The Hong Kong Polytechnic University

Department of
Industrial and Systems Engineering

THE OPTIMIZATION OF FUNCTION DEPLOYMENT IN DESIGN

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A thesis submitted in partial fulfillment of the requirements for the Degree of Master of Philosophy

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

New Product Development (NPD) is important for companies to retain their competitive advantage, to lead the customers and create a new market. Developing a product with creativity and innovation are the critical factors to make the product successful. Moreover, optimizing a product before launching it to the market will give customers more satisfaction. To address the above issues, this thesis proposed a new product development cycle for innovative product development together with a Function Deployment Model (FDM) to aid conceptual design. The proposed model involves the used of Quality Function Deployment (QFD) techniques to translate customer needs to engineering characteristics. It also uses an Analytic Hierarchy Process (AHP) to prioritize the customer requirements while a Linear Programming (LP) optimization method is used to determine the feasible solution of the design variables amid limited resources. Then, Finite Element Analysis (FEA) and Numerical Optimization techniques are used to optimize the product before launching. To aid the study, a FDM Development Tool system with Graphical User Interface (GUI) was developed for the designers to implement the proposed model easily. A case study of the proposed model on a real life example, called the "Rock Corer" is used, to demonstrate the capability and usefulness of the proposed model. The design was for a multi-function sampling instrument used in the ESA (European Space Agency) Beagle2 Mars Express mission.

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1. INTRODUCTION

1.1 Background

The competition of most products is fierce and demanding in the rapid changing business environment nowadays. Products that merely fulfil customers needs are not sufficient to gain the lion's share of the market. Instead, the manufacturers are expected to create a new market sector and lead the customers to the new market. To create a new market sector, some of the innovative ideas that are unknown amongst the customers must be transferred to the new product. This rule of thumb is subtle and critical for companies that wishes to retain their competitive advantages and continuing the success of their business. Therefore, a new strategy for innovative product development is necessary for service and manufacturing industries. The strategy should take into account creativity and innovation, both of which are drivers for product success in the new market.

The development and introduction of new products on the market has been a challenging activity for many companies. This is due to the changing nature of customer needs, technology, various forms of competition, uncertain business environment, and arduous management strategies. To circumvent the problems of new product development, it requires many factors such as financial and human resources, management tactics, technology advancement, etc. In the last two decades, many researches have concentrated in this area. Although there are extensive research on how to achieve success in product innovation, companies continue to deliver products that fail.

For manufacturers to gain a competitive advantage and successfully create a new market segment for such new products, the need to educate customers is critical. This reality underscores the need for an alternative strategy in product development. This strategy should focus on how creativity and innovation can be transformed into product successes in the market. Considering the high interest placed on innovative product development strategies, very little research has been done to address this particular challenge.

Taking a look at a conventional product development cycle, we can see that such a cycle presents problems, notwithstanding its great importance. In a systematic transformation cycle where the concept of design can be transformed into reality, an optimal design is often not achieved during the design stage. Such a problem emerges when there are contradictions in areas of design strategies, processes and environments. The transformation of customer requirements to engineering characteristics is a key to creating a successful product where the responsibility falls on the design engineer. He is responsible for finding out customer needs and fulfilling customer requirements. When the product has multi-objective criteria, the design engineer will often find it difficult to map requirements to design and find the best compromises, owing to the fact that too many combinations can be derived and the requirements sometimes may be fuzzy in nature. The designer/engineer may not have exact information from the customers because the information obtained are often vague. Moreover, to evaluate these requirements is highly subjective and the accurate meaning will depend upon designer/engineer's experiences. This is the typical situation faced by design engineers during the conceptual design stages of a new product.

Although there are a number of literatures available on new product development, very little presents the overall picture of the product development cycle for innovation and the implementation procedures. Noting the deficiency, this research attempts to propose a new product development cycle, and provides a theoretical framework and implementation details for innovation product design.

1.2 Problem formulation

The design process in a conventional product development cycle is of great importance but also difficult. Firstly, it is difficult to obtain an optimal design during the design stage. Such a problem is emerging when there are contradictions in areas of design strategies, processes, and environments. Therefore, the design engineer plays an important role of transferring customers' requirements into engineering characteristics. He/she is responsible for perceiving the customer needs and fulfilling the customer requirements. Secondly, when the product requires a multi-objective criterion, it is difficult to transfer requirements and find the best compromise to fit the design. This is because various variable combinations can be obtained. This is a common situation faced by the design engineers.

1.3 Objective of research

The purpose of this research is to investigate the following points:

- To develop a theoretical framework for optimal innovation product development.
- To develop a mechanism used for capturing the design requirements and their related mapping into a set of functions that assimilates the Quality Function Deployment matrix.
- To select appropriate design optimization methods that finds the best compromises for engineering design characteristics and for evaluating the impact of the product.

The research scope is mainly focused on the development of a function-based methodology for designing innovative products and the ways of optimizing the designed outcome.

1.4 Contributions of research

The research presented in this thesis contributes to the state of knowledge in the fields of new product development for product innovation. To summarize, there are three contributions of this research:

(1) It offers a conceptual model for designing innovative product.

(2) It demonstrates the effectiveness of the proposed model with a real application.

(3) It selects a suitable optimization methodology to optimize the design.

1.5 Thesis organization

The remainder of the thesis is organized as follows: Chapter 2 provides a detailed literature review on the New Product Development (NPD) and Process; current design conceptual matrix approaches for NPD, method of customer need prioritization and design optimization techniques. Chapter 3 describes the proposed framework of innovation product development cycle, Function development Model (FDM), and product design optimization method used in this research. Chapter 4 gives the implementation details of the proposed model. Chapter 5 and Chapter 6 demonstrate the usefulness of the proposed system model by a case study with the aid of self-developed software of FDM. Finally, discussion, conclusions and recommendations for future development are presented in Chapter 7 and Chapter 8.

2. LITERATURE REVIEW

2.1 New product development and process

New product development encompasses a wide variety of aspects from concept to reality. According to Rosenau (1996), a new product development (NPD) process defines and describes the means by which a company or organization can convert new ideas and innovative concepts into marketable product or services. The NPD process can broadly be divided into four phases, namely, (1) concept exploration; (2) design and development; (3) manufacturing and assembly; and (4) product launch and support.

NPD has been a hot topic over the last 2 decades and there are many models developed by different researchers. They have their own versions of the NPD process.

One of the most widely accepted NPD models is proposed by Booz-Allen and Hamilton (1982). This model presented a comprehensive process to enhance the long-term success of new product development and the stages are shown in Figure 2.1. The product innovativeness could be split into many categories. Kleinschmidt and Cooper (1991) collapsed into three level high (new to world), moderate (new items and existing line or less innovative and new line) and low (modifications).

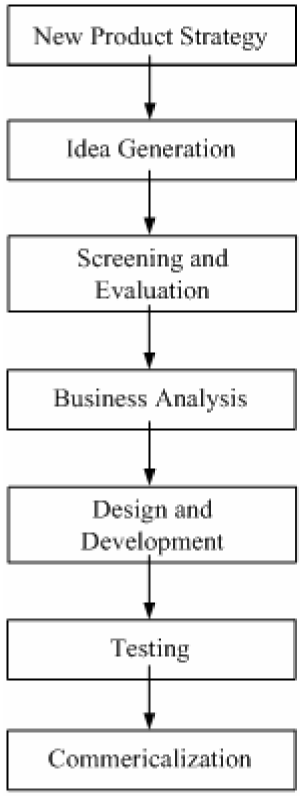


Figure 2.1 Seven stages of new product development

(Booz-Allen, and Hamilton 1982)

Calantone and Benedetto (1998) proposed an integrative model of the new product development process, which is based on technical and market factors for parallel implementation of the new product development process.

Song and Montoya-Weiss (1998), through research and literature review, identified the following six sets of general NPD activities: (1) Strategic planning for integration of product resource and market opportunities; (2) Idea generation and elaboration, and evaluation of the potential solution; (3) Business analysis for converting new product idea into design attributes that fulfil customer needs and desires; (4) Manufacturing development for building the desired physical product; (5) Testing the product itself which includes all individual and integrated components; (6) Coordination, implementation, and monitoring of the new product launch.

Also, Crawford and Benedetto (2006) divides the basic NPD process into five phases: (1) Opportunity identification and Selection; (2) Concept generation; (3) Concept Evaluation; (4) Technical and Marketing Development; and (5) Launch.

Similarly, Jones and Stevens (1999) proposed the NPD process which forms market strategy points of view and mainly concerns the use of marketing techniques for generating the new product idea. They suggested eight stages for their modelled NPD process: idea generation, idea screening, concept testing, marketing strategy development, business analysis, product development, market testing and commercialization.

Cooper (2001) conducted researches of NPD process in different areas of business and products. He established a framework with thirteen different stages of new product development process: (1) Initial screening; (2) Market assessment; (3) Technical assessment; (4) Market Research; (5) Financial Analyses; (6) Product Development; (7) Product testing; (8) Test of Product with Customer; (9) Test Market; (10) Prior production; (11) Business analyses; (12) Production start-up; and (13) Launch to market. This framework provides additional theoretical insights into the nature of products and the evaluation of their success.

Other suggestions on how to successfully lead product innovation include those from Poolton and Barclay (1998) who spelled out 17 critical factors for successful new product innovations, classified into two areas: Strategic and Tactical. Malhotra et al. (1996) proposed a framework for product innovation, which includes four groups: Inception, Feasibility, Realizability and Distributing.

From the above, it is identified that in the NPD process, “innovation” is a key requirement for success (Chapman and Hyland, 2004). The “innovation” herein refers to the creation of a product, service, or process while “product innovation” is the creation of new products. From the literature, there are different authors giving different definitions of a new product innovation (Song and Montoya-Weiss, 1998; Johne, 1985; Shenhar et al., 1995; Walsh and Linton, 2000; Garcia and Calantone, 2002; O’Connor and McDermott, 2004).

Apart from the innovation product development models, there have been a number of generic models for both typical and new product development cycles reported in literature. Cross (2000) offers a strategic approach and a number of tactics as aids for designing a products. It also reviews several other models for product design and development. Pahl and Beitz (1996) provides a systematic approach for product design and define the product design process into four main phases which are (1) product planning and clarifying the task; (2) conceptual design; (3) embodiment design; (4) detail design. Similarly, Otto and Wood (2001) also provide a tool for generic product development model and split it into three phases: (1) understanding the opportunity; (2) develop a concept; and (3) implement a concept.

2.2 Design conceptual matrix approaches for new product design

Conceptual design is the root and primary step of all product design. Since there are usually more than one concept can be mapped to a requirement, concept selection is one of the most critical decision-making exercises during conceptual design process. To make decisions effectively, one normally needs to minimize the possibility of misrepresenting an effective solution and fully consider the different consequences of a decision. To make decisions effectively, there are several major approaches, such as case-based or knowledge-based reasoning, decision tree, and matrix approach, developed for concept evaluation. Amongst these approaches, matrix approach is the most commonly used by design engineers due to its merits of simplicity, effectiveness and efficiency.

2.2.1 Pugh concept selection

There are many conventional screening methods, such as Technology Readiness Assessment (TRA), GO/NO-GO Screening (Ullman, 2003), etc., available for simple concept evaluation. However, for complex cases, Pugh Concept Selection method is generally used. This method is very effective for comparing concepts that are not well refined for direct comparison with the engineering requirements. Basically, it is an iterative evaluation that tests the completeness and understanding of requirements, followed by quick identification of the strongest concept. The procedures of this method are shown in Figure 2.2. It is particularly effective if each member of the design team performs it independently. The results of the comparison will usually lead to repetition of the method, with iteration continued until the team reaches a consensus.

The steps are summarized as follows and illustrated in Figure 2.2:

Step 1 –Select the criteria for comparison. The list of criteria must be developed from the customer needs and engineering specifications. All team members should contribute in making the list. The list then should be debated until consensus is reached.

Step 2 –Select the concepts to be compared. These alternatives should be those that proceed from the concept generation. It is important that all the concepts to be compared be at the same level of abstraction.

Step 3 –Generate the score. A favorite concept should be selected as a datum. All other designs are compared to it relative to each customer needs. For each comparison, the concept being evaluated is judged to be either better than ("+" score), about the same ("s" score), or worse than the datum ("-" score).

Step 4 –Compute the total score. Three scores are generated, the number of plus scores, the number of minus scores and the total. If a concept has a good overall score or a high "+" score, it is important to notice what strengths it exhibits, that is, which criteria it meets better than datum. Same for "-" score. If most concepts get the same score on a certain criterion, examine that criterion closely. More knowledge may have to be developed in the area of the criterion. Or, it may be ambiguous, is interpreted differently by different members.

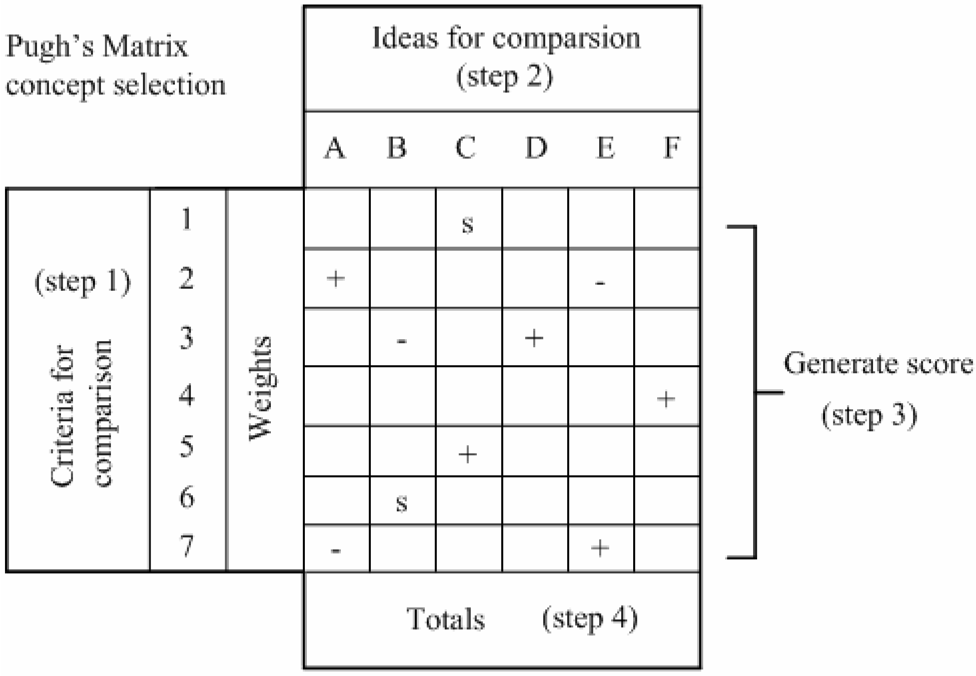


Figure 2.2 Pugh's matrix concept selection

2.2.2 Axiomatic design

Axiomatic design, developed by Suh (2001), is a more recent design methodology different from the conventional conceptual design methods. Its rationale is based on the concept of "There exists a fundamental set of principles that determines good design practice". It is basically a systematic product design model which makes use of the fundamental principles that govern good design practice. In this model, the design outputs associate with 4 distinct domains: the customer domain, the conceptual domain, the physical domain and the process domain. The design process begins in the customer domain with the identification of the customer needs. Then it maps the customer and conceptual domain to identify the functional requirements of the design object. After that, another mapping translates the functional requirements into design parameters, which are the set of properties describing the object in the physical domain. Finally, the physical domain is mapped to the process domain leading to the process variables, which outlines the method to produce the design object. The axiomatic design has many advantages such as reducing lead time, decrease costs and improve organizational competence as it provides: (1) a systematic scheme to decompose the design object into a well defined hierarchy; (2) a set of fixed criteria that is vital to promptly assess the engineering design decisions at any stage of the design process, with a strong focus on the functional requirement independency; (3) an intrinsically concurrent engineering environment which promotes the fast generation of new design solutions. The design process of mapping through domains in axiomatic design is shown in Figure 2.3.

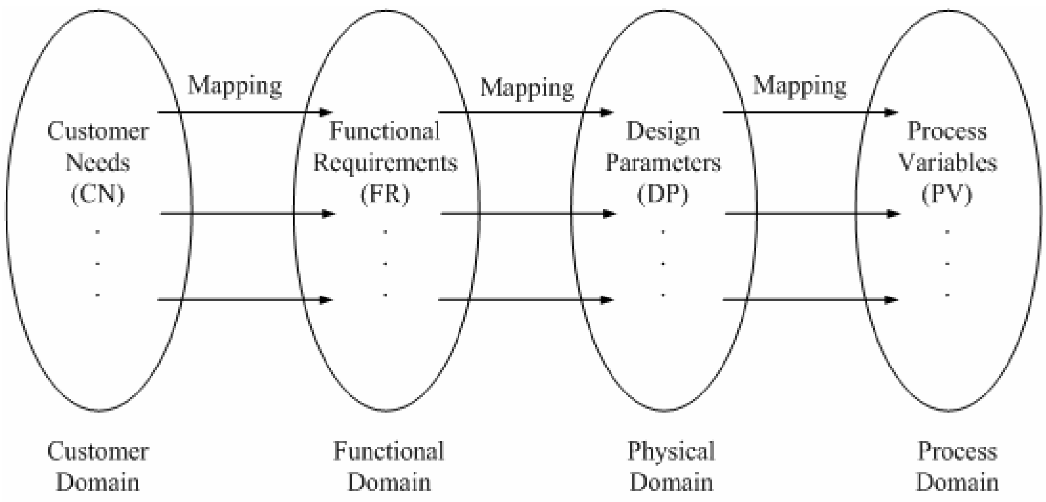


Figure 2.3 The design process of mapping through domains

2.2.3 Quality function deployment

To have a more detailed design including design parameters and process variables, Quality Function Deployment (QFD) is being most widely used method. QFD is originated in 1972 at Mitsubishi's Kobe shipyard site, and then Toyota and its suppliers developed it further for a rust prevention study. The result of using

QFD in Toyota was able to reduce start-up and pre production cost by 60% from 1977 to 1984 (Hauser and Clausing, 1988).

According to Akao (1990), QFD is defined as a mechanism for developing a design quality to satisfy the customer and translating the customer's requirement into product design and development throughout the production stage. It can provide a common language for transferring the qualitative information to quantitative data integrated together.

Upon 1993, Griffin and Hauser (1993) reported that over hundred famous companies are adopted QFD in the US, including Motorola, Hewlett Packard, Xerox, AT&T, NASA, Ford, Kodak and General Motors.

Nowadays, QFD has been widely applying in various areas such as Product Design and Development, Production Planning, Manufacturing and Quality and Service Management (Chan and Wu, 2002).

QFD, a four-phased model, consists of four matrices, each of which focuses on different kinds of mapping. For example, the first matrix in QFD modelling is so-called House of Quality (HoQ), which focuses on mapping the relationship between customers' requirements to engineering characteristics.

From modelling perspective, QFD process can be divided into four phases, each representing with a matrix form. The first phase is to collect customer needs for the product (or customer requirements, customer attributes) called WHATs and then to transform these needs into technical measures (or technical requirements, product design specification, engineering characteristics) called HOWs. The second phase transforms the prioritized technical measures in the first phase into part characteristics, called part deployment. Key part characteristics are transformed in the third phase, called process planning, into process parameters or operations that are finally transformed in the fourth phase called production planning into production requirements or operations. The four phase model is usually depicted in a conceptual form as shown in Figure 2.4.

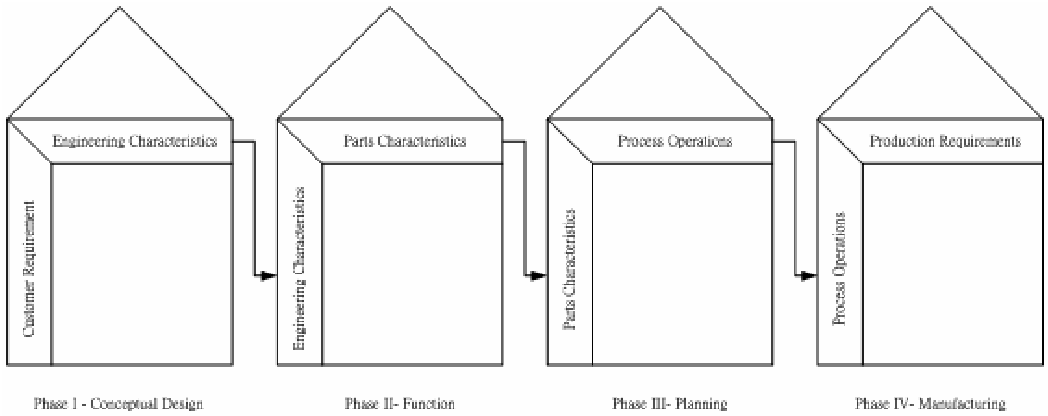
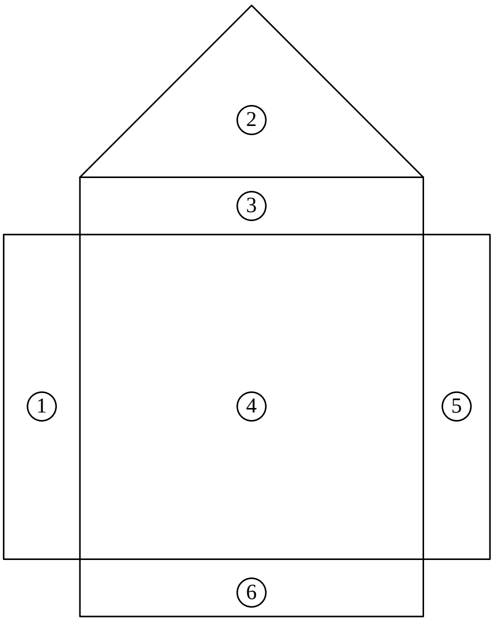


Figure 2.4 The four phases deployment of QFD

The first matrix in QFD is called house of quality (HOQ), which is a kind of conceptual map providing the means for internal planning and communications. Its adaptability to the needs of a particular project or user group is one of its strengths. Figure 2.5 shows the general format used for the HOQ matrix, which includes six major components: (1) Customer requirements, (2) Technical correlation matrix, (3) Engineering characteristics, (4) Interrelationship matrix, (5) Importance weighting and (6) Priorities, benchmarks and targets for technical descriptors.



(1) Customer requirements
(2) Technical correlation matrix
(3) Engineering characteristics
(4) Interrelationship matrix
(5) Importance weighting
(6) Priorities, benchmarks
and targets for technical descriptors

Figure 2.5 The house of quality

The following table shows the summary of functions and obtains methods for each component:

Table 2.1: The summary of functions and obtains methods for HOQ components

Components	**Functions**	**Methods**
1.Customer requirements	Capture customer needs, want, and idea.	By survey, interview, questionnaire and publications.
2. Technical correlation matrix	Provide an information relationship between each of engineering characteristics.	The correlation index is classified into four types. If the relationships of two engineering characteristics are strong, given the mark 9, medium given 3, weak is given 1 and no relationship is given 0.
3.Engineering characteristics	Identify all of the possible solution that can fulfill the customer required function, feature, or idea.	For example: measure the distance, record the data or protect the object, etc.
4.Interrelationship matrix	Relates which engineering	The relationship can be used strong, medium or

	characteristics affect the customers' requirements.	weak symbol to represent the marks 9, 3, and 1.
5.Importance weighting	Weight the importance of the requirements	The important degrees of customer requirements are shown in important weighting.
6.Priorities, benchmarks and targets for technical descriptions	Describes the performance index for design engineers to make a decision which one of engineering characteristics can be achieved in the requirement.	

QFD can help shorten the new product development time, reduce uncertainty of design problem and increase customer satisfaction advantage. However, it is disadvantageous (Park and Kim, 1998; Temponi et al., 1999; Vanegas and Labib, 2001; Chen and Weng, 2003) that QFD is too dependent on: (1) subjectively determine the degree of importance of customer requirements, (2) difficultly translate customer requirements to engineering characteristics, (3) not considering design resources and budget.

To improve the conventional QFD, there are some methods developed including some kinds of extensions and modifications such as Concurrent Function Deployment (CFD) (Prasad, 1996; 2000), TRIZ (Altshuller ,1984), Taguchi Method (Phadke, 1989), Cost-design-parameter Optimization (Iranmanesh et al., 2005), Tolerance Design (Yang and Naikan, 2003). In some cases when the customer requirements are very subjective and unquantifiable, the fuzzy techniques can be used for the decision making (Buyukpzkan and Feyzioglu, 2004).

2.3 Method of customer need prioritization

As is the case in conventional product design and development, resources allocation is a critical problem in new product innovation because customer need is sometimes unlimited and resources are scarce. It is necessary to prioritize customer requirements according to certain metrics. There are many possible solutions reported in literature to resolve resources allocation problem in product design and development. A widely used and promising method is called Analytic Hierarchy Process (AHP) originally developed by Saaty (1980) in the early 1970s in response to the search resource, allocation and planning needs for the military. This method first identifies the key elements (better allocation of resources) based on a well-defined mathematical structure of consistent matrices and their associated right-eigenvector’s ability to generate true or approximate weights. Then it is followed by converting individual preferences into ratio-scale weights that combine to form linear additive weights for the associated alternatives. These resultant weights are used to rank the alternatives and thus assist the decision maker in making a choice or forecasting an outcome. In fact, AHP has been commonly used in QFD for new product design and development and many promising results were obtained in the area of continuous product innovation (Armacost et al., 1994; Cristiano et al., 2000). However, no literature has been found to explore the application of AHP to product innovation with impossible customer requirements. Although encouraging results have been obtained by using AHP with QFD with possible customer requirements, this application may not always work in the case of impossible customer requirements. The reason for this is because those impossible customer requirements filtered by the AHP process. Hence, our proposed model attempts to use AHP in conjunction with both possible and impossible requirements to solve the resource allocation problem. For details of mathematical formulation and implementation of AHP, please refer to (Chuang, 2001).

The use of AHP can be found in the areas of assignment of weights to a set of pre-determined elements and make decision out of several alternatives. In other words, it helps to prioritize (rank) elements in order to identify the key elements (better allocation of resources).

Inspired by the mathematical rigorous in AHP framework that can facilitate prioritization, many researchers have incorporated in QFD framework to improve the conventional QFD limitation.

To improve the conventional AHP, there are some modified versions developed. Armacost et al. (1994) developed a framework for prioritizing customer requirements in QFD, improving industrialized housing design and manufacturing process. Moreover, Wang et al. (1998) reviewed the prioritization matrix method and AHP techniques by a comparison based on three factors: accuracy, difficulty and cost and time needed. Chuang (2001) proposed combines the AHP and QFD approach for location planning and decision to select an optimal location.

2.4 Finite element analysis in engineering design

Nowadays, Finite Element Analysis (FEA) is an indispensable tool based on Finite Element Method (FEM) for solving numerous engineering problems and engineering design optimization. There are mainly two types of problems related to engineering design, i.e. the static and transient problems. The target prototype is a solid model either in two-dimensional or three dimensional. It is widely accepted in many branches of industry. Indeed, it is not a new technique but was first developed in 1943 by R. Courant, who utilized the Ritz method of numerical analysis and minimization of variation calculus to obtain approximate solutions to vibration systems. Since it can simulate the structural integrity, frequency characteristics and temperature distribution, optimal design in terms of payload, strength, shape, size and many other attributes can be found.

Clearing the areas of application and the potential of finite element analysis are enormous. The growth of the technique is attributable directly to the rapid advances in computer technology and computing power, particularly over the last decade. There are many literature reviews on using finite element method to show the results are promising. For example, Wang et al., (2004) used finite element gradient optimization techniques for automobile body rigidity improvement and attained an optimal design which finally increases 4.7% of automobile body rigidity. Wang (2001) adopted finite element analysis for design optimization of rigid metal containers to saving the material cost. Akbulut (2003) proposed using finite element analysis to optimal the car rim design for saving 14.69% weight of the rim. Hardee et al. (1999) linked up one commercial

Computer Aided Design and one of Finite Element Analysis tools for parametrical design optimization.

However, these tools are not integrated in the same platform. These are very difficult for implementation and then still have various conversion requirement and compatibility problems. When the design changes, they require conversion and computation again. This issue may lengthen the time to market.

2.5 Optimization methods for product design

2.5.1 Linear optimization

Product design optimization is a technique widely used to improve a design in order to satisfy a single or multiple desired objective(s) by engineers and designers. The objective usually involves size, weight, shape, rigidity, topology, cost, etc. Optimal design is defined by Papalambros and Wilde (2000) as: "The best feasible design according to a pre-selected quantitative measure of effectiveness". Since the design is usually undertaken to fulfil a need, the grade of success is primarily based on the satisfaction of the need and the cost of implementation. Methods deployed for an engineering design optimization problem can be classified in two kinds of methods: numerical design optimization and experimental design optimization.

Experimental design optimization (e.g. design of experiments-Taguchi's Method) based on the number of samples for testing the various design parameters to find an optimal solution (Kunjur and Krishnamurty, 1997). It requires physical prototype and experimentation to set up equipments. For example, sensors are required to capture signals for testing different functionalities of product in areas of drop testing. The experimentation approach is expensive. Further it is very difficult and ineffective to simulate the problem if the product is very complex. Therefore, it is recommended to use numerical design optimization method for finding the optimal design in this research.

Numerical design optimization can be divided into linear and non-linear types. Both of linear and non-linear problems can be solved by numerical design optimization, which is based on mathematical computation to search optimal value within the available resources and constraints.

With respect to linear optimization, Linear Programming is commonly used, which has long been accepted as an approach for the optimal selection. Its cost functions are linear in terms of the variables. It is widely used in different areas such as design resource allocation, selection and planning (Akgunduz, et al., 2002). Most common known factors such as design budget considered in early product development process can also be solved by LP for finding the optimal planning.

2.5.2 Non-linear optimization

General formulation of nonlinear design optimization problems are given as follows:

Find the vector $x = x_1, x_2 \ldots x_n$ of design variables to

Minimize a cost function

$$f(x) = (x_1, x_2 \ldots x_n) \qquad (2.1)$$

Subject to the h_k equality constraints

$$h_k(x) = (x_1, x_2 \ldots x_n) = 0$$

$$k = 1, \ldots, k \qquad (2.2)$$

Subject to the g_j inequality constraints

$$g_j(x) = (x_1, x_2 \ldots x_n) \geq 0$$

$$j = 1, \ldots, j \qquad (2.3)$$

$$x_i^{(U)} \geq x_i \geq x_i^{(L)}$$

$$i = 1, \ldots, N \qquad (2.4)$$

Kress (2000) employing Finite Element Method and numerical optimization techniques to optimal the thickness of flywheel with accepted stress distribution. However, the research only used two-dimensional model for analysis. Lindby et al. (1999) presented using parametric CAD system for optimizing Three-dimensional model structure and using suspension control arm as an example to reducing 57.4% weight compare with the initial design.

With respect to nonlinear optimization, we can employ numerical methods (e.g. gradient-based searching, simulated annealing, genetic algorithms, etc.). Gradient based algorithms use the "direction of improvement" information in order to achieve a fast and accurate convergence towards the optimal solution. Simulated Annealing is an optimization method applicable to searching for the global minimum of the cost function. The mother of Simulated Annealing optimization methods originate from the Monte Carlo method proposed in 1953 by Metropolis et al. (1953). The first proper Simulated Annealing optimization method was investigated by Kirkpatrick et al. (1983) in 1983. Geman and Geman (1984) first proved a necessary and sufficient condition for the convergence of the algorithm to the global minimum in 1984. A genetic algorithm (GA) is an evolutionary optimization approach which is an alternative to traditional optimization methods. GA is most appropriate for complex non-linear models where location of the global optimum is a difficult task.

Amongst the currently available non-linear optimization algorithms, gradient based algorithm is the most classical and promising. In the application of product design optimization, the Feasible Direction Method has been one of the most popular numerical design optimization methods applied to finite element analysis (Vanderplaats, 1984). The method was first proposed by Zoutendijk (1960).

3. METHODOLGY

3.1 Framework of innovation product development cycle

To facilitate the development of innovation product, attempts are being made in this thesis to work out a complete and analytical product development cycle model for innovation from the practical engineering perspective especially the design engineers and R&D manager. As a design engineer, he/she needs to perform the following duties during the initial stage of product development process:

- Communicate with the customers and acquire the customer requirements accurately and completely without filtering.
- Apply the existing and/or new knowledge, technology and techniques which can be used to make the product.

As a R&D manager, he/she needs to perform the following duty during the whole product development process:

- Manage the whole product development process in order to make the product successful.
- Make the decisions during the new product development cycle.

The proposed model assumes to work in situation where customer needs or desires is well defined or bare of fuzziness. If the needs or desires are quite fuzzy that makes the customer requirements unarticulated, they cannot be supported with the current version of the proposed model.

The foundation of the proposed model, as shown in Figure 3.1, is based on the generic new product development approach developed by Ulrich, 2004. It consists of five stages: Concept Development, System-Level Design, Detail Design, Testing and Refinement, and Production Ramp-Up.

Figure 3.1 Conventional new product development cycle

The proposed model begins with the requirements phase in terms of customer desires. It is similar to Concept Development stage in identifying customer needs and establishing specifications. Followed by the second phase, A set of Functionalities phase, the product functionalities are defined. This phase is similar to the System-Level Design stage. The third phase – a set of attribute phase, characterizes the all design attributes, which is similar to the Detail Design stage. The forth phase – Product Prototyping phase, performs the design optimization and functional testing, which is similar to the Testing and Refinement stage. The fifth phase – Final Product phase, determines the manufacturing technology and production tools, which is similar to the objective of Product Ramp-up stage. The last phase – Validation phase in which the product functionalities is validated against customer satisfaction and expectation. This phase seems not provided in the conventional new product development approach but is essential for the new product success.

Figure 3.2 shows the proposed model, basically a loop consisting of 6 phases, (1) Customer desires in terms of requirements phase, (2) A set of functionalities phase, (3) A set of attribute phase, (4) Product prototyping phase, (5) Final product phase and (6) Validation phase. Each individual phase of the product development cycle is explained in the subsequent sections.

The major differences between the proposed new product development cycle and the conventional new product development cycle are as follows:

1. The proposed cycle has 6 phases with a phase on design optimization whereas the conventional cycle only has 5 phases and does not include design optimization.
2. The proposed cycle has a systematic and analytic model to effectively transform customer needs and wants to customer requirements, whereas the conventional cycle does not.
3. The proposed cycle uses function-based approach to converts the user requirements into product whereas the conventional cycle only uses requirement-based approach to develop new product.
4. The proposed cycle is validation by customers before product launch whereas the conventional cycle does not.

Compared with the currently used models, this model is integrated, more practical, and easier to implement than those currently available and have the following beneficial features:

(1) Product optimization is considered in this model. It can solve the problem of reworking the design when using the conventional models without consideration of optimization;

(2) Acceptance tests by the market are performed in this model to gauge market reaction to the product before launching. It helps to prevent the poor market issue when using the conventional models;

(3) Common language platform is provided in this model to effectively represent intangible idea and minimize the communication issue (e.g. misinterpretation) commonly found in the conventional models between customers and designers;

(4) A new innovative product generated by using the FDM approach can create a new market instead of product enhancement in the existing market when using the conventional models, since the FDM consider all the possible and impossible customer needs and wants but the conventional models only consider the possible ones;

(5) With the specially designed customer requirement to product function transformation mechanism in the FDM, customer desire can be predicted more easily

and accurately than the conventional models.

(6) The proposed model can provide a shorter time-to-market than the conventional models because most processes can be performed automatically with computer and little human intervention is needed.

Since the techniques and tools used in the proposed model are well established and proven, it is best for inexperienced users to obtain the highest chance of success.

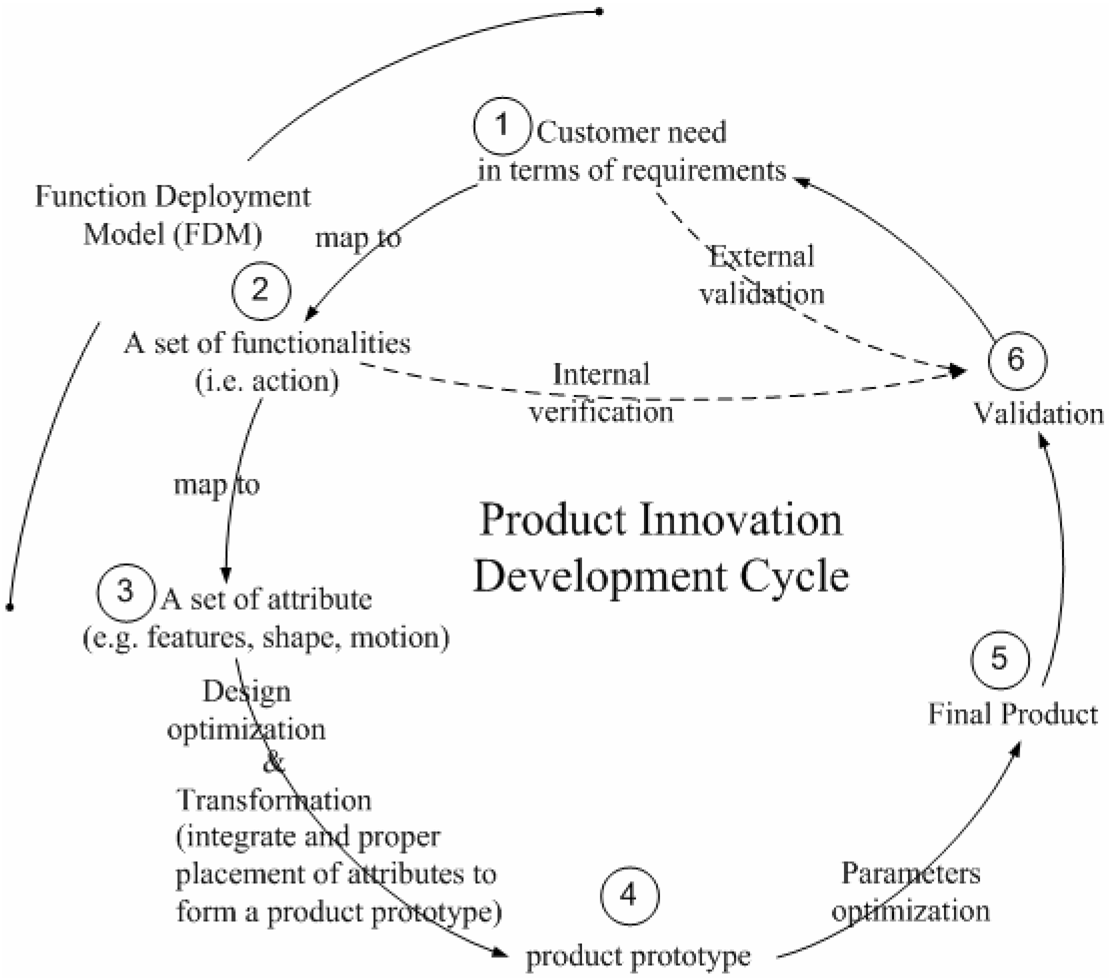


Figure 3.2 Product innovation development cycle

3.1.1 Customer-desires-in-terms-of-requirements phase

Since customer needs or desires are the origin and motivation of the whole innovation product development process, customer requirements must be acquired at the beginning. To make a product marketable, the requirements should be identified as thorough and accurate as possible. There are many ways to acquire the customer requirements in the new product development process. Several methods, such as focus groups and team brainstorming (Sandelands, 1994; Temponi et al., 1999; Griffin and Hauser, 1993), questionnaires (Abdul-Rahman et al., 1999; Mclaurin and Bell, 1993), past records and publications, are widely used to capture the desire of customers. Focus groups are in-depth, qualitative interviews with a small number of carefully selected people. This method is effective in bringing out spontaneous reactions and ideas of users but it can only assess what customers say they do and not the way customers actually operate the product. Team brainstorming is a most widely used and efficient method of creative thinking and shared problem solving in which a group of members with different degrees of expertise and different backgrounds such as design, management, engineering and marketing can spontaneously contribute ideas. The main disadvantage is that it lacks spontaneity. Questionnaire is an effective and low cost method for large sampling size. The disadvantage is that it does not collect the spontaneous idea from the users and the resulting data may apt to misleading if the questions are ambiguously phrased. Since these methods have their advantages and disadvantages. Past records and publications are usually used to develop new product similar to some established product but with a different scope. The advantages of using them are mainly less time consuming and low cost. However, the resulting data may be insufficient and too dependant on previous findings. To prevent misuse, they should be carefully selected with respect to the actual context of application.

After acquiring customer requirements, the next step is to identify the possible and impossible wants and needs of customers in terms of requirements and refine the requirements according to the production feasibility. To meet this objective, there are many well developed methods available such as Forced Choice Exercise (Newman, 1998), Requirements Taxonomy (Gershenson and Stauffer, 1999; Morris and Stauffer, 1994), conjoint analysis (Pullman et al., 2002), and Analytic Hierarchy Process (AHP) (Saaty 1980). Forced Choice Exercise is a method to select the most customer pleasing options out of a pool under constrained resources by a series of exercises conducted by different selection groups. This method is easy to implement and decision process is fast. Nevertheless, it may be subjective since the decision is made depends on the preference of a limited group of people. Requirements Taxonomy is a method that classifies those customer requirements that impact product design. In this method, a taxonomical cube consists of four requirement types, namely end user requirements, corporate requirements, regulatory requirements and technical requirements, is constructed. End-user requirements include the expectations of the end users about the capabilities of the product, aesthetics and usability. Corporate requirements encompass business issues and product lifecycle issues. Corporate issues are of concern to the individuals involved in the related engineering and non-engineering disciplines. These individuals are commonly the source for the requirements. Regulatory requirements include safety/health, environmental/ ecological, disposal and/or political issues. This taxonomy allows for an organized method of gathering, managing, and retrieving the requirements. Generic in nature, this taxonomy provides a template with which to create taxonomies for a given product within a given company or industry. However, this method may not be appropriate for every application. When creating a taxonomy for use with a specific product or family of products, it is necessary to create a unique taxonomy that takes into account the specific needs of the product. Conjoint analysis is a feature based approach to pairwise compare the most preferred features to profit maximizing features. It effectively helps marketers to determine the most desired level of each feature included in the analysis with the aid of choice simulators which allow designers to explore the impact of different design decisions on sales, profits and cannibalization. However, it seems that the method is a black box and may not be transparent enough to the marketers. If a more analytic, objective and transparent method is required; AHP can be used to prioritize the requirements. The AHP can be used to measure the relative degree of importance of each customer requirement by comparing each pair of customer requirements to indicate the level of relative importance of each member in each pair with the others. In addition, it is a powerful tool that can be used to make decisions in situations involving multiple objectives. Details of this method will be presented in Section 3.2.2.

To minimize or eliminate the subjectivity of data collected from the customers throughout the FDM processes, more than one of the data collection methods should be used by the designers. In addition, the designer should apply one than one selection methods to work out the customer requirements for the final product.

3.1.2 A-set-of-functionalities phase

Based on the customer requirements collected and prioritized in the previous phase, a set of functionalities can be defined by mapping the customer requirements with the functionalities. There are many methods developed to map the basic functions to customer requirements such as (i) Function Analysis System Technique (FAST)/Function-Means Tree (Akiyama, 1991), (ii) Functional Decomposition Tree, or (iii) Axiomatic Design (Suh, 2001).

FAST is a mapping technique which simply expresses all the functions in verb-noun combinations to describe complex systems. This technique uses the How-Why diagram to describe how a system function is performed and explain the reason of that function performed. With this logic rule and graphical displays of linkage of function dependencies, customers and technical people with different technical backgrounds can effectively communicate such that the basic, low order and high order functions can be determined. Functional Decomposition Tree is a top down approach to break down the overall functionality of a system into a number of functions and the relations are represented as a tree diagram.

Apart from the fore-mentioned methods, a well regarded, powerful method is developed to generate creative and innovative function ideas. It is the Theory of Inventive Problem Solving (TRIZ) (Saulovich, 2002), developed by Genrich S.

Altshuller, which uses 40 Inventive Principles and 39 Engineering Parameters to generate ideas for problem solving. This method can be implemented by a stepwise approach including (1) identification of the specific problem; (2) formulation of the problem with the use of Prism of TRIZ; (3) searching for related contradicting inventive principles and engineering parameters; (4) looking for analogous solutions with the use of Table of Contradictions and adaptation to the specific solution. The TRIZ approach to problem solving is illustrated in Figure 3.3.

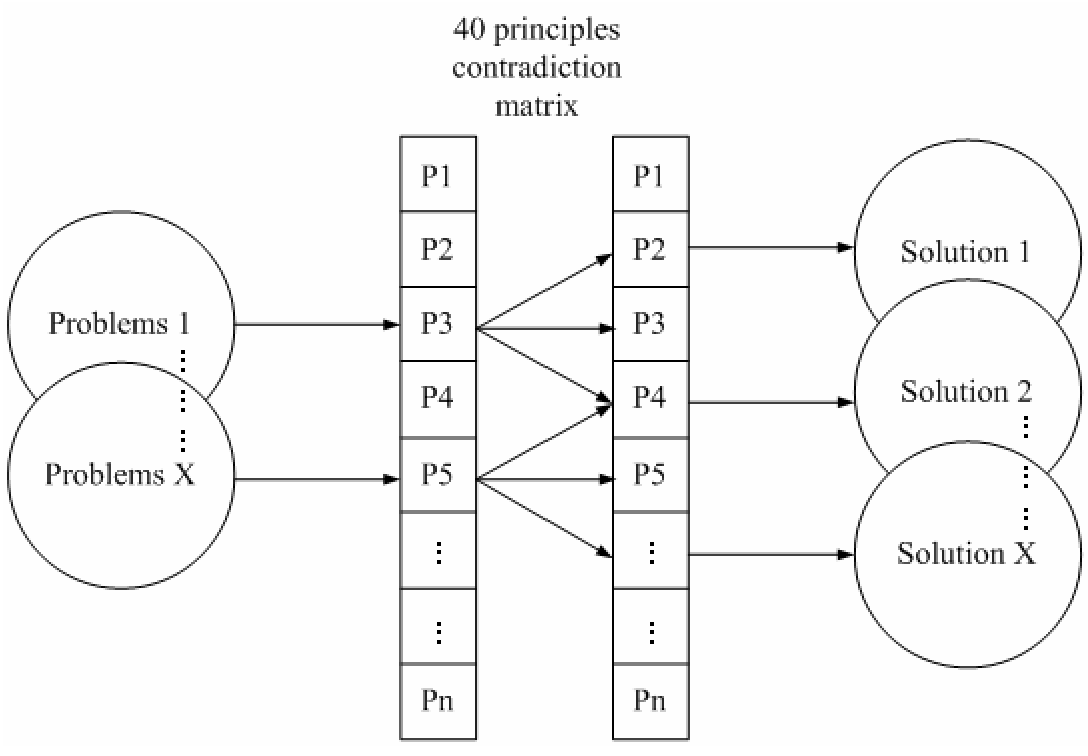


Figure 3.3 TRIZ approach to problem solving and innovative idea generation

In contrast to the conventional method of mapping the customer requirements into functionalities, we propose a new concept called Function Deployment Model, where the function is defined as a motion that can perform an action/operation. In the proposed method, the form of a function is treated as an action and represented as "verb + ing" such as drilling. To allow freedom in design and effective communication, the verb is a lexical vocabulary. The advantage of considering functions in new product development in this form is that it can fill the knowledge gap between customers and engineers from different backgrounds (a) to identify each requirement clearly and precisely; (b) to make functions understandable to anyone; and (c) to make the innovation process easier in starting up with abstract ideas and crude concepts. The detailed discussions on the function deployment model are given in Section 3.2.1.

3.1.3 A-set-of-attribute phase

With the set of functionalities defined in the previous phase, design attributes as form, shape, size or material property is characterized and blended in this phase to make the product perform its functionalities. Since the resources are limited but design attributes are enormous and some of them may be more important than others, resources optimization is necessary to determine the optimal selection of the attributes. Linear Programming (LP) is a recommended technique for general resources optimization problem which is linear in nature. After that, the design attributes can be mapped to product functionalities by using the modularity method. The modularity method breaks down the overall product architecture into a number of modules. A module is defined as a physical structure that has a one-to-one correspondence with a functional structure which is analogous to a Lego brick. Each module can be combined to form a modular product that accomplishes an overall function. According to Ulrich (2004), there are three types of pattern for component or module connection. They are namely slot, bus and sectional, see Figure 3.4. For slot, each of the component interfaces is specifically of different type from the others and it cannot be interchangeable.

For bus, each of the component interfaces is common and can be interchangeable. It is easy for relocation and expansion when there is not enough spacing. Also the assembly sequence is not limited. For sectional, all of the interfaces are the same type and can be as chained in more than one interface entry.

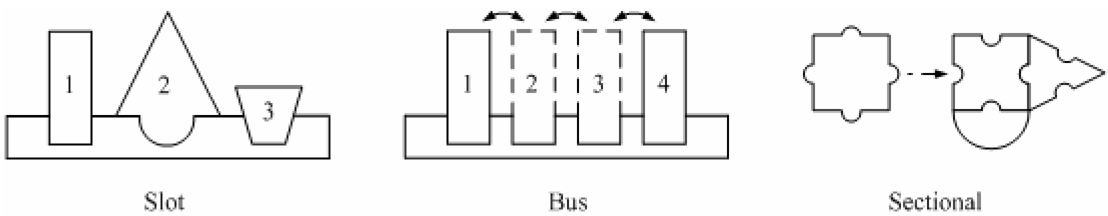


Figure 3.4 Three types of function modularity

In this stage, there are too many design concepts for a Pugh concept selection technique to compare. Since the attribute mapping process is inherently complex, Computer Aided Design (CAD) tools can be used for integrating and simulating the design attributes and the virtual product in computational space.

3.1.4 Product prototyping

In this phase, product prototype for design optimization and functional testing is generated according to the design attributes assigned in the last phase. Nowadays, rapid prototype (RP) is widely used for product design in the initial design stage (Chua et al., 1999). It can also reduce time-to-market, reduce costly design errors, reduce design cycle time and refine conceptual ideas. After prototyping, parameters optimization is performed to find the optimal design. Parameters optimization is a process by which design parameters of the physical product attain their respective optimal values. Finite Element Analysis (FEA) and a gradient-based optimization method are recommended to reduce computational complexity and simulate the product behaviors. Design optimization problem from different fields of engineering can be transcribed into the standard model.

3.1.5 Final product phase

With the optimal design found in the previous phase, appropriate production tools and manufacturing technology are selected in this phase. Since innovation products may involve special requirements, there may be a need for non-conventional tools or fabrication technology such as micro/nano-technology and ultra-precision machining.

3.1.6 Validation phase

In the validation phase as shown in Fig.3.2, there are two audits (dotted lines), namely internal verification and external validation. The internal verification is a test by academic exercise while an external validation examines the customer preference by survey to test potential customer expectation and responses. The verification ensures that the final product satisfies or matches the original design. It is a low-level checking to make sure the manufacturer build the product right. The validation checks that the product design satisfies or fits the intended usage. It is a high-level checking to make sure the manufacturer built the right product. The internal verification always comes before external validation. If validation phase is successful, production can be started and the product can be launched in the market..

If tests have shown that the functionalities of the product are higher than customer expectation, then the product is acceptable for production. Otherwise, the validation process should be redone to check whether any of the customer requirements are redundant.

3.1.7 Modifications of conventional new product development cycle

Basically it is similar to the conventional new product development (NPD) cycle as shown in Figure 3.1 but has some new modifications introduced to improve the new product development cycle success of product innovation. The modifications are made in two aspects. On one hand, it introduces a new function deployment model based on the promising and highly regarded Quality Function Deployment (QFD) concept to translate customer needs to engineering characteristics in conceptual design. The proposed model provides a common language platform between the customer, designer and engineer to communicate both the tangible and intangible idea efficiently and effectively. Details of the proposed function deployment model will be addressed in Section 3.2. On the other hand, it integrates the proven decision making technique, Analytic Hierarchy Process (AHP), to prioritize customer requirements in resource optimization. This technique offers a clear rationale to help the production planner set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered under the limited design constraint. Details of the design optimization method will be discussed in Section

3.2.3. This versatile framework can be easily implemented and applicable to many different areas, such as domestic appliances, industrial equipment, software, etc. and is robust under the frequently changing business conditions nowadays.

3.2 Function deployment model

To successfully apply the framework of innovation product development, a novel and analytical model, called Function Deployment Model (FDM) is proposed. It consists of the first three phases - described in Section 3.1.1 to 3.1.3 - of the product development cycle for innovation. To apply the proposed mathematical formulation for product innovation, it is assumed that customer requirements are articulated such that the comparison matrix coefficients are well defined. If the customer requirements are fuzzy, the proposed method may not be valid and modification on the comparison method is necessary.

Although this model shows some similarities with the first phase of the Quality Function Deployment (QFD) method (Hauser and Clausing, 1988; Akao, 1990; Chan and Wu, 2002) widely employed in new product design and development, there are many differences in terms of model structure, method of customer needs prioritization and scope of application. The differences in model structure and method of customer prioritization will be presented in Section 3.2.1 and Section 3.2.2 respectively.

3.2.1 Model structure

Compared with the structure of the model applied in the first phase of QFD, our model includes two correlated matrixes while that of QFD has only one matrix to transform the customer's requirements and needs into a set of engineering characteristics during the conceptual design phase. The matrix used in QFD is called House of Quality (HOQ) which is a kind of conceptual map providing the means for internal planning and communications between customers and design engineers. Citing from the abundant successful cases published in literature (Schmidt, 1997; Hsiao, 2002; Hsiao and Liu, 2005), there is no doubt that HOQ is one of the most effective, useful and promising ways in new product design and development in the continuous sense. However, it seems that no literature has been found so far in applying HOQ to new product innovation. This proposed FDM model attempts to use the concept of HOQ matrix while revising it to fit the new product innovation. The modifications can be summarized in two aspects. Firstly, a new concept of "function characteristics" as described in Section 3.1.2 is introduced. It serves as a common language platform between customers and design engineers to enhance the efficiency and effectiveness of their communications, and accurately represents customer needs. Secondly, instead of a single HOQ matrix used in QFD, two design matrixes are used in FDM. Figure 3.5 shows the general format of the two correlated matrices, which includes seven major components: (1) Customer requirements, (2) Function characteristics, (3) Design parameters (4) Correlation matrix, (5) Interrelationship matrix, (6) Relative Importance and (7) Design Optimization. Compared with the six major components of the HOQ used in QFD, an additional link of "function characteristics" is introduced to shorten the new product development time, reduce subjectivity and uncertainty of the design problem, and increase customer satisfaction.

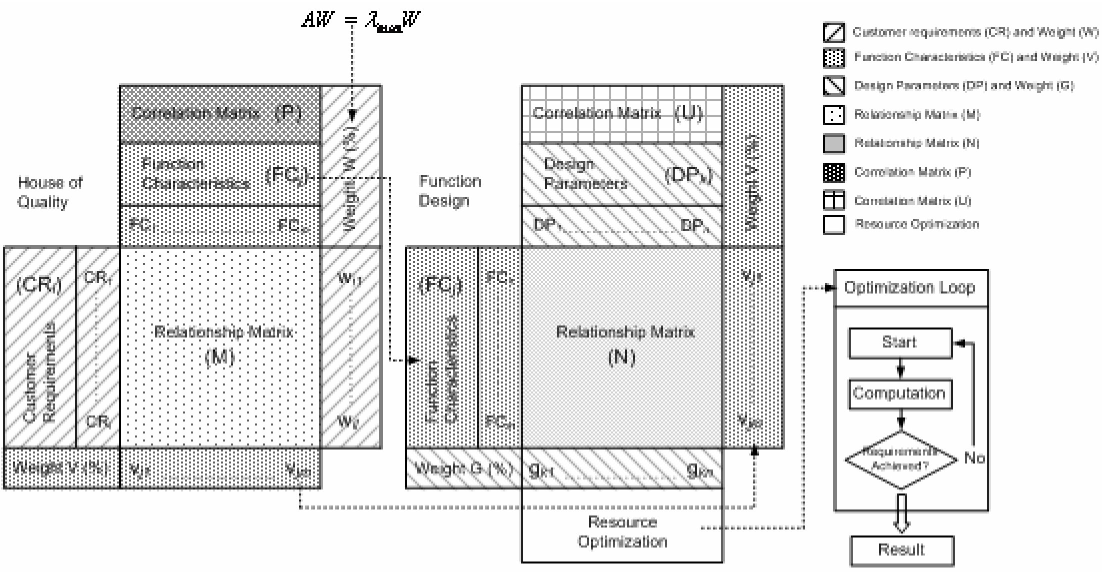


Figure 3.5 The proposed Function Deployment Model.

3.2.2 Method of customer need prioritization

3.2.2.1 Analytic hierarchy process

In the case of conventional product design and development, resources allocation is a critical problem in new product innovation because customer needs are sometimes unlimited and resources are scarce. It is necessary to prioritize customer requirements according to certain metrics. There are many possible solutions reported in literature to resolve resources allocation problem in product design and development. In our proposed model, one of the widely used and encouraging methods called Analytic Hierarchy Process (AHP) is adopted. This method first identifies the key elements (better allocation of resources) based on a well-defined mathematical structure of consistent matrices and their associated eigenvector(s) to generate true or approximate weights. Then it is followed by converting individual preferences into ratio-scale weights that combine to form linear additive weights for the associated alternatives. These resultant weights are used to rank the alternatives and thus assist the decision maker in making a choice or forecasting an outcome. In fact, AHP has been commonly used in QFD for new product design and development and many promising results were obtained in the area of product innovation (Armacost et al., 1994, Cristiano et al., 2000). However, no literature has been found to explore the application of AHP to new product innovation. Although encouraging results have been obtained by using AHP with QFD in product enhancement, this application may not always work in the case of new product innovation. The reason for this is because those seemingly impossible customer requirements filtered by the AHP process in product innovation may be the essential elements in new product development. Hence, our proposed model attempts to use AHP in conjunction with both possible and impossible requirements to solve the resource allocation problem in new product innovation. For details of mathematical formulation and implementation of AHP, please refer to Chuang (2001).

3.2.2.1.1 Procedures of AHP

The AHP consists of the following major steps:

1) Creation of a decision hierarchy by breaking down the problem into a hierarchy of decision elements (criteria and alternatives).
2) Assessment of the relative importance of criteria by pair-wise comparison using a scale such as the follows:

Table 3.1: The pair-wise comparison judgement

Verbal judgement	Degree of importance
Extremely more important	9
Very strongly more important	7
Strongly more important	5
Moderately more important	3
Equally important	1
Intermediate values	2,4,6,8
Inverse comparisons	Reciprocals

For instance, if criterion X is judged to be “very strongly more important’ than criterion Y, a score of 7 is given. The reciprocal values of those reported in table are used to express the opposite judgements. If criterion Z is moderately less important than criterion W, a rating of 1/3 is assigned. The pairwise comparison data are organized in the form of a matrix (A) and are translated into the absolute importance weights (Wj).

$$A \cdot W_j = K \cdot W_j \quad (3.1)$$

where:

A = the pairwise comparison matrix;

W_j= the vector of the absolute values of the importance weights;

K = the highest eigenvalue in matrix A.

3) Pairwise assessment of the decision alternatives with respect to criteria, using the same procedure as described in step 2. The output of this step is the absolute ratings of the alternatives for all criteria;

4) Calculation of the overall suitability ratings (priorities) of the decision alternatives, weighing the absolute ratings for each criterion with the corresponding absolute importance weights.

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3.2.3 Design parameters optimization

During the design phase of a practical product innovation process, usually more than one conceptual design exists and a trade-off between different resources and requirements has to be made. In order to find the best design, a set of objective function(s) and design constraints or criteria should be set up. Optimal design is defined by Papalambros and Wilde (2000) as: "The best feasible design according to a pre-selected quantitative measure of effectiveness". Since the design is usually undertaken to fulfill a need, the grade of success is primarily based on the satisfaction of the need and the cost of implementation. In most optimization problems of the conceptual design, the objective function can be represented by a linear equation in terms of the input parameters and is considered to be linear. In such case, Linear Programming (LP), which is widely accepted as the most effective approach for linear optimization in design resource allocation, selection and planning (Lee and Hsu, 2004). Details of the mathematical formulation for design optimization in the proposed FDM model can be found in Section 3.2.4.

3.2.4 Mathematical formulation of FDM

Notation for the Function Deployment Model are as follows:

CR_i	=	number of customer requirements, $i = 1,\ldots,l$
FC_j	=	number of function characteristics, $j = 1,\ldots,m$
DP_k	=	number of design parameter attributes, $k = 1,\ldots,n$
S	=	overall customer satisfaction,
A	=	pairwise comparison matrix between CR_i,
P	=	correlation matrix between FC_j,
U	=	correlation matrix between DP_k,
M	=	interrelationship matrix between CR_i and FC_j,
N	=	interrelationship matrix between FC_j and DP_k,
R	=	product dot matrix between CR_i and FC_j,
T	=	product dot matrix between FC_j and DP_k,
B	=	total budget for criteria fulfillment,
c_k	=	the cost of committing one resource unit to each improvement ratio of DP_k, $k = 1,\ldots,n$
$\lambda_{\max}$	=	the maximum eigen-values,
W, w_i	=	relative importance of CR_i, $i = 1,\ldots,l$
V, v_j	=	relative importance of FC_j and the number of j in FC_j,
G, g_k	=	relative importance of DP_k and the number of k in DP_k,

x_k, $x_k^{(U)}$, $x_k^{(L)}$ = the improvement ratio of DP_k, upper limit and lower limit of ratio, $k = 1,\ldots,n$

l_k, $l_k^{(U)}$, $l_k^{(L)}$ = the value of DP_k, upper limit and lower limit of DP_k, $k = 1,\ldots,n$

Figure 3.5 shows the proposed function deployment model used to guide the design engineer for function deployment and design tradeoffs during the conceptual stage. It includes three stages, house of quality, function design and design resource optimization. The first stage is applied in the conceptual design, which includes customer requirements CR_i, function characteristics FC_j, interrelationship matrix M, correlation matrix P, relative importance of customer requirements W and relative importance of function characteristics V. The importance weighting of each customer requirement can be determined by using the Analytic Hierarchy Process (AHP) method as follows:

$$A \cdot W = \lambda_{\max} \cdot W \tag{3.8}$$

where $0 < w_i < 1$, $\sum_{i=1}^{l} w_i = 1$, and V can be expressed as

$$V = \frac{RW}{\|RW\|_1} \tag{3.9}$$

where $0 < v_j < 1$, $\sum_{j=1}^{m} v_j = 1$, while R is the normalization for eliminating the cause of the calculation error. Its suggested form is described in the following equation:

$$R_{ij} = \frac{\sum_{k=1}^{n} m_{ik} p_{kj}}{\sum_{j=1}^{n} \sum_{k=1}^{n} \left| m_{ij} p_{jk} \right|} = \frac{(MP^T)_{ij}}{\sum_{j=1}^{n} \left| (MP^T)_{ij} \right|} \tag{3.10}$$

The second stage is used for function design. It includes function characteristics FC_j and design parameters DP_k, interrelationship matrix N and correlation matrix U, and relative importance weighting of design parameters G.

$$G = \frac{TV}{\|TV\|_1} \tag{3.11}$$

where $0 < g_k < 1$, $\sum_{k=1}^{n} g_k = 1$ and T is similar to R in equation (3.10) which is used for normalization, while its corresponding form can be described by the following equation:

$$T_{jk} = \frac{\sum_{j=1}^{n} n_{ik} u_{kj}}{\sum_{j=1}^{n}\sum_{k=1}^{n} |n_{ij} u_{jk}|} = \frac{(NU^T)_{jk}}{\sum_{k=1}^{n} |(NU^T)_{jk}|} \tag{3.12}$$

The last stage of the model is design optimization, which is placed on the right hand bottom part of the map-plan of the model. It is used for determining the optimal value of each design parameter in the form of a linear programming problem. The design optimization section includes three elements, objective function, constraints, and variables. They are formulated as follows:

Maximize

Overall customer satisfaction for requirements (x_1, x_2…, x_k),

Subject to

Total design budget constraints (B),

Minimum and Maximum improvement ratio of design parameters (x_k.)

The other constraints may be added by design engineers according to the product into the above formulation as appropriate. Each element of the design optimization will be discussed as follows:

Objective Function

The objective of this model is to maximize the overall customer satisfaction within the available resource. It is equivalent to finding the optimal values of each parameter in the feasible solution. It can be expressed as:

Maximize

$$S_{(x_k)} = \sum_{i=1}^{n} g_k x_k \qquad (3.13)$$

where g_k is computed from equation (3.11) and x_k is the improvement ratio of $DP_{k.}$ Illustration of the application of the objective function will be illustrated in the case studies of Section 5.2 and 6.2.

Constraints and Variables

Subject to design constraints in equation (3.14)

$$\sum_{k=1}^{n} c_k x_k = c_1 \cdot x_1 + c_2 \cdot x_2 + \ldots + c_n \cdot x_n \le B \qquad (3.14)$$

and minimum and maximum improvement ratio of design parameters in equation (3.15). The design constraint refers to the costing of each requirement c_k (e.g. material cost, tooling cost, development overhead, production cost, manpower cost, etc.) and the customer satisfaction x_k for the requirement is given by the range:

$$x_k^{(U)} \ge x_k \ge x_k^{(L)} \qquad k = 1, \ldots, n \qquad (3.15)$$

where $x_k^{(L)} = 1$, and $x_k^{(U)} = \frac{l_k^{(U)}}{l_k^{(L)}}$ (3.16)

Since in some applications, the objective is to minimize a target quantity (e.g. cost) but in other applications, the objective is to maximize the target (e.g. strength), the starting value should be considered separately. For maximization, it should start from the lower limit whereas for minimization, it should start from the upper limit.

Situation 1: Larger is better (maximization), starting from $x_k^{(L)} \rightarrow x_k^{(U)}$

Situation 2: Smaller is better (minimization), starting from $x_k^{(U)} \rightarrow x_k^{(L)}$

<u>Solution</u>

$$l_k = x_k \cdot l_k^{(L)} \qquad k = 1, \ldots, n \tag{3.17}$$

Where l_k is the optimal value of design parameter

3.2.5 Procedures of the FDM model

For implementation of the FDM model, there are total of seven steps, as seen in Figure 3.6. The procedures of each step can be described as follows:

Step 1: Obtain customer possible needs and impossible needs in terms of requirements by survey, interviews, publication, or technical report.

Step 2: Function deployment - translate function characteristics FCs by using “verb + ing” form to represent the function to generate the ideas for satisfying CRs.

Step 3: Prioritize the customer requirements using AHP method which includes possible and impossible requirements and the pairwise comparison judgement as shown in Table 3.2. Then, calculate and normalize the degree of important in each of the requirements CRs, by using equation (3.8).

Step 4: Build the House of Quality (HoQ) model.

(4a) Assign the relationship matrix between CRs and FCs. The relationship can be given the marks 1, 3, 9 to represent the relationship as weak, medium and strong respectively, while mark 0 represents no relationship.

(4b) Assign the correlation matrix between FCs. The correlation can also be given the marks 1, 3, 9 to represent the correlation as weak, medium and strong respectively, while mark 0 represents no correlation.

(4c) Calculate the importance weighting of each FCs in equation (3.9) and normalization R_{ij} by using equation (3.10).

Step 5: Design parameters – translate functions characteristics FCs to design parameters DPs. Each design parameter is a quantitative variable and in terms of unit for measurement.

Step 6: Build Function Design model.

(6a) Assign the relationship matrix between FCs and DPs. The relationship can be given the marks 1, 3, 9 to represent the relationship as weak, medium and strong respectively, while mark 0 represents no relationship.

(6b) Assign the correlation matrix between DPs. The correlation can also be given the marks 1, 3, 9 to represent the correlation as weak, medium and strong respectively, while mark 0 represents no correlation.

(6c) Calculate the importance weighting of each DPs by using equation (3.11) and normalization T_{jk} by using equation (3.12).

Step 7: Design resource optimization. Define the objectives, constraints and parameters by using LP to find the optimal value that satisfies the customers.

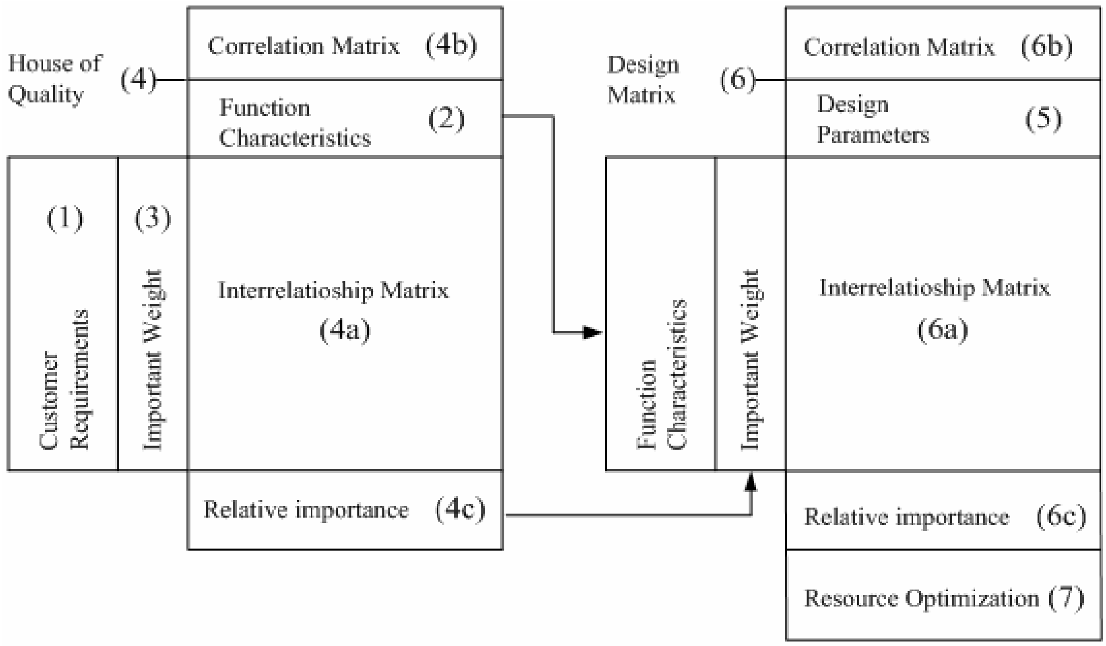


Figure 3.6 The implementation procedures of function deployment model.

3.3 Product design optimization

Since the proposed FDM is mainly used to optimize the model in terms of functional requirements, the outcome model may need to be optimized in terms of the physical size, shape, weight, etc. For example, a notebook may have very powerful functions but its size may be too large or its weight too heavy which cause inconvenience to the users. To further improve the functional model in these considerations, Finite Element Analysis (FEA) can be used. With FEA, an optimized physical model can be obtained. As a result, the final product can be more competitive functionally and physically, and brings higher satisfaction to the customers. There are many algorithms developed for physical quantities optimization and the most common is numerical optimization algorithm.

3.3.1 Numerical optimization algorithm used

Feasible Direction Method, which is one of the most widely used numerical optimization algorithm in FEA (Vanderplaats 1984) software due to its incomparable merits of easy to implement and computational less expensive. In this paper, the product model optimization algorithm is based on Feasible Direction Method which is used to achieve the goal and search for optimal result. The detail implementation procedures of the method, please refer to Zoutendijk (1960).

This chapter presents a new product development cycle for innovation product with detailed description of the procedures. Also, it proposed a new analytic model, FDM, to generate conceptual design of innovation products. Optimization of all the design parameters is considered in the model so that the design is optimized.

4. IMPLEMENTATION OF PROPOSED SYSTEM MODEL

4.1 Model architecture

In order to successfully implement the proposed methodology, a modular system model is proposed. It consists of 3 modules, namely Function Deployment Model (FDM) Module, Solid Modeler Module and Design Analysis and Optimization Module. The whole system is implemented in Windows© platform and using the commercially available software including Matlab© as a mathematical library, SolidWorks as a CAD modeling tool, and Cosmosworks as a Finite Element Analysis (FEA) package. Architecture of the proposed system is shown in Figure 4.1.

For the FDM Module, a Graphical User Interface (GUI) is built for the design engineer to interact with the algorithm development tool. The GUI is written in Visual Basic (VB) language. It links to algorithm development tool by using Microsoft Component Object Model (COM) technology.

For the Solid Modeler Module and Design Analysis and Optimization Module, third party commercial software of SolidWorks and Cosmosworks are used respectively. SolidWorks is one of the widely used CAD modeling software to convert the conceptual design into functional design. Cosmosworks is an FEA software used to optimize the functional design. Implementation details of the modules will be presented in the following sections.

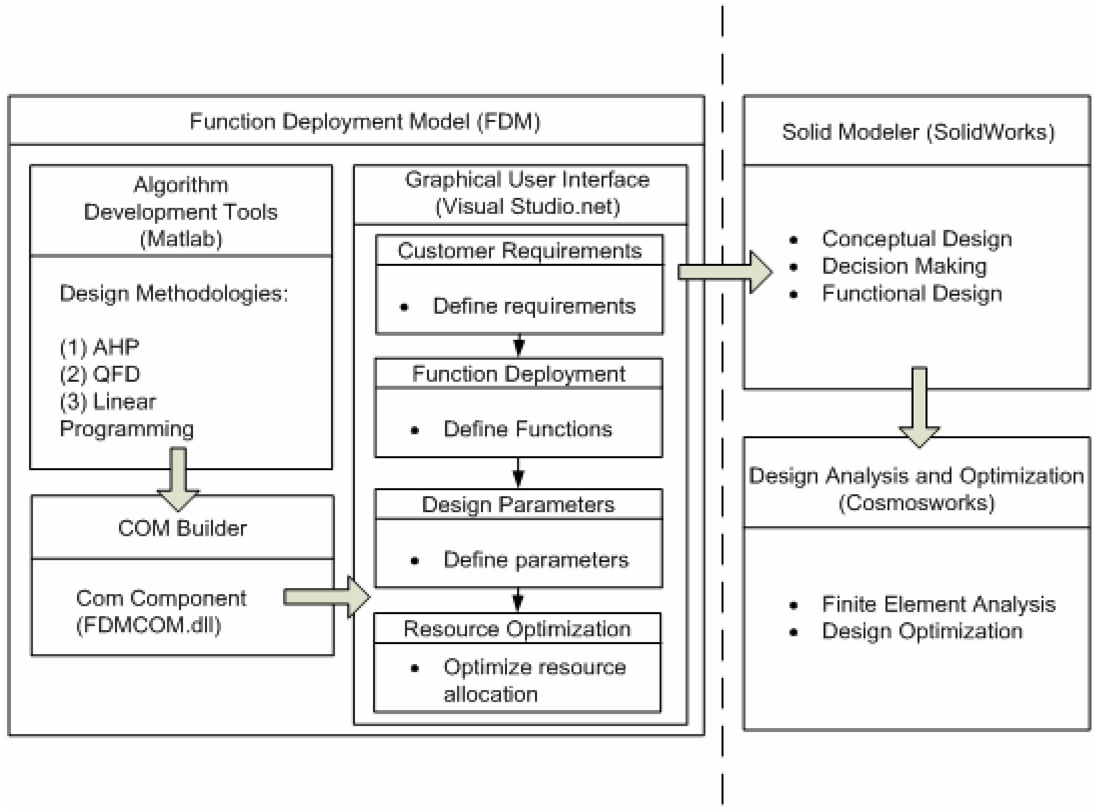


Figure 4.1 Architecture of proposed system model

4.2 FDM module

In the FDM Module, a program called FDM Development Tool is proposed. It is divided into three parts:

1) Algorithm Development Tool,

2) COM Builder and

3) Graphical User Interface.

In the part of Algorithm Development Tool, Matlab was used as a computational library to calculate the results of the three design methodologies: AHP, QFD and linear programming. The main source coding of the tool is shown as follows:

(1) Customer Requirements

```
function [w] = cr(C)
%Open the M-file named "cr.M" in Matlab to input Pairwise comparison matrix C

[V,D]=eig(C);
%Find eigenvalues D and eigenvectors V of matrices C


w=V(:,1)/norm(V(:,1),1);
%calculates several different types of matrix for normalization form and calculates the output Relative important of Customer Requirements w
```

(2) Function Characteristics

```
function [v] = fd(M,P,w)
% Open the M-file named "fd.M" to input interrelationship matrix M, correlation matrix P and Relative important of Customer Requirements w


r=M*P';
%r is the product dot matrix between Customer Requirements (CR) and FC Function Characteristics (FC)


R=[r(1,:)/norm(r(1,:),1);
r(2,:)/norm(r(2,:),1);
r(3,:)/norm(r(3,:),1);
r(4,:)/norm(r(4,:),1);
r(5,:)/norm(r(5,:),1)];


v=R*w/norm(R*w,1)
%calculates several different types of matrix in normal form and output Relative important of Function Characteristics v
```

(3) Design Variables

```
function [g] = dp(N,U,v)
% Open the function file named "dp.M" to input interrelationship matrix N, correlation matrix U and Relative important of Function Characteristics v

t=U2*P2';
%t is the product dot matrix between FC and DP
```

```
T=[t(1,:)/norm(t(1,:),1);
t(2,:)/norm(t(2,:),1);
t(3,:)/norm(t(3,:),1);
t(4,:)/norm(t(4,:),1);
t(5,:)/norm(t(5,:),1)];

g=T*v/norm(T*v,1)
%calculates several different types of matrix in normal form and output Relative important of Design Parameters g
```

<u>(4) Resource Optimization</u>

```
function [x] = lp(f,A,B,LB,UB)
% Open the function file named lp.M file to input coefficients values of A, B, Lower Bound LB and Upper Bound UB


x=linprog(-f,A,B,[],[],LB,UB,[])
%solve linear programming problem and find the optimal value (min) of output x
```

The COM component is a back end part which links up the input from end user with the Algorithm Development Tool. With a front end Graphical User Interface, end user can interact with the Algorithm Development Tool.

The MATLAB COM Builder is an extension to the MATLAB Compiler which enables developers to automatically convert MATLAB applications to Component Object Model (COM) objects. Developers can use MATLAB to perform modeling and analysis and convert the models to ready-to-use COM objects. These objects can be readily integrated with any COM-based application. The independent COM object from the MATLAB application can be called from Visual Basic, C/C++, Microsoft Excel, or any other COM-compliant technology.

Using MATLAB COM Builder to create a COM component requires a sequence of the following four steps.

(1) Creating a Project

(2) Managing M-Files and MEX-Files

(3) Building a Project

(4) Packaging and Distributing the Component

For further information about the application of MATLAB COM Builder, please refer to (LePhan, 2004). In the proposed system, a COM component object called FDMCOM.dll is created and can be called by the specially designed GUI. For details of the source code, please refer to Appendix. This object is used for processing the input data of customer requirements, functions, and parameters sections from the GUI and returned the computed values in resource optimisation section by the algorithms of AHP, QFD and Linear Programming in the proposed FDM.

Microsoft Visual Studio 6.0 software was used to build a Graphical User Interface (GUI) for user interaction. The GUI was divided into four sections: 1) customer requirements section to define all requirements of the customers, 2) Function Deployment section to define all functions to be provided in the design, 3) Design Parameters section to define all parameters of the design, 4) Resource Optimization section to optimize resource allocation. The structure of Function Deployment Model Module is shown in Figure 4.2

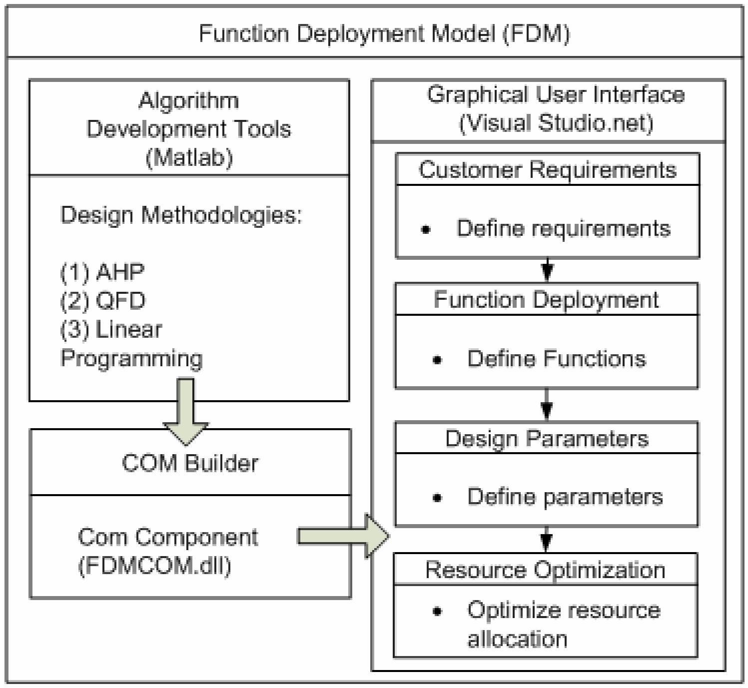


Figure 4.2 The structure of Function Deployment Model Module

4.2.1 A guide to using FDM development tool

The FDM Development Tool is developed as a computer program which guides the end user to go through the FDM step by step from inputting necessary data to generating result. Figure 4.3 shows the detailed workflow of FDM Development Tool.

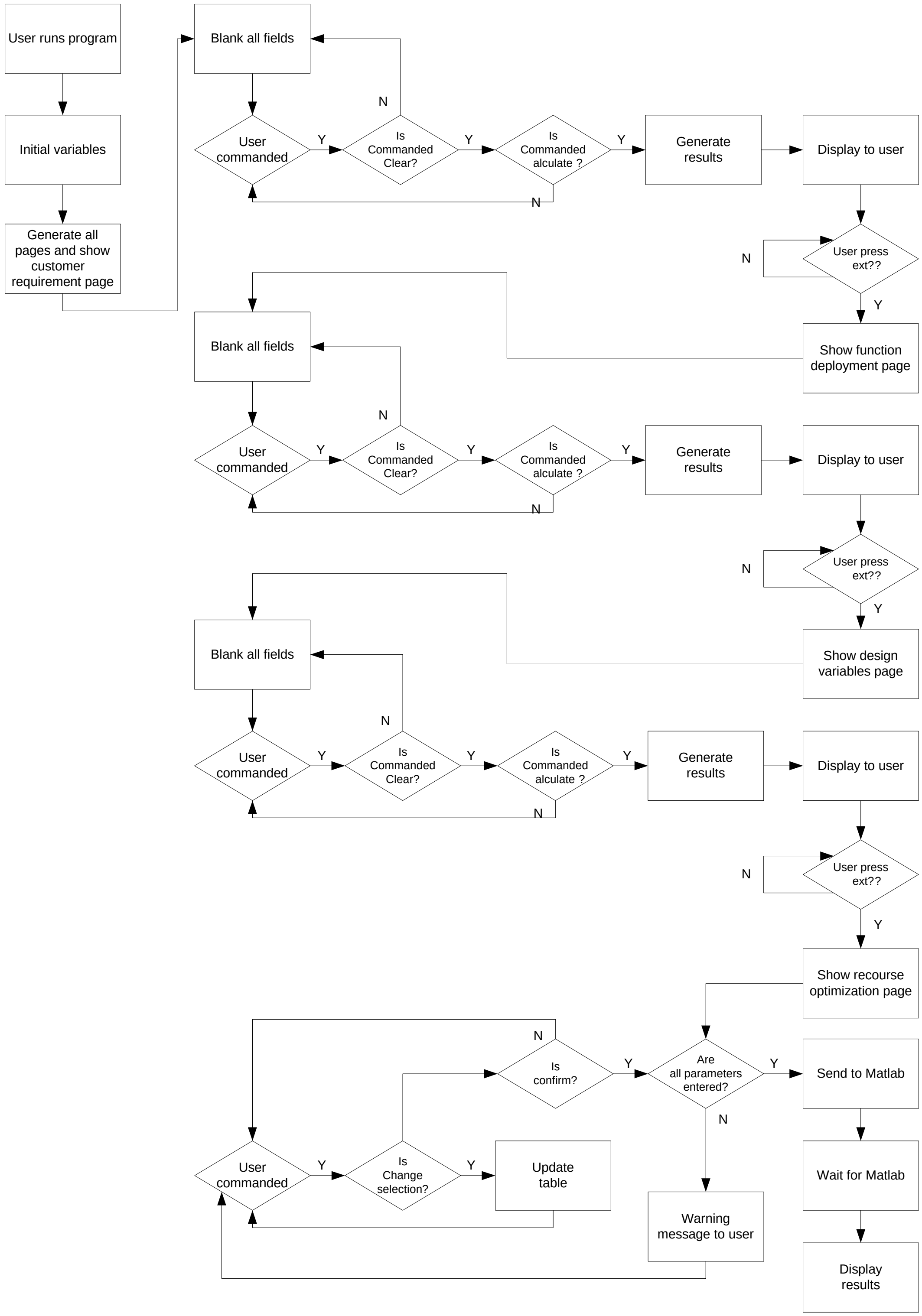


Figure 4.3 The flowchart of FDM

A GUI interface was designed to facilitate the usage of the proposed methodology. The interface of the GUI was shown in Figure 4.4. The GUI designed contains four spreadsheets:

1) Customer requirement,

2) Function deployment,

3) Design Variables,

4) Resource optimization.

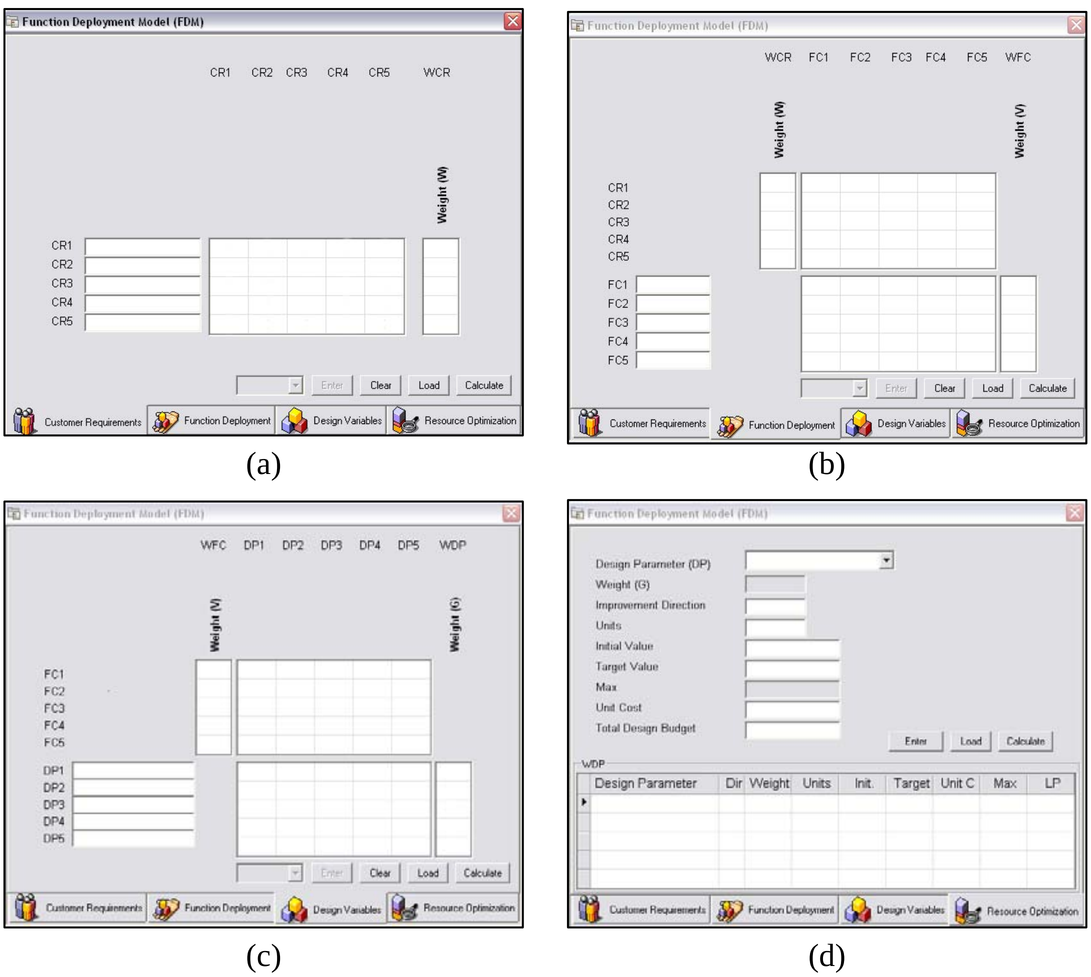


Figure 4.4 GUI interface of FDM module (a) customer requirements; (b) function deployment; (c) design variables; (d) resource optimization

The data should be entering stepwise from the left to the right for correct calculation and the overall procedures for using FDM are described as follows:

Step 1: Click the first spreadsheet named "customer requirements" on the left hand-side. Input all customer requirement in the boxes located in the left portion of the spreadsheet.

Step 2: Assign marks to each requirement and click "enter" to store the marks. If the user want to clear the data entered, click on the "Clear" button to empty the marks and enter again. Repeat the steps until all marks are inputted and stored.

Step 3: Click the button "Calculate" for weight calculation. The weighting of each customer requirement will be calculated and display in the column called "Weight (W)" The highest value in the column interprets the highest importance of the requirement.

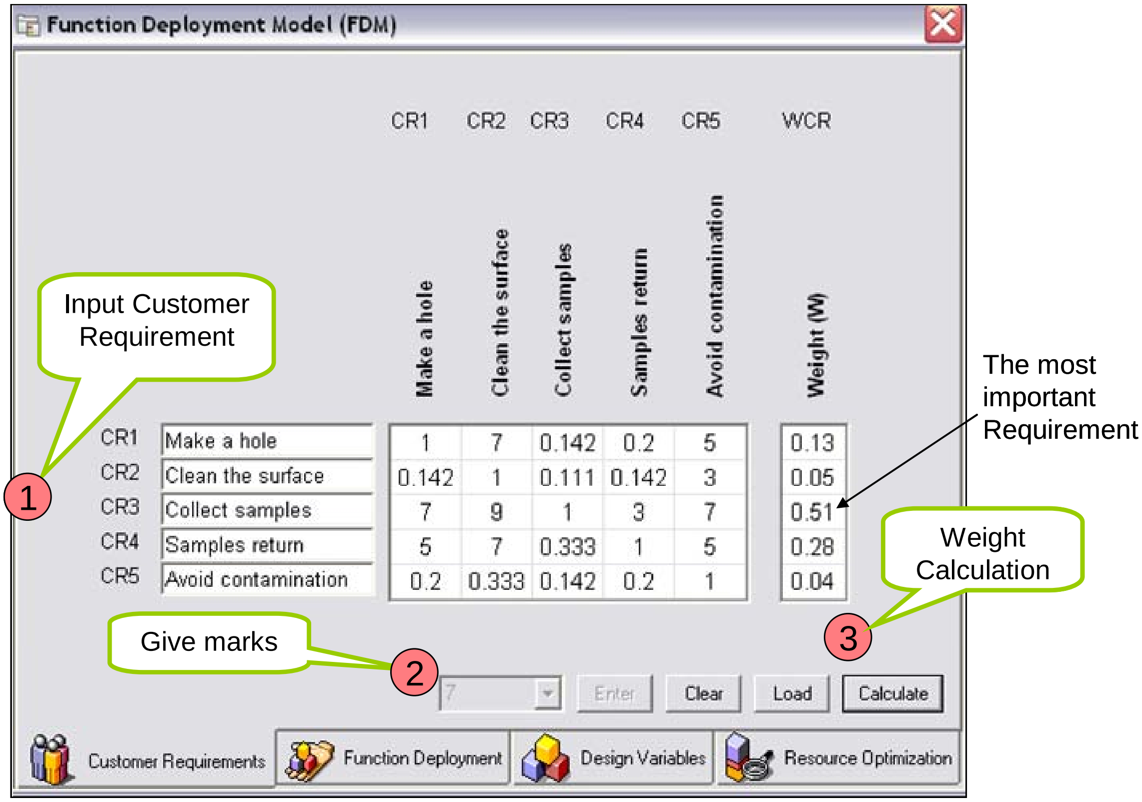


Figure 4.5 Steps 1-3 of FDM-GUI

Step 4: Click on the second spreadsheet "Function Deployment". The layout of the spreadsheet is illustrated in Figure 4.6. The weighting of each requirement calculated in the first spreadsheet is shown on the top left corner. Input the product function in the boxes provide in the left- bottom portion of the spreadsheet.

Step 5: Give marks to each product function and click "enter" to store the value. Repeat the step until all marks stored.

Step 6: Click the bottom "Calculate" to calculate the importance of each product function. The importance of each FC is shown in the right-bottom portion. The highest value interprets the highest importance of the Product function.

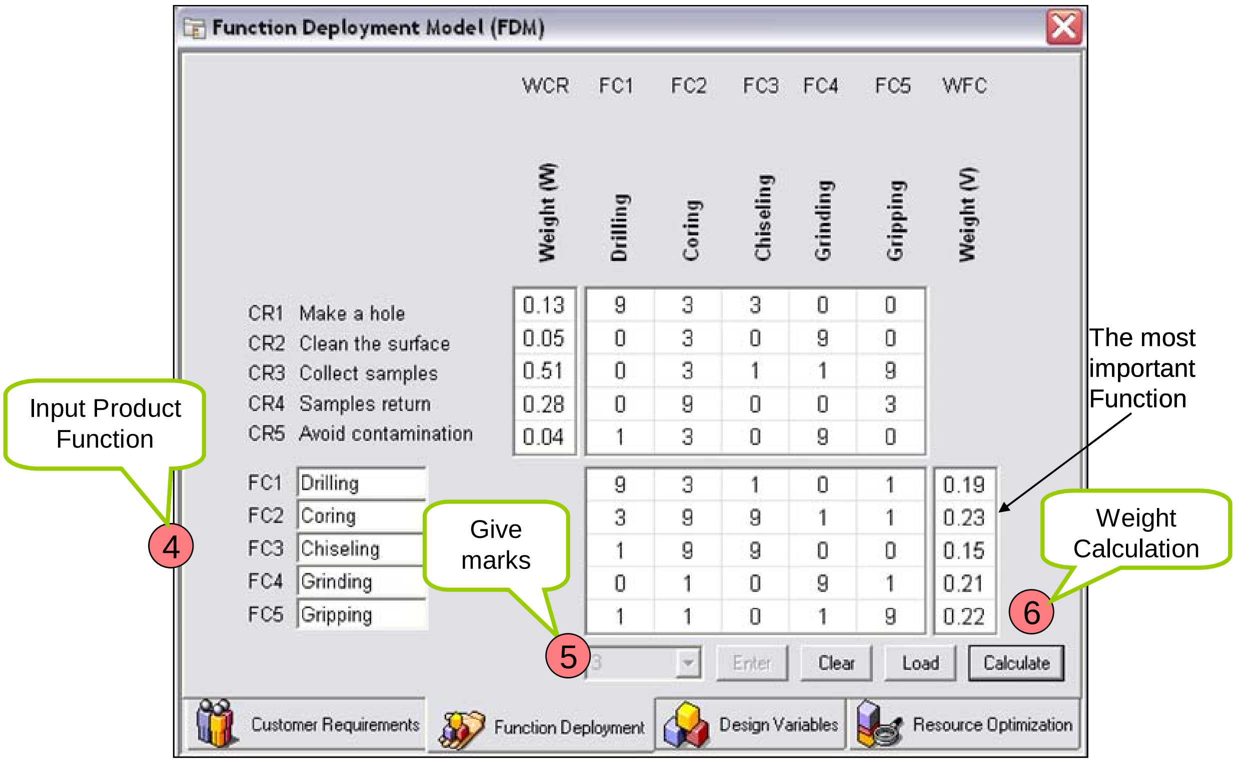


Figure 4.6 Steps 4-6 of FDM-GUI

Step 7: Click on "Design Variables" spreadsheet and input the design variables.

Step 8: Give marks to each design parameters and click "enter" to store the value. Repeat the step until all marks stored.

Step 9: Click the bottom "Calculate" to calculate the weighting of each design parameter.

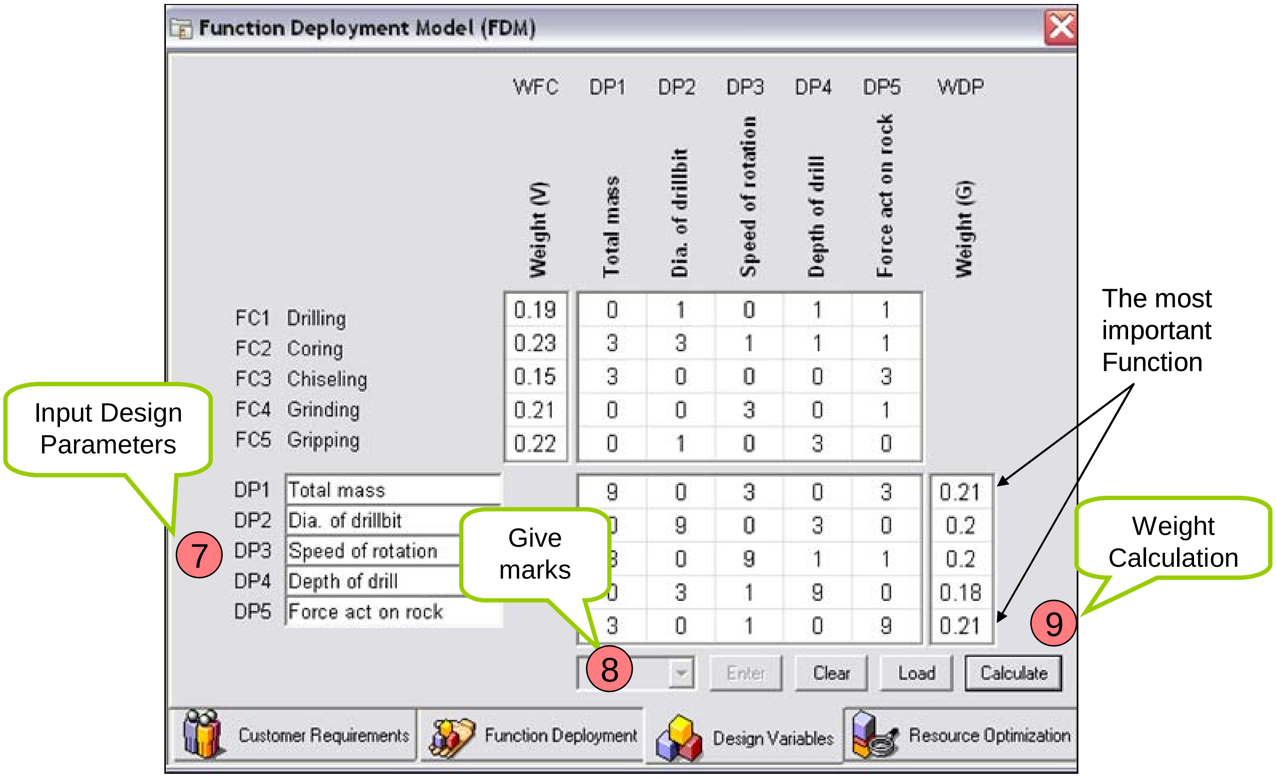


Figure 4.7 Steps 7-9 of FDM-GUI

Step10: Click on the final spreadsheet "Resource optimization". Select ONE design parameter from the pull down menu located at the top. The Weight (G) calculated at the previous spreadsheet will be shown in the relevant box.

Step 11: Input all necessary data in the boxes provided. Indicate the improvement direction in the third column where 'up' means to maximum the value and 'down' means minimum the value. Enter Units, Initial Value, Target Value, Unit cost and total design budget of the parameter in the box provided. The maximum improvement ratio (Max) will be shown in relevant box automatically. After inputting the information for that design parameter, click "enter" to store it. Repeat the step until all necessary data of each parameter are entered.

Step 12: Click "Calculate" to calculate the optimized improvement ratio by using Linear Programming. The result will show in the column named "LP".

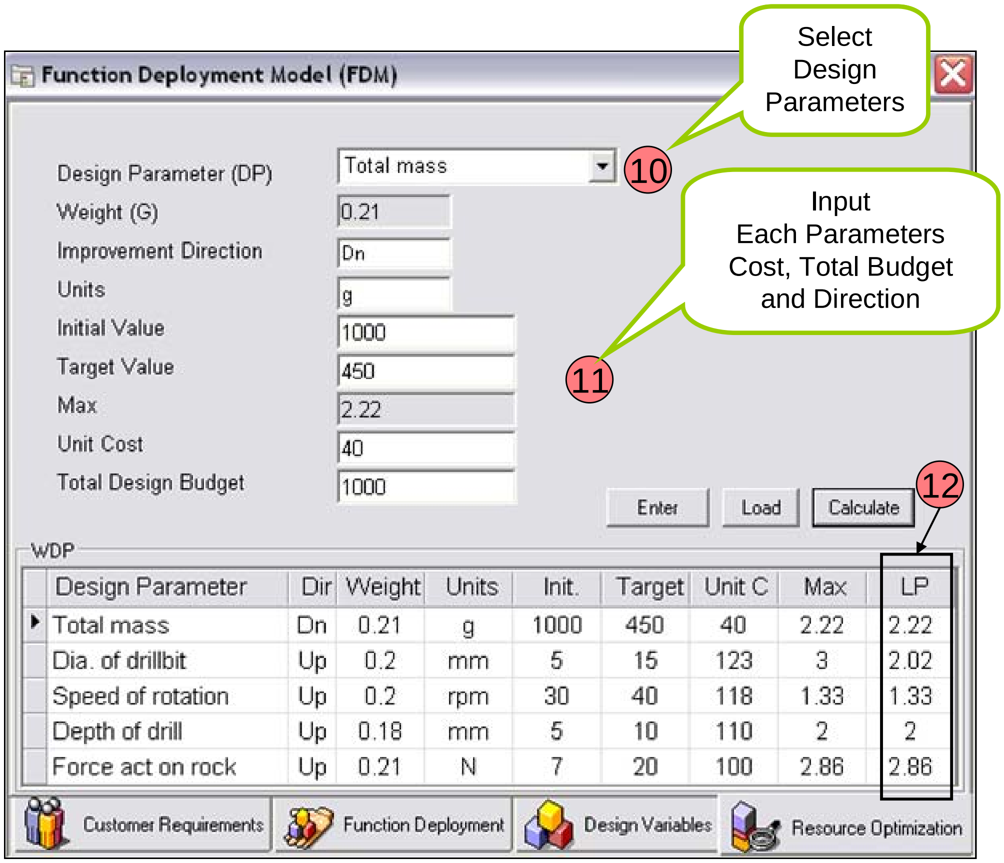


Figure 4.8 Steps 10-12 of FDM-GUI

4.3 Solid modeler module

In the Solid Modeler Module, see Figure 4.9, the feasible concepts, generated in the FDM Module according to the requirements, functions, parameters and optimised resources criteria, are transformed into actual functional designs. Geometric model of the concept is constructed with the use of CAD software. Most of the commercial CAD software such as ProEngineer, Unigraphics, etc., can be use but for illustration, Solidworks is adopted in the proposed implementation due to its ease to use and powerful modelling capability. In some cases where several functional designs may be turned out, decision must be made according to the functional priority and other criteria. The output of this module is a functional design which is represented as a solid model.

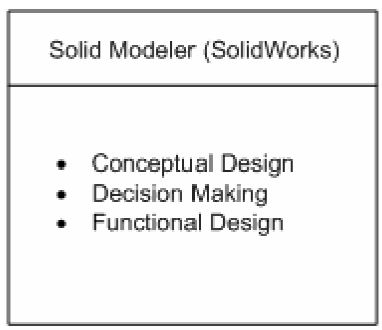


Figure 4.9 The solid modeler module

Although construction of 3D geometry via CAD software is a well established technique, certain skill in CAD is still required in yielding a good model which is critical for the successes implementation of the subsequent two stages. An example skill is that the logical sequence of model should be followed in order to maintain the design intent and to avoid calculation error when rebuild the model.

4.4 Design analysis and optimization module

To refine the functional design to satisfy certain design objective(s) such as maximising strength, minimizing cost, etc., Design Analysis and Optimization Module are performed on its model created by the Solid Modeler Module, see Figure 4.10. Cosmosworks is suggested for illustration purpose in this module due to its supreme compatibility with SolidWorks and the high performance provided. However, other FEA software, such as Ansys, etc., can also be adopted if necessary. The output of this module is an optimised model of the functional design.

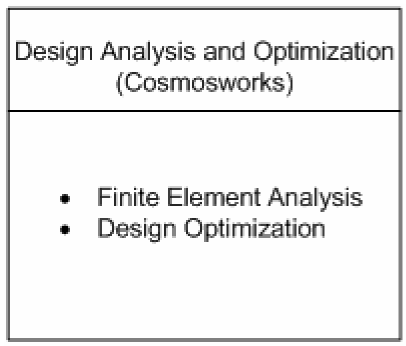


Figure 4.10 Design analysis and optimization module

4.4.1 Procedures of product design optimization

The optimization of the structure can be obtained through the use of a common software platform and the procedure is shown in Figure 4.11. Use 3D Solid model constructed by using commercial CAD modeller such as Pro/Engineer, Solidworks or Unigraphics in solid modeller stage.

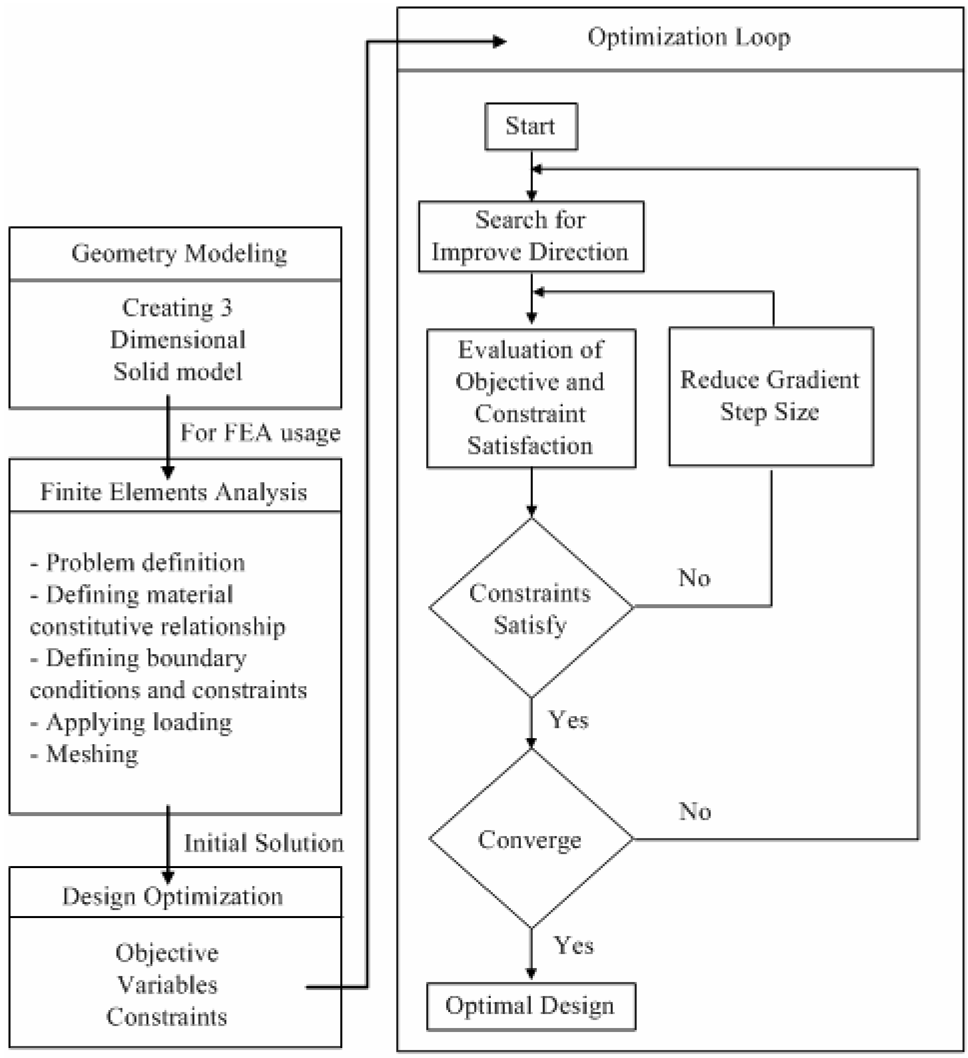


Figure 4.11 The procedures of design optimization

The most common form of the finite element analysis method is the displacement method, and the form is shown in equation (4.1):

$$[K][U] = F \tag{4.1}$$

where the displacement matrix U is to be determined given the known stiffness matrix K , and applied load matrix F. To analyse the component behaviour under loading, three essential steps are necessary to be performed:

Step (1) defines the material of component, each material has a specific property such as density, elasticity modulus, and yield stress.

Step (2) defines the constraints and loads to control the boundary conditions.

Step (3) creates a mesh to breakdown the model into many small elements for simulation and describe the behaviour of the whole component with large set of simultaneous equations.

The final stage is design optimization. In this stage, it includes three factors: objective function, constraints and control variables. The objective function usually aims to minimize the cost by weight and material reduction, increase productivity and reliability. Constraints refer to the criteria or limitations of the design. In this stage, there are abundant combinations of design variables to be adjusted to trade-off between upper ranges and lower ranges such as height, diameters and thickness. The general form of optimization problems is defined in equation (4.2):

$$\begin{aligned} &\text{Minimize:} && F(X) && \text{(objective function),} \\ &\text{Subject to:} && g_i(X) \leq 0 && \text{(inequality constraint),} \\ &&& X_j^l \leq X_j \leq X_j^u && \text{(design variables)} \end{aligned} \tag{4.2}$$

After formulating the optimization equations, the process can be started to iterate the values until the objective function converge. During the iteration, the step size is reduced and looping continues.

This chapter describes the architecture and the implementation procedures of the proposed FDM in a computer. Modular-based design is adopted and the FDM system is divided into 3 modules, namely Function Deployment Model (FDM) Module, Solid Modeler Module and Design Analysis and Optimization Module. With a step-by-step approach, the user operation and limitation of each module are explained.

5. CASE STUDY- DEVELOPMENT OF A MICRO INJECTION MOLDING MACHINE BY USING FDM

5.1 Background

With the recent advances of microsystems technology, there is a rapid growing and large demand of miniature plastic components, especially those produced by injection molding technique. This enormous demand distributes over a wide range of areas such as biomedical, electronics, computers, telecommunication, automobile, etc. Although micro injection molding machines have been available in the market over years, they are still in its infancy and some problems related to precision, stability, costing, material wastage, micro mould design are remain unsolved. This is because there are many existing challenges in micro injection molding such as effective plasticization, stable melt quality, fast injection speed, shot volume accuracy, part handling, etc.

In an attempt to solve these issues with innovative ideas, a project of development of miniaturized micro/nano injection molding machine was initiated by the Department of Industrial & Systems Engineering, The Hong Kong Polytechnic University in 2004. This project was funded by Hong Kong Government. The project work was conducted by a group of researchers and technologist from various areas of expertise, such as industrial design, advanced manufacturing technology, machine control, material engineering, etc., which are the core competencies to the development of micro injection molding machine. Currently, the target end users of the machines are mainly the sponsors and partners from industry. The overview of Miniaturized Plastic Injection Molding machine is shown in Figure 5.1. This Injection Molding machine was used as an example to demonstrate the effectiveness of proposed first three stages of FDM in the innovative product development cycle.

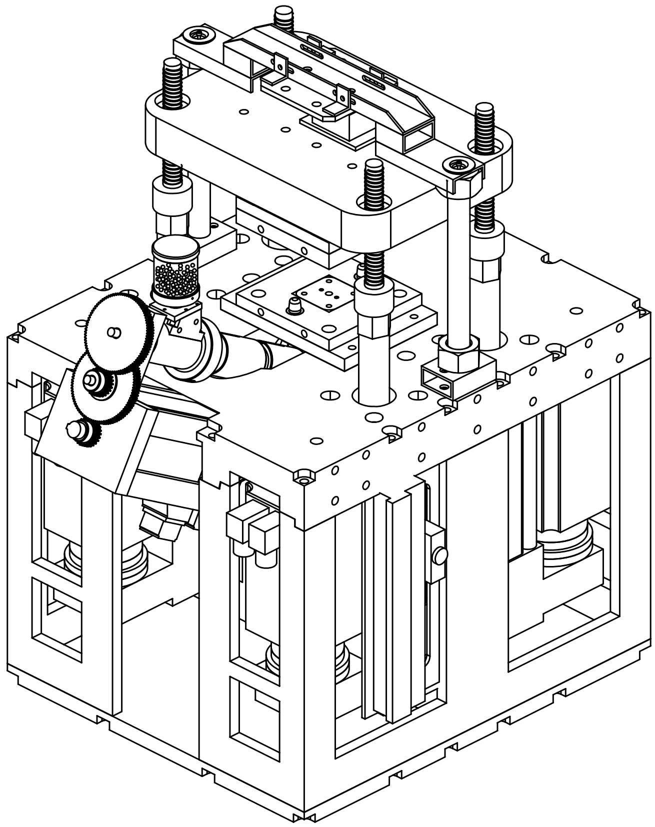


Figure 5.1 The overview of miniaturized plastic injection molding machine

5.2 Application of FDM module

In order to construct FDM, the data is collected during different stages of the proposed FDM by the methods and personnel shown in Fig.5.2

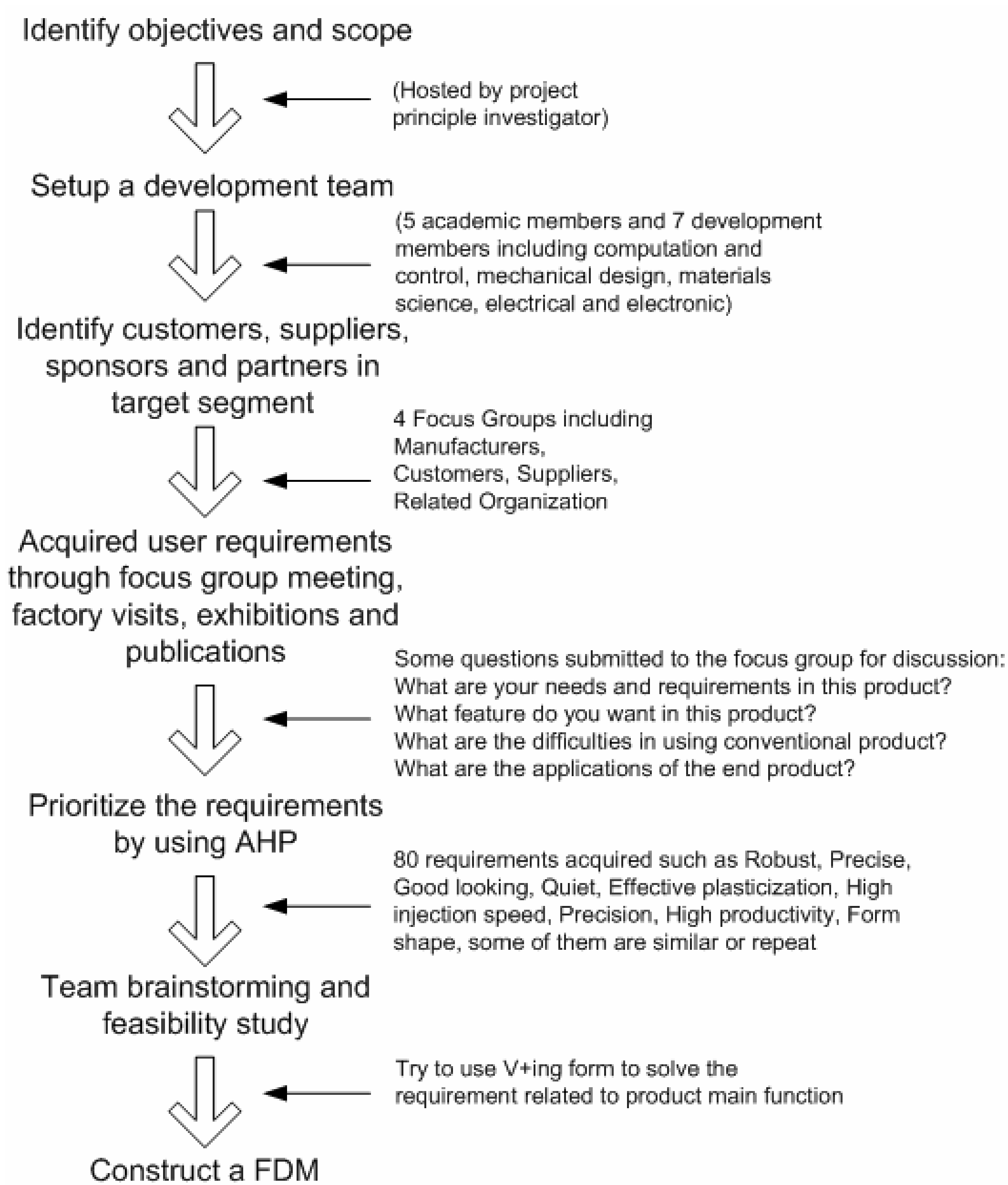


Figure 5.2 The workflow of data collection

To demonstrate the application of the proposed FDM model for design of this machine, the following steps are taken:

Step 1: The mission objective of developing a machine is considered. Basing on the record of experienced technologist and sponsors' advice, the designer concludes that the five basic customer requirements are ‘Form Shape’, ‘Precision’, ‘Energy Saving’, ‘Production Rates’, and ‘Quality’.

Step 2: Using AHP method suggested by the proposed model, the maximum eigen-values ($\lambda_{\max}$), the pairwise comparison matrix (A), and the relative importance weighting of each CRs (W) are calculated as follows:

$$A = \begin{bmatrix} 1.00 & 3.00 & 7.00 & 5.00 & 3.00 \\ 0.33 & 1.00 & 7.00 & 3.00 & 3.00 \\ 0.14 & 0.14 & 1.00 & 3.00 & 0.20 \\ 0.20 & 0.33 & 0.33 & 1.00 & 0.14 \\ 0.33 & 0.33 & 5.00 & 7.00 & 1.00 \end{bmatrix}$$

$\lambda_{\max} = 5.66$, $W = (0.43,0.27,0.06,0.05,0.19)^T$

Step 3: The degree of importance of each CRs is determined.

Step 4: The above requirements are transferred to functional characteristics by using a function-oriented design approach. There are five functional characteristics assigned by the design engineer using the proposed form. They are ‘Plasticizing’, ‘Molding’, ‘Clamping’, ‘Cooling’ and ‘Monitoring’.

S**tep 5, 6 & 7:** Build the HOQ. Two relationship matrixes are assigned in this model, namely interrelationship matrix (between CRs and FCs) and correlation matrix (between FCs and FCs). After two matrixes are assigned, the relative importance of each function characteristics V is calculated. The details are shown as follows:

$$M = \begin{bmatrix} 0 & 9 & 3 & 3 & 0 \\ 1 & 9 & 3 & 1 & 9 \\ 3 & 0 & 3 & 9 & 1 \\ 0 & 3 & 0 & 3 & 0 \\ 1 & 3 & 1 & 1 & 3 \end{bmatrix} P = \begin{bmatrix} 9 & 3 & 0 & 0 & 1 \\ 3 & 9 & 3 & 3 & 3 \\ 0 & 3 & 9 & 0 & 1 \\ 0 & 3 & 0 & 9 & 1 \\ 1 & 3 & 1 & 1 & 9 \end{bmatrix} R = \begin{bmatrix} 0.10 & 0.37 & 0.20 & 0.20 & 0.12 \\ 0.12 & 0.32 & 0.16 & 0.16 & 0.29 \\ 0.13 & 0.23 & 0.13 & 0.39 & 0.11 \\ 0.09 & 0.35 & 0.08 & 0.35 & 0.12 \\ 0.14 & 0.31 & 0.14 & 0.14 & 0.27 \end{bmatrix}$$

$V = (0.20, 0.22, 0.18, 0.19, 0.22)^T$

Step 8: Five critical design parameters affecting the functions including ‘cycle time’, ‘temperature’, ‘speed’, ‘force’, and ‘tolerance’ are defined.

Step 9, 10 & 11: Build the Design matrix. Similar to the procedures in Step 5, 6 & 7, the relative importance of each design parameters *G* is calculated. The design matrix is formulated as follows:

$$N = \begin{bmatrix} 3 & 3 & 1 & 0 & 0 \\ 3 & 9 & 1 & 3 & 3 \\ 1 & 0 & 0 & 9 & 3 \\ 9 & 9 & 3 & 0 & 0 \\ 0 & 9 & 3 & 9 & 3 \end{bmatrix} U = \begin{bmatrix} 9 & 1 & 9 & 0 & 0 \\ 1 & 9 & 0 & 0 & 9 \\ 9 & 0 & 9 & 9 & 0 \\ 0 & 0 & 9 & 9 & 3 \\ 0 & 9 & 0 & 3 & 9 \end{bmatrix} T = \begin{bmatrix} 0.28 & 0.21 & 0.26 & 0.06 & 0.19 \\ 0.12 & 0.29 & 0.17 & 0.12 & 0.31 \\ 0.03 & 0.10 & 0.33 & 0.33 & 0.20 \\ 0.28 & 0.21 & 0.26 & 0.06 & 0.19 \\ 0.07 & 0.21 & 0.21 & 0.23 & 0.27 \end{bmatrix}$$

$G = (0.20, 0.21, 0.19, 0.20, 0.20)^T$

Step 12: The final stage of the proposed model is to optimize design parameters. The optimization process starts by using Linear Programming to optimize the design resource planning. The Graphical User Interface (GUI) of FDM for “Micro Injection Molding Machine” is formulated as shown in Figure 5.3. where design constraints are optimized by:

Maximize $S(x) = 0.20x_1 + 0.21x_2 + 0.19x_3 + 0.20x_4 + 0.20x_5$

Subject to

$180x_1 + 210x_2 + 220x_3 + 160x_4 + 230x_5 \leq 2000$

$1 \leq x_1 \leq 2.5,\ 1 \leq x_2 \leq 5,\ 1 \leq x_3 \leq 2.67,\ 1 \leq x_4 \leq 2.5,\ 1 \leq x_5 \leq 5$

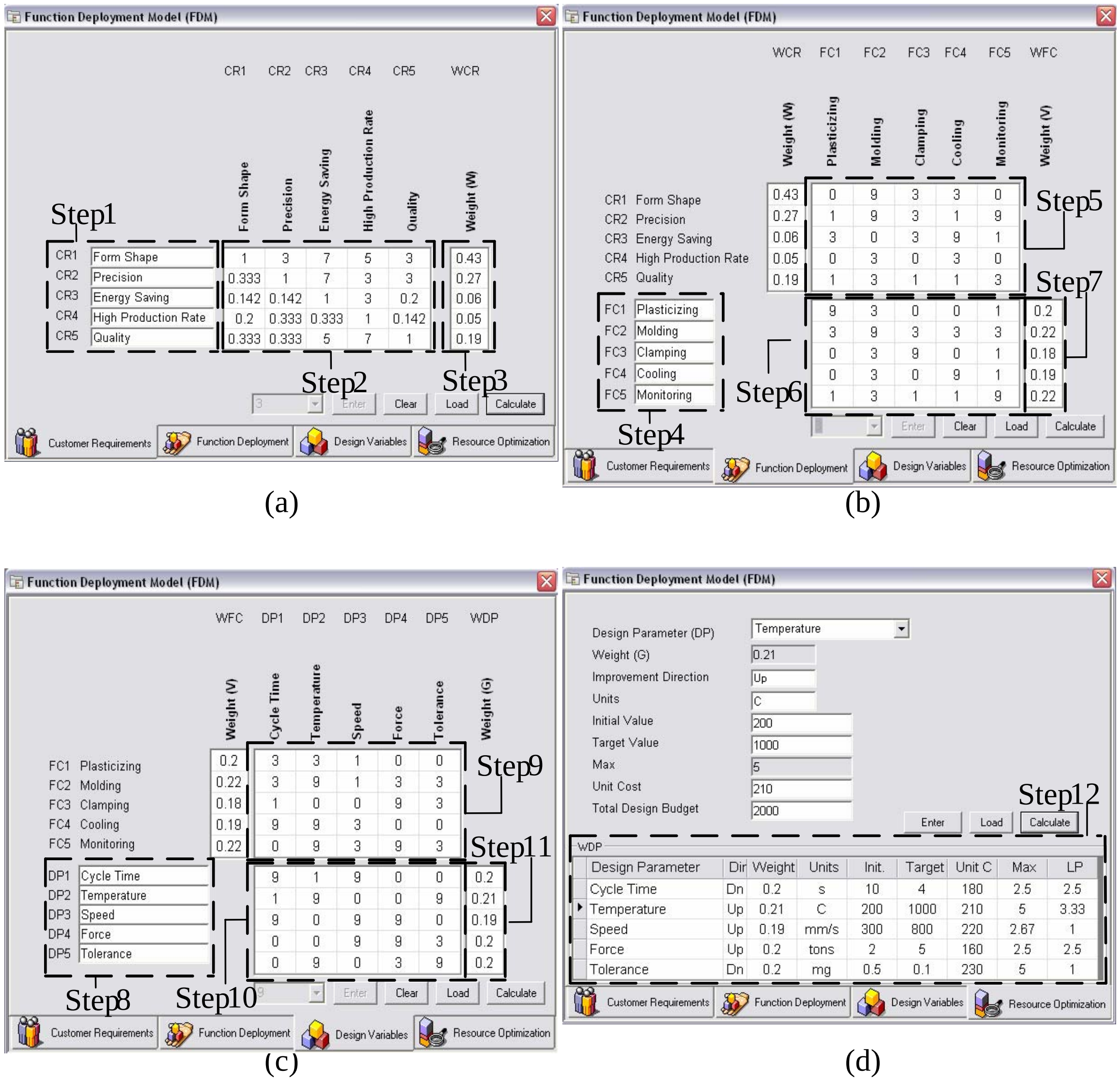


Figure 5.3 GUI implementation procedures of Function Deployment Model: (a) customer requirements; (b) function deployment; (c) design variables; and (d) resource optimization

In order to solve this model, an algorithm tools "Matlab" is being used in the back end to generate the result and display the result with GUI. The result of the computation for the improvement ratio of each design parameter is shown in Figure 5.3(d). According to the result, "Form Shape" is the most important Customer Requirement. "Molding" is the most important Function Characteristics and "Temperature" contributes to the highest weighting to the budget. It implies that the design engineer should first consider these elements. After the linear programming stage, the value of each element was adjusted to its optimal value where the cycle time and force were optimized to its target value (i.e. 4 second and 5 tons respectively). The capable temperature was improved from 200°C to 660°C with an improvement ratio of 3.33. Although it's different from its target value, its improved value (i.e. 660 °C) was already an adequate amount for the process. The speed and tolerance were 300 mm/s and 0.5 mg respectively, which is different from the target value. Based on the relative importance of the model, although these two parameters could not reach its target value, the overall performance of the machine was not affected. The conceptual design can make use of the result to form a product prototype, and carry out design optimization and finite element analysis subsequently. This example shows the proposed model can be applied to an application for conceptual design and product development. For the coming "Product Prototyping" stage and other subsequent stages in the proposed product development cycle, they will not be discussed in this section since the prototype is still under fabrication at the moment.

6. CASE STUDY - DEVELOPMENT OF SAMPLING INSTRUMENT FOR INTER-PLANETARY MISSION

6.1 Background

In 2003, the European Space Agency (ESA) sent an orbiter called the Mars Express to the planet Mars. This mission carried a single lander called ‘Beagle 2’ which was to be released to land on Mars. The principal configuration of the actual lander is of clamshell shape which was to open and orient itself in an upright position after landing, as shown in Figure 6.1 (Richter et al., 2002). The scientific objective of this mission was focused on searching for signatures of past and present life forms. The lander carried many innovative instruments. One of these is called “Rock Corer”, which is mounted on the end of the robotics arm of the lander. This instrument performs several functions including coring into rocks to acquire samples and depositing them into an oven in the GAP (Gas Analysis Package) for content analysis of signature of life forms. Other functions of the instrument include grinding off rind from the top surface of the rock for more accurate reading of the Alpha Proton X-ray spectrometer; and chipping off corners of rocks for examination of the fresh cut surface. This instrument - considered to be the first space-qualified “all-in-one” lightweight instrument – is an innovation developed outside existing markets. This lightweight space-qualified instrument has the exceptional advantage of being able to combine the functions of drilling, coring, chiselling, grinding and gripping in a single bit. Other instruments for similar functions would need to change their bits and hence be less reliable and much heavier. For details of this instrument, please refer to U.S Patent No. 2003/0209092.

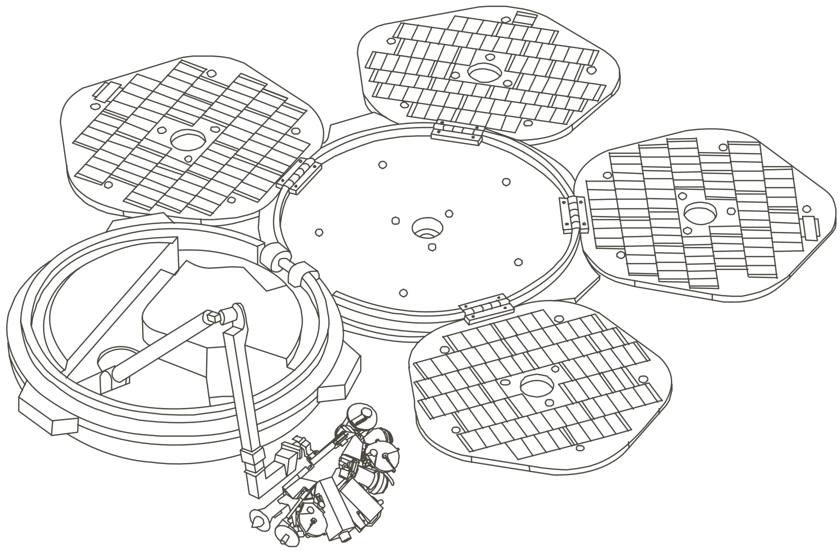


Figure 6.1 The overview of Beagle 2 lander with sampling instruments.

6.2 Application of proposed system model

6.2.1 FDM module

To demonstrate the application of the proposed FDM model for design of this instrument, the following steps are taken:

Step 1: The mission objective of searching for life on other planets is considered. Based on the record of past mission and some expert advice (Chicarro et al., 1998; Sims et al., 1999 and 2002; Yung et al., 2000; Westall, 2000; Wright et al., 2003), the designer concludes that the five basic customer requirements are ‘Clean the surface’, ‘Make holes’, ‘Collect samples’, ‘ Return samples’, and ‘Avoid contamination’.

Step 2: The above requirements are transferred to functional characteristics by using a function-oriented design approach. There are five common function characteristics assigned by the design engineer using the proposed form (verb+ing). They are ‘Drilling’, ‘Coring’, ‘Chiselling’, ‘Grinding’ and ‘Gripping’. Each functional characteristic, as shown in Figure 6.2 has different design parameters depending on the direction of movement such as vertical, horizontal, rotational and angular. For example: "Coring" is a method to retrive cores samples from the surface using a hollow device.

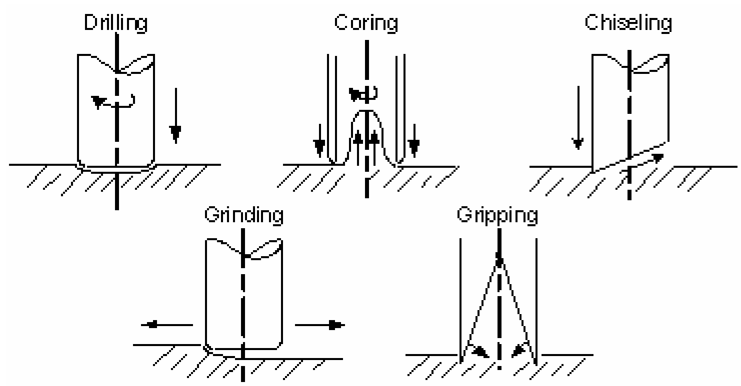


Figure 6.2 The five function characteristics of an instrument.

Step 3: The degree of importance of each CRs is determined. Using AHP method suggested by the proposed model, the maximum eigen-values (λ_{max}), the pairwise comparison matrix (*A*), and the relative importance weighting of each CRs (W) are calculated as follows:

$$A = \begin{bmatrix} 1.00 & 7.00 & 0.14 & 0.20 & 5.00 \\ 0.14 & 1.00 & 0.11 & 0.14 & 3.00 \\ 7.00 & 9.00 & 1.00 & 3.00 & 7.00 \\ 5.00 & 7.00 & 0.33 & 1.00 & 5.00 \\ 0.20 & 0.33 & 0.14 & 0.20 & 1.00 \end{bmatrix}$$

$\lambda_{max} = 5.76$, $W = (0.13, 0.05, 0.51, 0.28, 0.04)^T$

S**tep 4:** Build the HOQ. Two relationship matrixes are assigned in this model, namely interrelationship matrix (between CRs and FCs) and correlation matrix (between FCs and FCs). After two matrixes are assigned, the relative importance of each functional characteristics V is calculated. The details are shown as follows:

$$M=\begin{bmatrix}9&3&3&0&0\\0&3&0&9&0\\0&3&1&1&9\\0&9&0&0&3\\1&3&0&9&0\end{bmatrix}\quad P=\begin{bmatrix}9&3&1&0&1\\3&9&9&1&1\\1&9&9&0&0\\0&1&0&9&1\\1&1&0&1&9\end{bmatrix}\quad R=\begin{bmatrix}0.37&0.32&0.25&0.01&0.05\\0.05&0.21&0.16&0.50&0.07\\0.09&0.22&0.17&0.10&0.41\\0.12&0.35&0.33&0.05&0.15\\0.10&0.21&0.15&0.46&0.07\end{bmatrix}$$

$V=(0.19,0.23,0.15,0.21,0.22)^T$

Step 5: Five critical design parameters affecting the functions including 'total mass', 'diameters of drill bit', 'speed of rotation', 'depth of drill', and 'force acting on rock' are defined.

Step 6: Build the Design matrix. Similar to the procedures in Step 4, the relative importance of each design parameters G is calculated. The design matrix is formulated as follows:

$$N=\begin{bmatrix}0&1&0&1&1\\3&3&1&1&1\\3&0&0&0&3\\0&0&3&0&1\\0&1&0&3&0\end{bmatrix}\quad U=\begin{bmatrix}9&0&3&0&3\\0&9&0&3&0\\3&0&9&1&1\\0&3&1&9&0\\3&0&1&0&9\end{bmatrix}\quad T=\begin{bmatrix}0.08&0.32&0.05&0.32&0.24\\0.27&0.25&0.17&0.16&0.16\\0.43&0&0.14&0&0.43\\0.22&0&0.51&0.05&0.22\\0&0.35&0.06&0.59&0\end{bmatrix}$$

$G=(0.22,0.20,0.20,0.17,0.21)^T$

Step 7: The final stage of the proposed FDM model is to optimize design resources. The optimization process starts by using Linear Programming to optimize the design resource planning. The FDM for "Rock Corer" is formulated as a template for designers shown in Table 6.1 where resources are optimized by:

Maximize

$$S(x)=0.22x_1+0.20x_2+0.20x_3+0.17x_4+0.21x_5 \tag{11}$$

Subject to

$$40x_1 + 120x_2 + 115x_3 + 110x_4 + 100x_5 \leq 1000 \quad (12)$$

$$1 \leq x_1 \leq 2.22,\ 1 \leq x_2 \leq 3,\ 1 \leq x_3 \leq 1.33,\ 1 \leq x_4 \leq 2,\ 1 \leq x_5 \leq 2.86 \quad (13)$$

The result of the computation for the improvement ratio of each design parameter is shown in Table 6.2. According to the result, “Collect samples” is the most important Customer Requirement. “Coring” is the most important of the Function Characteristics and “Total mass” contributes to the highest weighting to the budget. It implies that the design engineer should first consider these elements. In order to solve this model, a Matlab program is being used to generate the result. After the linear programming stage, the value of the element was adjusted to its optimal value where the total mass was reduced from 1000g to 450g. The drilling depth and the backing force were also optimized to its target value (i.e. 10 mm and 20 N respectively). The diameters of the drillbit and the speed of rotation were 7.5 mm and 30 rpm respectively, which is different from the target value. Based on the relative importance of the model, although these two parameters could not reach its target value, the overall performance of the corer was not affected. The conceptual design can make use of the result to form a product prototype, and carry out parameters optimization by using gradient-based search optimization and finite element analysis which will be presented in the following chapter.

Table 6.1 The FDM for the “Rock Corer”.

		CR_1 Make a hole	CR_2 Clean the surface	CR_3 Collect samples	CR_4 Samples return	CR_5 Avoid contamination	W_{CR} Weight (W)	FC_1 Drilling	FC_2 Coring	FC_3 Chiseling	FC_4 Grinding	FC_5 Gripping	W_{FC} Weight (V)	DP_1 ↓ Total mass	DP_2 ↑ Diameters of drillbit	DP_3 ↑ Speed of rotation	DP_4 ↑ Depth of drill	DP_5 ↑ Force acting on rock
CR_1	Make a hole	1.00	7.00	0.14	0.20	5.00	0.13	9	3	3								
CR_2	Clean the surface	0.14	1.00	0.11	0.14	3.00	0.05		3		9							
CR_3	Collect samples	7.00	9.00	1.00	3.00	7.00	0.51		3	1	1	9						
CR_4	Samples return	5.00	7.00	0.33	1.00	5.00	0.28		9			3						
CR_5	Avoid contamination	0.20	0.33	0.14	0.20	1.00	0.04	1	3		9							
FC_1	Drilling							9	3	1		1	0.19		1		1	1
FC_2	Coring							3	9	9	1	1	0.23	3	3	1	1	1
FC_3	Chiseling							1	9	9			0.15	3				3
FC_4	Grinding								1		9	1	0.21			3		1
FC_5	Gripping							1	1		1	9	0.22		1		3	
DP_1	Total mass													9		3		3
DP_2	Diameters of drillbit														9		3	
DP_3	Speed of rotation													3		9	1	1
DP_4	Depth of drill														3	1	9	
DP_5	Force acting on rock													3		1		9
W_{DP}	Weight (g_k)													0.22	0.20	0.20	0.17	0.21
	Units													g	mm	rpm	mm	N
	Lower limit $l_k^{(L)}$													450	5	30	5	7
	Upper limit $l_k^{(U)}$													1000	15	40	10	20
	Cost c_k (X1,000)													40	120	115	110	100

Table 6.2 The improvement ratio of each design parameters.

max S(x)	x_1	x_2	x_3	x_4	x_5
1.933	2.22	1.52	1.00	2.00	2.86

6.2.2 Function transformation to product prototype

Based on the proposed FDM, the concept will then transferred to form the product prototype. According to the modularity method developed by Ulrich (2004), the concept can be realized through a three level hierarchy approach into the product prototype. The three levels are namely Functions level, Modular level and Components level. The approach is illustrated in Figure 6.3.

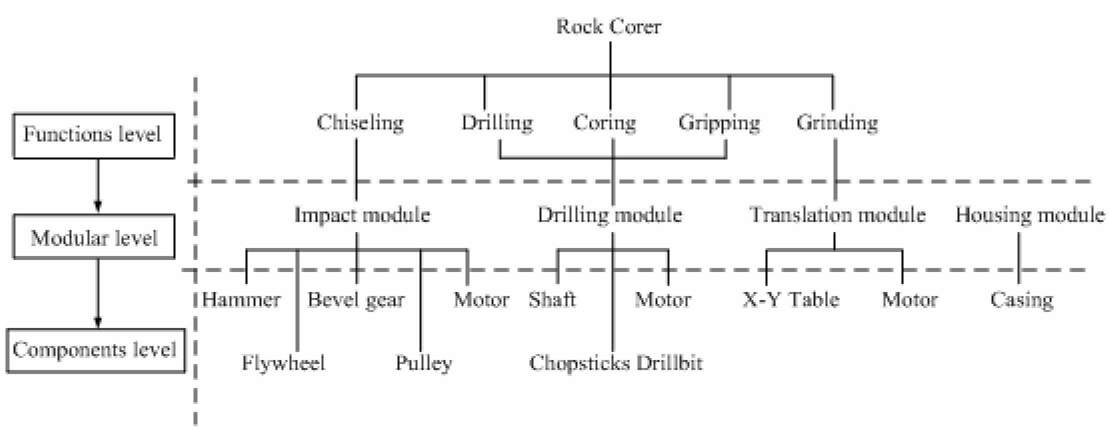


Figure 6.3 Transformation hierarchy for product prototype

In the beginning of the Functions level, the concept is represented by a set of functions in the form of "Verb + ing" to represent the functions provided by the coming product. In this case, the functions are "Drilling", "Coring", "Chiseling", "Gripping" and "Grinding".

In the subsequent Modular level, the related function(s) is / are integrated to form one module. Each module can use slot, bus and sectional method to link up together. In the case of the Rock Corer, all interfaces used are of slot type. For example, the interface between Housing and Translation modules is using slot type for connection. Figure 6.4 shows one of the examples for Rock Corer.

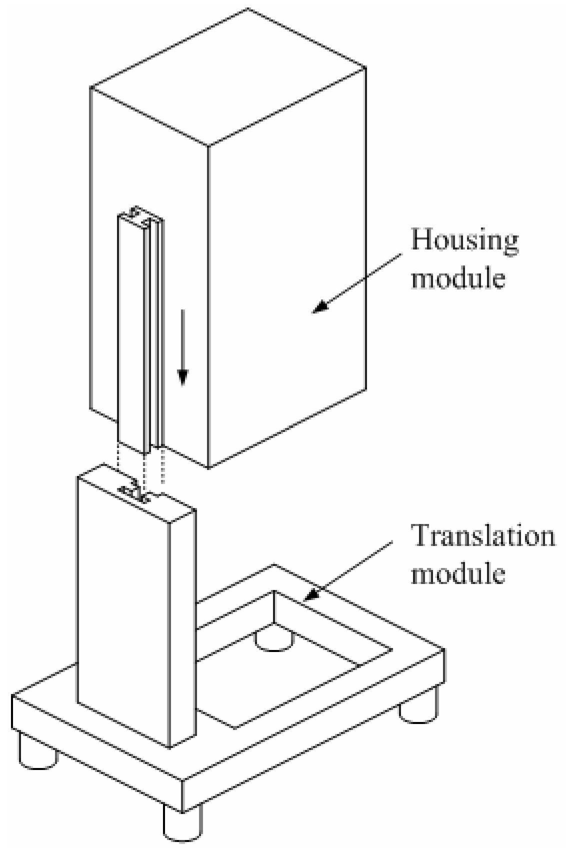


Figure 6.4 An example of slot type modularity for “Rock Corer”

In the final Components level, each component refers to an individual part or integral parts (e.g. gear trains) which can perform a function but must be attached to a support or framework to provide the function. It cannot be taken apart or run separately. It requires an interface to connect with other parts through fastener such as bolt and nut, rack and pinion, etc.

Using the function-oriented modular based method to construct the product prototype has several advantages:

- Reduce development time and cost due to all module can be develop at the same time
- Reduce large number of components complexity and easy find out their relationship
- Provide product configuration variety and easy replacement in new product development process
- Easy maintenance and replacement when module occur problems
- Easy for manufacturing and purchasing similar parts

Figure 6.5 illustrates a schematic diagram of the "Rock Corer" prototype based on the five functions: Drilling, Coring, Gripping, Chiseling and Grinding. Each function is mapped into a module. There are 4 modules proposed, namely Impact module, Drilling module, Translation module and Housing module. Chiseling mapped to impact module as it is like a using hammer to impact the nail by pulse. To perform the function, this module provides a large energy by using a spring to store up and release. Drilling, Coring and Gripping grouped into Drilling module. Since the principle of drilling is the production of holes by the relative motion of rotating the drill-bits and coring is similar to drilling but it has a hollow section to contain the samples through the open ended the drill-bits, whereas gripping is like a tweezers to perform in open and closed direction for holding the samples. Grinding is mapped to Translation module as it is a process to remove the large surface areas in x and y directions. Finally, a Housing module is designed to accommodate the other modules.

Moving down to the component level, the Impact module is divided into a set of components such as hammer, flywheel, bevel gear, pulley and motor. The Drilling module is broken down into shaft, chopsticks drillbit and motor. The Translation module is decomposed into X-Y table and motor. The Housing module consists of casing.

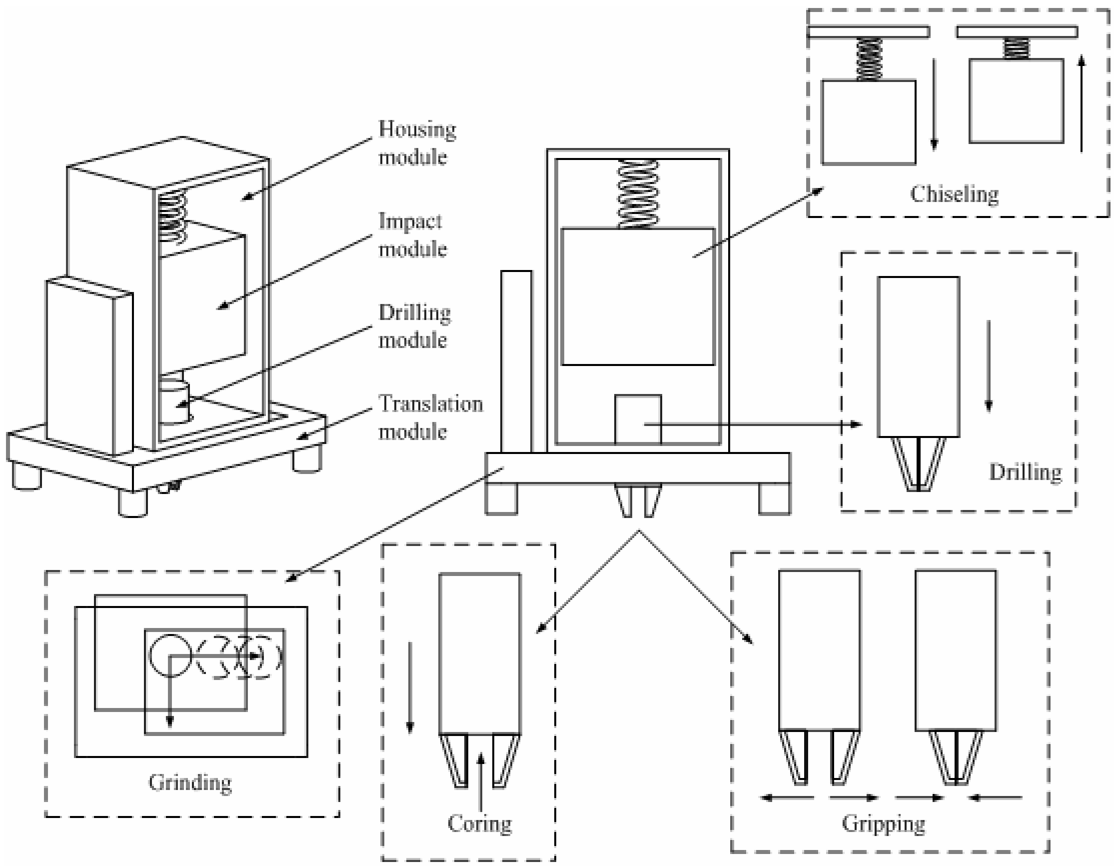


Figure 6.5 Schematic diagram of the “Rock Corer” prototype

6.2.3 Design analysis and optimization module

After the Rock Corer prototype was generated, the design had to be optimized by FEA to become the final product. To demonstrate the proposed method, the chopsticks drill-bits of Rock Corer was used as an example for design analysis and optimization, the Structure of chopsticks drill-bits is shown in Figure 6.6. Figure 6.7 shows the three-dimensional solid geometry constructions of drill-bits by using method of Boolean operations. The geometries at the bottom level in the Figure 6.7 are considered to be the base control level and are the independent variables for design optimization. There are totally six design variables. Figure 6.8 and Figure 6.9 show the resultant solid model of chopsticks drill-bits by using Solidworks.

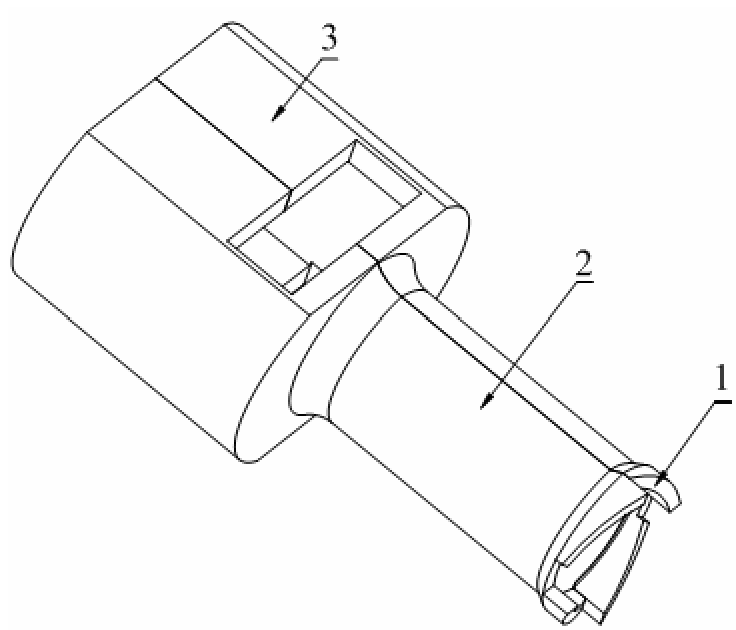


Figure 6.6 Structure of chopsticks drill-bits (1) cutting tip, (2) samples storage and (3) shank.

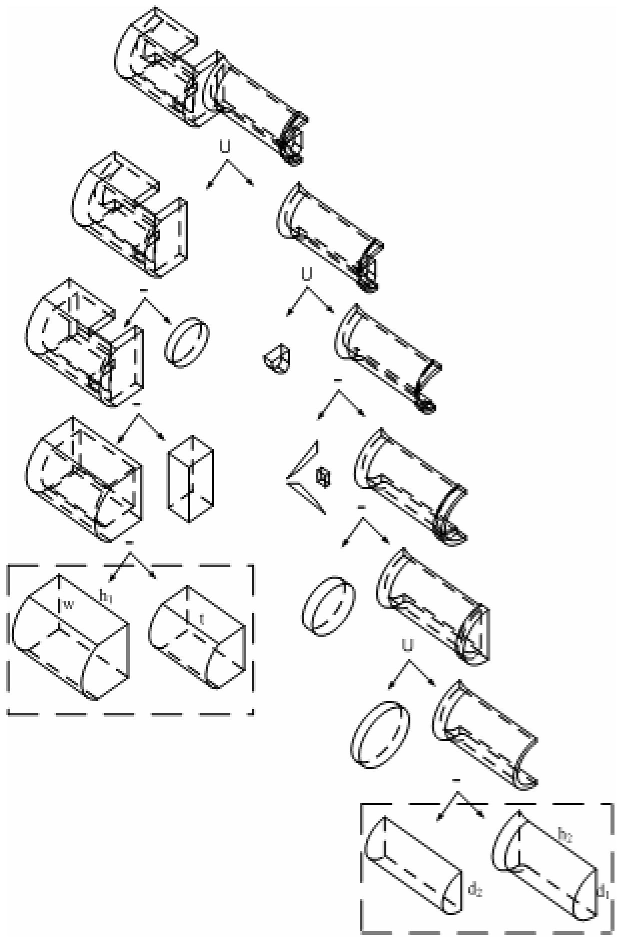


Figure 6.7 Three-dimensional solid geometry constructions via Boolean set operation

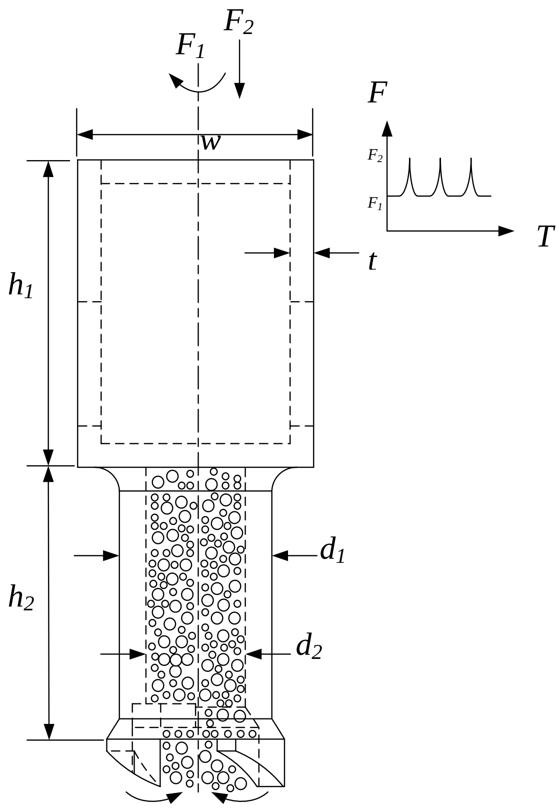


Figure 6.8 Definition of design variables for optimization

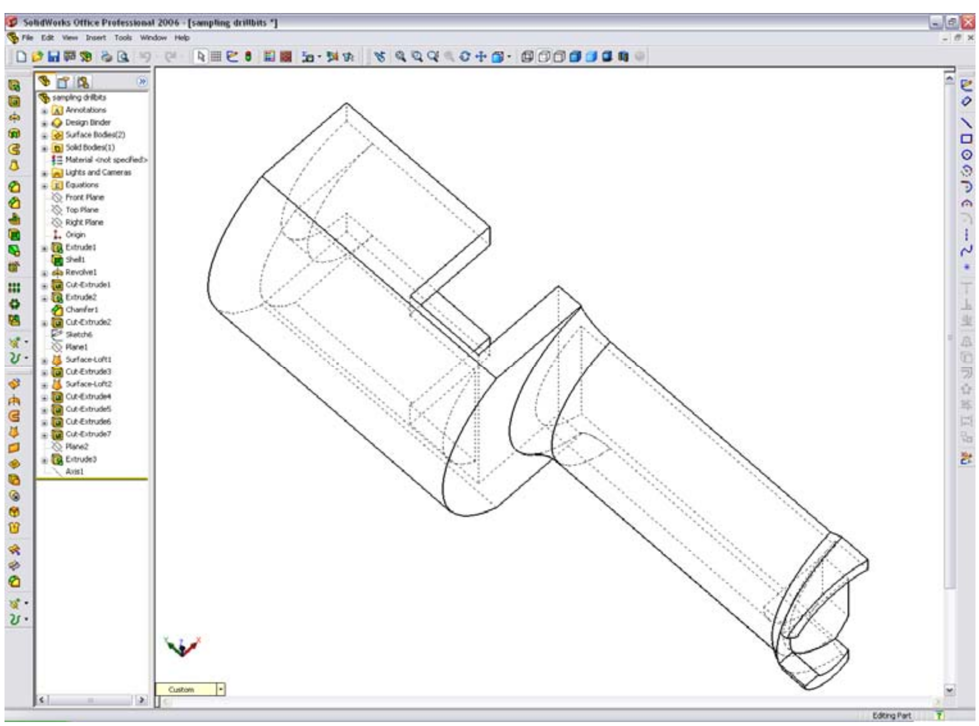


Figure 6.9 Three-dimensional solid model constructed by using Solidworks

6.2.3.1 Finite element analysis

The FEA model is created with CosmosWorks® which can be fully integrated as a plug-in into SolidWorks® platform for easy operation, reduce conversion time and eliminate compatibility problem. CosmosWork is one of the commercial CAE software which provides both Finite Element Analysis and Design Optimization. It has been widely used in different industries such as aerospace, automotive, medical, consumer electronics, etc. Figure 6.10 shows the finite element solid model.

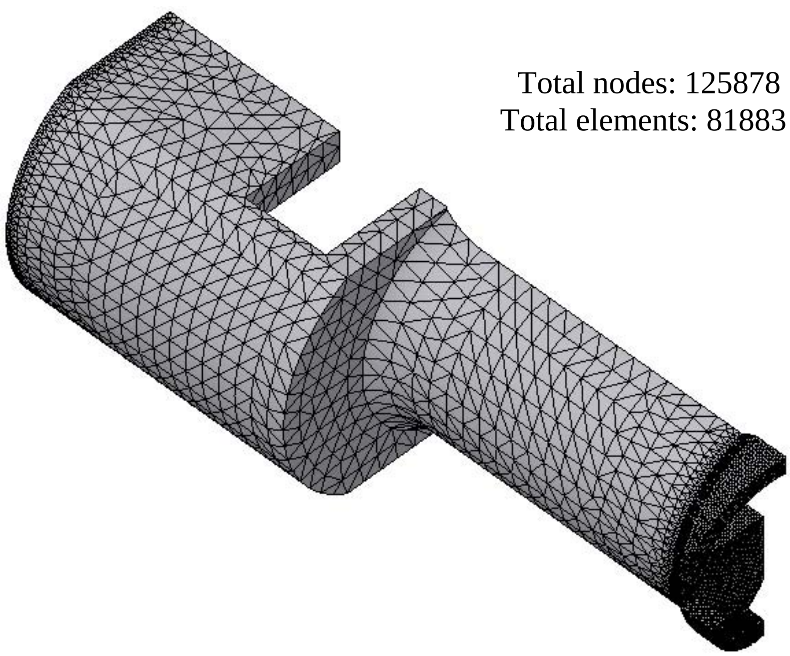


Figure 6.10 The h-element mesh refinement for using CosmosWork

After building the finite element solid model, the next step is to define the material, loading conditions and boundary constraints. The material used for the drillbit is high speed steel and the properties are listed in Table 6.3.

Table 6.3 The physical properties of material

Material properties (High Speed Steel M2)	
Elasticity modulus, *E*	1500 MPa
Poisson's ratio, *v*	0.29
Yield stress, σ_y	6.204e+008 N/m^2
Density, ρ	8160 g/mm^3

The loading conditions and boundary restraints are illustrated in Figure 6.11. The initial result is obtained and shown in Figure 6.12. In this analysis, a safety factor of 1 (i.e. 6.204e+008 N/m^2) and a maximum Von Mises Stress of 4.099e+008 N/m^2 is adopted.

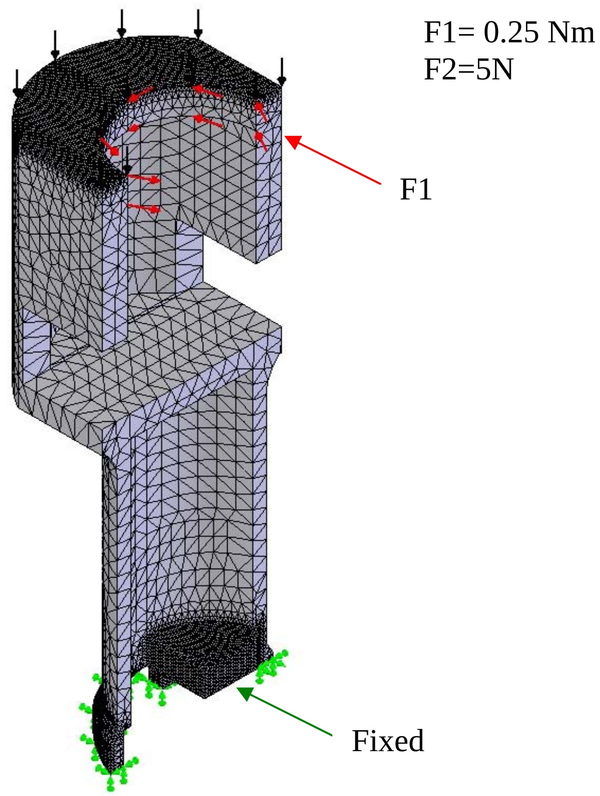


Figure 6.11 Illustration of loading conditions and boundary restraints applied

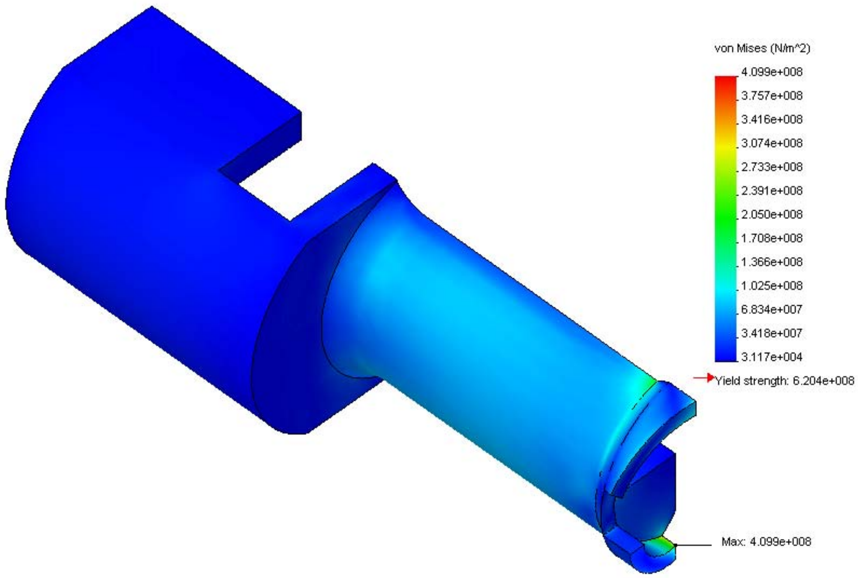


Figure 6.12 Initial result: maximum Von Misses stress

6.2.3.2 Design optimization

In this case study, the objective is to minimize the weight of the chopsticks drill-bits subjected to a set of constraints listed in equation (6.1) and (6.2).

Objective Minimize $W_c(\mathrm{X})$ (6.1)

Subject to

$$\begin{aligned} &\sigma_v \le \sigma_y / s.f \\ &w_l < w < w_u \\ &t_l < t < t_u \\ &d_1^l < d_1 < d_1^u \\ &d_2^l < d_2 < d_2^u \\ &h_1^l < h_1 < h_1^u \\ &h_2^l < h_2 < h_2^u \end{aligned} \qquad (6.2)$$

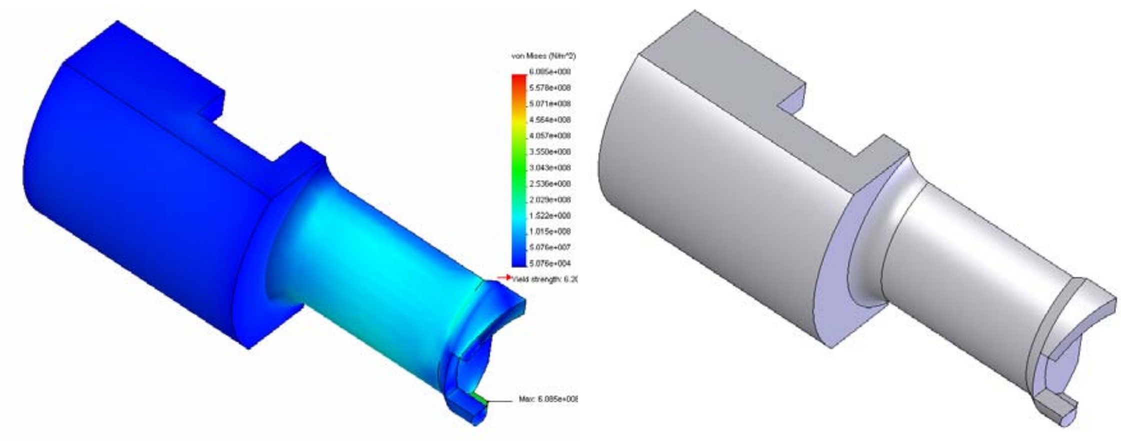
Where W_c is the weight of drill-bits, σ_v is von miss stress, σ_y is the material yield stress, *s.f* is safety factors, w is the width of drill-bits head, t is the thickness of the drill-bits head, d_1 is the diameters of drill-bits, d_2 is the diameters of core samples, h_1 is the height of the head and h_2 is the height of drill-bits.

According to the geometry of the drill-bits and functional requirements, a set of initial design variables is defined and its configuration is given in Table 6.4.

Table 6.4 The initial configuration of design variables

Symbols	Description	Limit Range (mm)	Initial values
w	Width of head	$10<w<14$	14
t	Thickness of head	$0.5< t<2$	2
d_1	Diameter of drill-bits	$8<d_1<12$	12
d_2	Diameter of core samples	$6<d_2<10$	10
h_1	Height of the head	$12<h_1<18$	18
h_2	Height of drill-bits	$10<h_2<20$	20

The optimization process starts with the above initial configuration and run iteratively. It stops automatically until the design solution converges to a final solution. After a set of 12 times simulations with different mesh sizes, the final maximum VonMises stress (i.e. 6.085×10^{-8} N/mm^2) was obtained and shown in Figure 6.13 (a). The result shows that there is one weak point with maximum stress concentration. It is on the cutting tip of the blade. Figure 6.13 (b) shows the final optimal design. The optimization problem took 12 design cycles to converge and the optimization history is shown in Figure 6.14. Compared with the weight of the initial design, the weight of the final design was reduced by about 76.7 %. This case took 20 minutes and 15 seconds to solve on a Dell precision 530 workstation with 1 GB RAM. The optimal design results obtained for each design parameters are shown in Table 6.5.



(a) (b)

Figure 6.13 Final results: (a) maximum von misses stress (b) 12 iteration

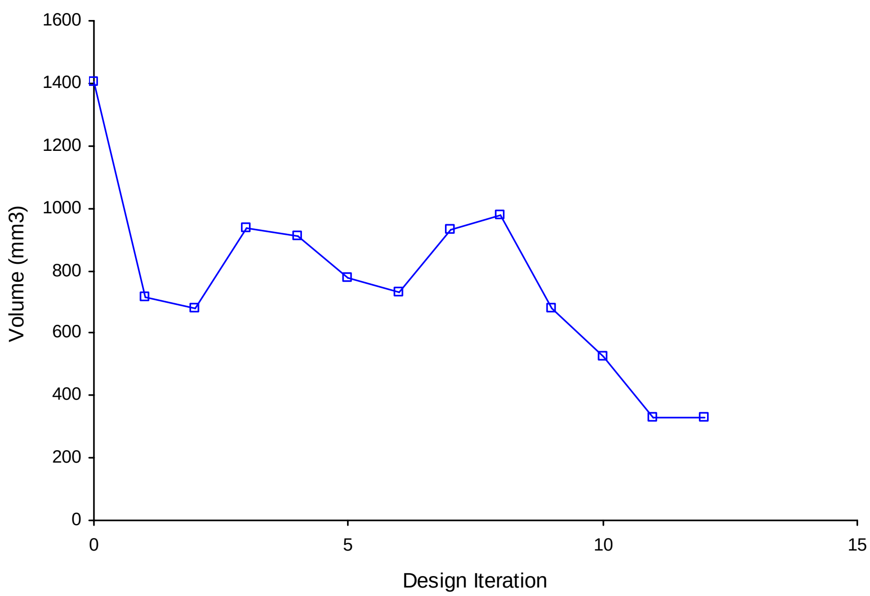


Figure 6.14 Optimization history of drill-bits

Table 6.5 The optimal configuration of design variables

Symbols	Description	Limit Range (mm)	Initial values	Optimal values
w	Width of head	$10<w<14$	14	10
t	Thickness of head	$0.5< t<2$	2	1
d_1	Diameter of drill-bits	$8<d_1<12$	12	5
d_2	Diameter of core samples	$6<d_2<10$	10	5
h_1	Height of the head	$12<h_1<18$	18	13
h_2	Height of drill-bits	$10<h_2<20$	20	11.5

6.3 System limitations

There are some limitations of the proposed system during implementation and are listed as follows:

1. The current FDM Development Tool in the proposed system can only manage matrix up to 5 x 5 but it can be extended to higher dimensions and the number of row and column can be different.
2. Only the main functions of the new product are handled by the proposed system. The sub-functions are not being considered.
3. The current system has not included any fuzzy logic manipulations although unarticulated customer requirements may be present in some cases.
4. Only linear optimization, such as linear programming, for the product design can be handled by the current system. Non-linear optimization cannot be performed with the current system.
5. Design optimization of the current system only applies to the component level instead of the assembly level.
6. Only single objective optimization can be solved by FDM development Tool of the proposed system

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7. DISCUSSION

7.1 Transformation mechanism of customer requirements to product functions

For new product development, a systematic mechanism to transform complex customer requirements to engineering characteristics is a key to product success. To deal with this issue, a new method called Function Deployment Model (FDM) is proposed and discussed in details in Chapter 3. FDM consists of the first three phases of the proposed product development cycle for product innovation: customer-need-in terms of requirements, a-set-of-functionalities, and a-set-of-attributes. In the first phase, customer requirements are identified and prioritised using AHP which helps to clarify the weighting of different customer requirements and ensures the proper usage of resources in the subsequent stages. In the second phase, the customer requirements are transformed into the product functions which are defined clearly and systematically using "verb+ing" approach. In the third phase, engineering characteristics are quantified and mapped to each function analytically. To illustrate the proposed model, two case studies are given. For example, in the case of the micro injection molding machine shown in Chapter 5, "Form Shape" is the most important Customer Requirement, "Molding" is the most important Function Characteristic and "Temperature" attribute contributes to the highest weighting to the budget. It implies that the design engineer should first consider the primary function of molding by providing the optimal temperature range in order to achieve low cost objective and the greatest customer satisfaction based on the molded part shape. In the case shown in Chapter 6, "Collect samples" is the most important Customer Requirement. "Coring" is the most important of the Function Characteristics.

and “Total mass” contributes to the highest weighting to the budget. The definition of coring is given in Section 6.2.1. It implies that the design engineer should first consider the main function of coring by minimizing the weight in order to satisfy the major requirement of collecting samples.

In the conventional QFD model, the functions and engineering characteristics of the product are mixed and considered in the same stage. This may cause a problem of confusing and overlooking the interrelations between functions and characteristics. Also, since the conventional model has only one HOQ, the engineering characteristics of a function may not be completely identified and clearly represented. To overcome these problems, a new concept of “function characteristics” is introduced in the proposed FDM model. In the proposed model, there are two HOQs. To start with, the functions of a product are identified and represented in the first HOQ. The engineering characteristics for each function are worked out and represented in the second HOQ. With the two HOQ, the interrelations of functions and engineering characteristics can be more systematically and clearly represented. Hence, compared with the conventional QFD, the model can better enhances the efficiency and effectiveness of the communications between design and more accurately represents customer needs.

In order to facilitate the implementation of the proposed methodology, an open-source FDM Development Tool with Windows based Graphical User Interface (GUI) is developed and the details are shown in Chapter 4. This development tool guides the end user to go through the FDM step by step and helps to facilitate the usage of the proposed methodology. This development tool is very user friendly and is suitable for inexperienced person to go through and enjoy the powerful methodology.

7.2 Application of design optimization

During the new product development, design resources planning and maximization of customer satisfaction are the main key issues affecting decision making of design engineer. To deal with these two issues, two design optimization methods were used – Linear and Non-linear methods. In Chapters 5 and 6, two examples were used to illustrate how optimization helps in designing a new product within limited resources and ensures the design to provide more customer satisfaction before launching to the market.

In the case study shown in Chapter 5, there are many customer requirements being transferred into the design variables. Linear Programming method was chosen for the case study of Miniaturized Plastic Injection Molding machine to illustrate optimization of the design resources in the early design stage such as budget and time. The proposed method ensures that the design engineer is aligning with the strategic goals, making compromises and deciding on the total resources and budget constraints. Most resources issues are related to the cost function. Hence, the case study mainly uses the cost function to demonstrate the usage of the proposed method. Other constraints can be added depending on the actual situation.

In the case study shown in Chapter 6, non-linear design optimization was used to ensure adequate customer satisfaction can attain within limited resource for developing a new product.

In many cases of product design optimization, product weight and size is taken as the highest concern. This is because little increase in product weight or size will reduce the customers buying desire significantly. For examples: notebook computer and mobile phones should be as light and compact as possible because this kind of products is usually portable. Moreover, when the product is used in aerospace industry such as Aircraft and Rocket, the manufacturers may not be able to afford expensive experimental testing to modify and improve the design. Also, their development cost may depend heavily on the product weight and size for optimization. Therefore, FEA and numerial optimisation techniques are used to optimize the weight of the drill-bits (the most important part) of the “Rock Corer” in Chapter 6. The result shows that the total weight of sampling drill-bits was reduced over 76.7 %. This makes customers more satisfactory and increases their acceptance. The proposed methodology can also be applied in different engineering design applications and provides a total integrated solution as a generic template for design engineers in developing a new product.

8. CONCLUSION

8.1 Future works

Although the proposed FDM model has shown to be useful in certain applications, some further investigations is necessary to enhance the solution:

- TRIZ method can be introduced and integrated into the proposed model to facilitate product innovation more systematically in the technological perspective.

- The built-in Application Programming Interface (API) of the solid modelling software can be used to develop an add-in module for Solid modeller in the proposed system. Further modifications on this module may be needed to allow the end users to use it more easily.

- Since the current FDM Development Tool can only handle matrix up to 5 x 5, it may be necessary to modify it to handle higher dimensional matrix in some complex cases.

- Internal and external verification in the last phase of the proposed cycle should be carried out by some means such as questionnaire or interview for checking the customer expectation with the final product.

- Multi-objective optimization can be further investigated and improved to make the current model tackle more realistic problems.

- The proposed model should be tested with other different products to validate its effectiveness.
- Design optimization can be extended to the whole product assembly level instead of individual component level.
- A Knowledge-Based system for product innovation can be explored to solve the functional and physical model optimization issues.
- Customer requirements cannot be handled if they are unarticulated or fuzzy.

8.2 Achievements of the investigation

A comprehensive product development cycle that deals with the development of innovation product is presented in this thesis. In the proposed cycle, a analytic Function Deployment Model (FDM) that helps to transform customer wants and needs to a set of well-defined product functions is presented. The proposed model is based on the conventional Quality Function Deployment (QFD) model but with its capability further enhanced. The design objectives, with the aid of the proposed FDM, can be clearly defined to find the optimal trade-off between customer requirements and design resources. To facilitate the implementation of the proposed methodology, an open-source FDM Development Tool with Windows based Graphical User Interface (GUI) is developed. Moreover, to demonstrate its usefulness, it has been applied to two cases. One is the "Rock Corer" model used to the design of a multi-function sampling instrument which was used in the ESA (European Space Agency) Beagle2 Mars Express mission. Another case is the "Miniaturized micro/nano injection molding machine" which is used to fabricate micro plastic parts. In addition, the proposed model can be extended to solve a variety of design problems having multi-objectives after some modifications.

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