's requirement of "good looking" for products.

5.3 Future work

There are several potential areas for future work.

Firstly, components may not independent each other in some complicated products, which means correlations or technical conflictions may appear. The method may be adapted and refined according to a more complex design situation.

Secondly, performance rating of each component is roughly implemented and estimated by designers. More comprehensive rating methods may lead a more effective result. For example, Fynes investigated the various dimensions of quality performance and relationships [59].

Finally, the alternative product forms, shapes and colors are pre-defined by designers through the morphological analysis. A better method should involve the customers to define their preferred product style. Therefore, hearing more customers' voice is another improvement direction for the further work.

Bibliography

[1]. Sasseville, A. and M. Hébert, Using blue-green light at night and blue-blockers during the day to improves adaptation to night work: a pilot study. Progress in Neuro-Psychopharmacology and Biological Psychiatry, 2010. 34(7): p. 1236-1242.

[2]. Sullivan, L.P., Quality.Function Deployment, Quality Progress. 1986.

[3]. Cohen, L. and L. Cohen, Quality function deployment: how to make QFD work for you. 1995: Addison-Wesley Reading, MA.

[4]. Shai, O., Y. Reich and D. Rubin, Creative conceptual design: extending the scope by infused design. Computer-aided design, 2009. 41(3): p. 117-135.

[5]. Mizuno, S., Y. Akao and K. Ishihara, QFD, the customer-driven approach to quality planning and deployment. 1994: Asian Productivity Organization.

[6]. Prasad, B., Concurrent engineering fundamentals. 1 ed. 1996: Prentice Hall PTR.

[7]. Pugh, S. Concept selection: A method that works. in Proceedings from the International Conference on Engineering Design, Rome, March. 1981.

[8]. Saaty, T.L., What is the analytic hierarchy process? 1988: Springer.

[9]. Hari, A., M.P. Weiss and A. Zonnenshain, Design quality metrics used as a quantitative tool for the conceptual design of a new product. WDK Publications, 2001: p. 413-420.

[10]. Hauser, J.R. and D. Clausing, The house of quality. 1988.

[11]. Prasad, B., A concurrent function deployment technique for a workgroup-based engineering design process. Journal of Engineering Design, 2000. 11(2): p. 103-119.

[12]. Minniti, M., W.D. Bygrave and E. Autio, GEM Global Entrepreneurship Monitor: 2005 Executive Report. 2006: London Bussiness School.

[13]. Yan, W., C.H. Chen and L.P. Khoo, A radial basis function neural network multicultural factors evaluation engine for product concept development. Expert Systems, 2001. 18(5): p. 219-232.

[14]. Reich, Y. and E. Levy, Managing product design quality under resource constraints. International Journal of Production Research, 2004. 42(13): p. 2555-2572.

[15]. Pahl, G., K. Wallace and L. Blessing, Engineering design: a systematic approach. 157 ed. 2007: Springer.

[16]. Wei, X., W. Juan-Li and W. Xiao-Tun. Product Concept Generation and Evaluation based on QFD and Rough Set Theory. in Information Management, Innovation Management and Industrial Engineering (ICIII), 2010 International Conference on. 2010: IEEE.

[17]. Yang, M.C., Observations on concept generation and sketching in engineering design. Research in Engineering Design, 2009. 20(1): p. 1-11.

[18]. Lo, C., K.C. Tseng and C. Chu, One-step QFD based 3D morphological charts for concept generation of product variant design. Expert Systems with Applications, 2010. 37(11): p. 7351-7363.

[19]. Sonalkar, N., A. Mabogunje and L. Leifer, Developing a visual representation to characterize moment-to-moment concept generation in design teams. International Journal of Design Creativity and Innovation, 2013. 1(2): p. 93-108.

[20]. Bloch, P.H., Seeking the ideal form: product design and consumer response. 1995: p. 16-29.

[21]. Luce, R.D. and J.W. Tukey, Simultaneous conjoint measurement: A new type of fundamental measurement. Journal of mathematical psychology, 1964. 1(1): p. 1-27.

[22]. Green, P.E. and V.R. Rao, Conjoint measurement for quantifying judgmental data. Journal of Marketing research, 1971: p. 355-363.

[23]. Johnson, R.M., Trade-off analysis of consumer values. Journal of Marketing Research, 1974: p. 121-127.

[24]. Green, P.E. and V. Srinivasan, Conjoint analysis in consumer research: issues and outlook. Journal of consumer research, 1978: p. 103-123.

[25]. Gustafsson, A., Customer focused product development by conjoint analysis and QFD. 1996: Linköping University.

[26]. Green, P.E. and V. Srinivasan, Conjoint analysis in consumer research: issues and outlook. Journal of consumer research, 1978: p. 103-123.

[27]. Schutte, S., Engineering emotional values in product design. Kansei Engineering in Development, Department of Mechanical Engineering, Linköpings University, Sweden, 2005.

[28]. Grimsæth, K., Kansei Engineering: Linking emotions and product features. Department of Product Design, Norwegian University of Science and Technology, 2005.

[29]. Lee, S., A. Harada and P.J. Stappers, Pleasure with products: Design based on Kansei. Pleasure with products: Beyond usability, 2002: p. 219-229.

[30]. Schütte, S., Designing feelings into products: Integrating kansei engineering methodology in product development. 2002.

[31]. Nagamachi, M. Workshop 2 on Kansei engineering. in Proceedings of International Conference on Affective Human Factors Design. 2001.

[32]. Kano, K.H., et al., How to delight your customers. Journal of Product and Brand Management, 1984. 5(2): p. 6-17.

[33]. Hauser, J.R. and D. Clausing, The house of quality. 1988.

[34]. Browner, C.M., Hearing the Voice of the Customer.

[35]. http://www.robertdyas.co.uk/P~158548~Lifemax-SAD-Therapy-Light.

[36]. http://healing.about.com/od/sad/fr/golite.htm.

[37]. http://news.cnet.com/8301-17938_105-10456661-1.html.

[38]. Chan, L. and M. Wu, A systematic approach to quality function deployment with a full illustrative example. Omega, 2005. 33(2): p. 119-139.

[39]. Khoo, L.P. and N.C. Ho, Framework of a fuzzy quality function deployment system. International Journal of Production Research, 1996. 34(2): p. 299-311.

[40]. Liu, S., Rating design requirements in fuzzy quality function deployment via a mathematical programming approach. International Journal of Production Research, 2005. 43(3): p. 497-513.

[41]. Fung, R.Y., D.S. Law and W.H. Ip, Design targets determination for inter-dependent product attributes in QFD using fuzzy inference. Integrated Manufacturing Systems, 1999. 10(6): p. 376-384.

[42]. Bode, J. and R.Y. Fung, Cost engineering with quality function deployment. Computers & industrial engineering, 1998. 35(3): p. 587-590.

[43]. Schrijver, A., Combinatorial optimization: polyhedra and efficiency. 24 ed. 2003: Springer.

[44]. Gendreau, M. and J. Potvin, Handbook of metaheuristics. 146 ed. 2010: Springer.

[45]. Vose, M.D., The simple genetic algorithm: foundations and theory. 12 ed. 1999: The MIT Press.

[46]. Bies, R.R., et al., A genetic algorithm-based, hybrid machine learning approach to model selection. Journal of Pharmacokinetics and Pharmacodynamics, 2006. 33(2): p. 195-221.

[47]. Kirkpatrick, S., D.G. Jr. and M.P. Vecchi, Optimization by simmulated annealing. science, 1983. 220(4598): p. 671-680.

[48]. Gutin, G., A. Yeo and A. Zverovich, Traveling salesman should not be greedy: domination analysis of greedy-type heuristics for the TSP. Discrete Applied Mathematics, 2002. 117(1): p. 81-86.

[49]. Bäck, T. The Interaction of Mutation Rate, Selection, and Self-Adaptation Within a Genetic Algorithm. in PPSN. 1992.

[50]. Sun, H. Optimizing part machining service combination using simulated annealing. in Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology. 2010: Springer.

[51]. Van Laarhoven, P.J. and E.H. Aarts, Simulated annealing. 1987: Springer.

[52]. Johnson, D.S., et al., Optimization by simulated annealing: An experimental evaluation; part I, graph partitioning. Operations research, 1989. 37(6): p. 865-892.

[53]. Szu, H. Fast simulated annealing. in AIP conference proceedings. 1986.

[54]. Belaziz, M., A. Bouras and J. Brun, Morphological analysis for product design. Computer-Aided Design, 2000. 32(5): p. 377-388.

[55]. Hsiao, S. and C. Chen, A semantic and shape grammar based approach for product design. Design studies, 1997. 18(3): p. 275-296.

[56]. Jones, J.C., Design methods. 1992: Wiley. com.

[57]. Kano, N., et al., Attractive quality and must-be quality. The Journal of the Japanese Society for Quality Control, 1984. 14(2): p. 39-48.

[58]. Berger, C., et al., Kano's methods for understanding customer-defined quality. Center for Quality Management Journal, 1993. 2(4): p. 3-36.

[59]. Fynes, B. and S. De Burca, The effects of design quality on quality performance. International Journal of Production Economics, 2005. 96(1): p. 1-14.