An Intelligent System for Sustainable Product Design at the Concept Development Stage

Kevin C. Tseng[1], Borshy Lin[2] and Chang-Mu Han[3]

[1]Chang Gung University, ktseng@pddlab.org
[2]National Chiao-Tung University, borshyhlin@mail.nctu.edu.tw
[3]Chang Gung University, chan@pddlab.org

ABSTRACT

Recent studies have proposed a product design and development model that includes consideration of sustainability in order to solve serious ecological issues and environment problems. However, emphasizing the benefits of concept development at an early stage only partly addresses these issues. A more significant problem is that design systems are insufficient to assist designers to manage requirements and develop products. Therefore, in the paper, a significant and intelligent design system has been proposed. During the design process of SPDD, the system allows designers to establish the concept without limits of time and distance because of its web-based structure. Furthermore, sustainability derivatives management provides a design that will determine requirements efficiently. In the end, a case study was suggested to apply and test the system.

Keywords: intelligent system, sustainability, product design, function deployment.
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1 INTRODUCTION

Awareness of ecological issues and environment problems has been emphasized for more than two decades [1]. In addition to authorities all over the world announcing policies for protection of the environment, many scientists proposed new approaches to solve the ecological issues and waste management problems. For example, the United Nations stipulated the Kyoto Protocol for fighting global warming; the European Community announced the Waste Electrical and Electronic Equipment directive (WEEE) and the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment directive (RoHS) for setting collection, recycling, and recovery of electrical and electronic goods; and the United Nations proclaimed the ISO 14000 series for set to provide guidelines for organizations so that they can minimize their impact on the environment [2-5]. On the other hand, scientists analyzed the relationship between ecology and the economy, and they proposed many solutions such as EcoDesign, Life Cycle Engineering (LCE), and Design for X (DfX) [6-8] to decrease negative effects of growth on the environment, and to balance economic growth and environmental considerations to achieve sustainable development.

In order to achieve sustainable development, the essential concept is to incorporate product life cycle design (PLCD) into the design process. PLCD provides a solution for reduction of waste and recycle and reuse of products. Therefore, most current research applies computer-aided systems or services to help designers, who play significant roles in the sustainable product design process [9], complete the projects [10].

However, most studies show that product development teams leave life cycle design for the final stage of product development and comply with the requests of directives during product development or develop sustainability in parallel through the entire design process, which causes inefficiency because of feedback and rechecks in every design stage [11-13]. Therefore, Johansson indicated that there will be a lot of benefits such as reduced cost and higher efficiency if sustainable design were incorporated into the very beginning stage, which is one of the goals in this study [8]. Moreover, in the product development and design process, designers have applied computer-aided design (CAD) software such as Pro/E, Alias, and AutoCAD to sketch ideas as 3D models and produce prototypes. However, some studies have indicated that design tools and assistances are still insufficient for designers to develop products, especially at the early conceptual stage [10, 14]. Furthermore, the available CAD software mostly is not suited for design at the early concept development stage because it lacks a generative and managing mechanism to help designers evaluate and choose ideas efficiently. Therefore, this study aims to develop an intelligent system based on the sustainable product design and development (SPDD) model to incorporate sustainable design into early concept development stage and emphasizes a generative and managing mechanism to assist designers determine key themes in the early stages efficiently.

In the following sections, section 2 describes the concept of sustainable product design. First, the model of SPDD which is based on innovative product design and development (IPDD) approach will be introduced. Second, the integration of SPDD into the sustainable product design system and its architecture is presented. In section 3, the system is applied to design a clinical display to verify the application. Furthermore, the flow of sustainable product design and the SPDD system will be discussed based on the verification of the clinical display in section 4. Finally, section 5 concludes the study.

2 METHDOLOGY

In this study, in order to develop a SPDD system, we applied IPDD and quality function deployment (QFD) to develop SPDD. First, the main concept of IPDD is to develop and design a product in the early conceptual development stage. Second, QFD is a significant design technique which turns customer requirements into comparable quantities for designers to evaluate. Third, we depended on the design process of SPDD to establish the architecture of the assistant design system. Finally, the SPDD system was developed.

2.1 Concept of SPDD

2.1.1 Green QFD

QFD is a significant method used to transform customer requirements into comparable design quantities and help designers efficiently evaluate and determine priority to user requirements [15]. According to QFD, design quantity can be organized and become a house of quality. The house of quality is a matrix that incorporates design characteristics based on customer needs, but it is a tool for analysis. Designers can also communicate with customers using the house of quality to define the customers' needs. On the other hand, QFD for the environment (QFDE), which is one of the proposed approaches for sustainability, incorporates environmental considerations into QFD [16].

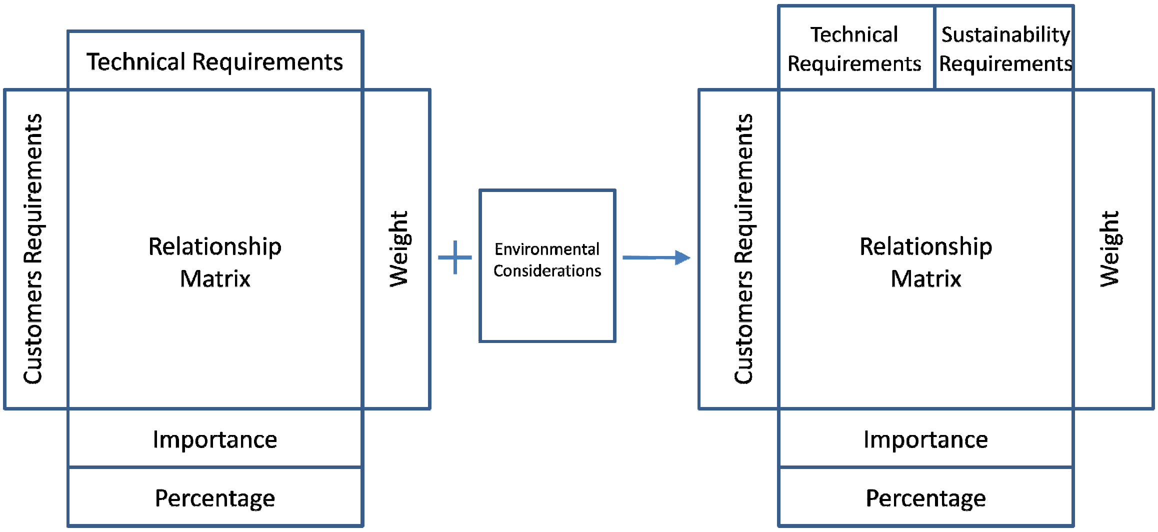


Fig. 1: Traditional QFD (left) and green QFD (right). After incorporating environmental considerations into QFD, it becomes green QFD.

However, QFDE needs to complete four phases to obtain the final decision of design [16], which is complex and inefficient. Therefore, we learned advantages from both QFDs and proposed a modified, green QFD, to be more suitable for our SPDD system. Fig. 1 shows all the elements that comprise green QFD. The column of customer requirements and relationship matrix are the same as traditional QFD. However, the sustainability requirements, which come from the directives and policies [2-5], are incorporated into the technical requirements in order to directly calculate the weight and importance. The percentage shows the degree of importance (percentage = one of importance/ sum of importance).

2.1.2 Design process of SPDD

SPDD is based on IPDD. IPDD, which was proposed by Tseng et al. [17], is a new product design and development approach in order to modify the inconvenience and misalignment of the conventional cascading design process and integrate the techniques of different domains to achieve customer requirements in the early design stage. Therefore, we learned from IPDD to develop SPDD. However, there are two differences between IPDD and SPDD. First, we modified the design process of IPDD in order to be more suitable for developing the system. Second, we integrated sustainability checking and green QFD analysis into the second and third stage of the design process of SPDD. Thus, the process of SPDD can be simply categorized into four steps, as shown in Fig. 2: (a) definition of customer requirements, (b) product design, (c) prototype manufacturing, and (d) demonstration of product and feedback from customers. On the other hand, there are some advantages to integrating sustainability checks and green QFD in the first and second stage. First, we can increase the efficiency of design, compared with the design model which checks sustainability in every stage [13]. Second, putting green QFD in the end of the second stage would help designers develop sustainable product design comprehensively after customer, design, and engineering requirements and sustainability checking were finished.

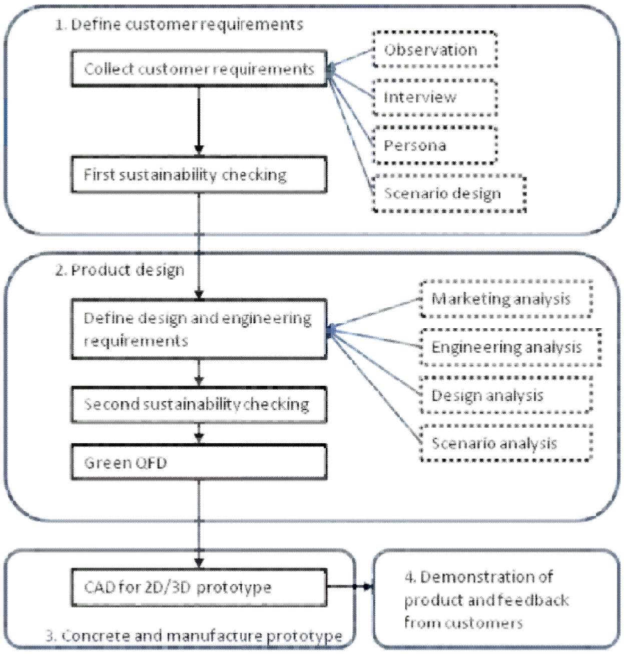


Fig. 2: Design process of SPDD.

The dashed rectangles represent design methods or analyses. In the first stage, we apply observation, interview, persona, and scenario design to collect the customer requirements directly. Furthermore, the end of this stage is the first sustainability checking for the emphasis of concept development in the early stage. In the second stage, there are three steps: First, start with marketing, engineering, design, and scenario (MEDS) analysis in order to define design and engineering requirements. Second, check the sustainability for the second time and confirm the requirements. Third, construct green QFD depending on these requirements. In the third stage, apply CAD software such Pro/E, Alias, and AutoCAD to manufacture the prototype. Finally, demonstrate the prototype to customers and get feedback.

2.2 SPDD System

In this section, we focus on developing a system-generative and managing mechanism. The system can be classified into four modules: a personnel management module (PMM), marketing module (MM), techniques definition module (TDM), and assistant design module (ADM). The description of system architecture and each module is as follows:

2.2.1 Overall system architecture

The SPDD system is a web-based system in order to get rid of the limit of time and distance and include the consideration of system performance and information security. The architecture, which is shown in Fig. 3, can be classified into three parts: interface, server, and database.

Fig. 3: System architecture.

First, according to the web-based system, designers can use the system without the limit of an operating system and simply apply ordinary browsers to use the system. Therefore, the system supports multiple users' simultaneous application for discussion and communication online. Second, in order to use the system without the limit of operating systems, we applied Apache as the server and developed it by means of HTML, PHP, and JavaScript. Third, the web application was developed using PHP. We used MySQL to create the database because PHP supports most databases such as Oracle, Informix, and MS-SQL. Furthermore, in order to ensure data security and system performance, the database is managed by one particular server; different users have different users' limits of authority (LoA) for the separated database at server.

Fig. 4 shows the flow of manipulation of the SPDD system. The system identifies the user before releasing suitable LoA. Then, customers and administration staff with low LoA only update news and suggestions. The project manager (PM) can set customer and technical requirements and choose sustainability requirements through the system after discussing them with clients and developers. Moreover, only the PM can set and modify the requirements in green QFD. However, the PM, clients, and developers have the authority to review archives.

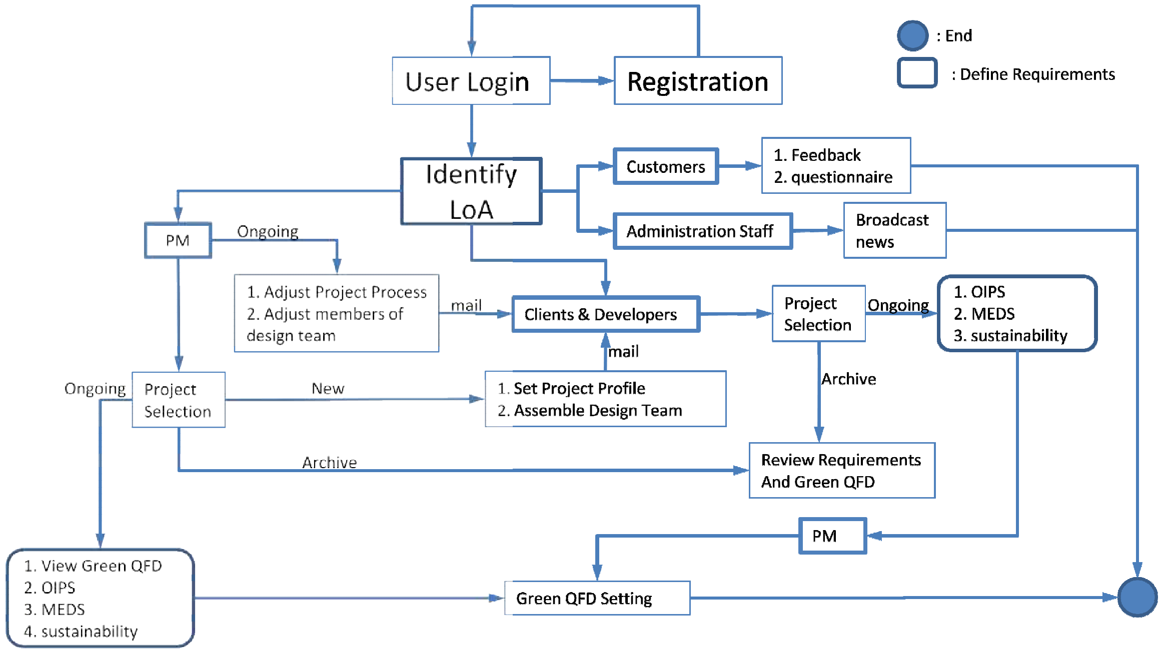


Fig. 4: Flow of manipulation of the SPDD system.

2.2.2 Personnel management module

The personnel management module (PMM) defines the different LoAs and users in order of system information security and human resource management. The module will release authority depending on the user. The highest authority is assigned to the PM, who needs it for supervision, convenience, and decision making. The PM needs to supervise the project, decide the starting and finishing dates and process sequence of the project, and determine the specific requirements of the project. Furthermore, users with the second level of authority are developers, such as designers, engineers, and manufacturers, as well as clients, who can construct sub-projects and QFD. However, the final requirements of QFD are decided by the clients, PM, and developers and set only by the PM. Moreover, users with the third level of authority are customers who can log in the system for feedback and questionnaires. In human resource management, the module helps the PM manage members in different domains and choose suitable members to group a design team at the beginning of a new project. Fig. 5 shows the member selection in the system.

Fig. 5: Human resource management for member selection.

The first block shows which members that the PM can add to the project, the second block is the member list which has already been categorized into the MEDS domain and others in the system, and the third block shows the current PM and project. Moreover, the PM still can trace the finished project during new project development for review.

2.2.3 Marketing module

The purpose of the marketing module (MM) is to realize the market trends and understand customer requirements when new product development begins or a product needs to be improved. Therefore, this module can be classified into feedback and questionnaires. In feedback, there are two avenues for customers to provide feedback: one is through administration staff, and the other one is through the system by customers themselves. In the questionnaires, the purpose is for the PM to collect advice and suggestions before and after product development.

2.2.4 Techniques definition module

This module includes requirements, evaluation, and analysis:

Requirements: It represents customer, design and engineering, and sustainability requirements. Following the design process of SPDD, the PM, developers, and clients need to get together and brainstorm the requirements. During the process, this module helps users save and amend the requirements for constructing green QFD. Moreover, the sustainability requirements have been programmed for users to choose the directives conveniently, which is shown in Fig. 6. Users decide which directives are feasible in the project or define a new one for the specific project. All the directives can be traced and reviewed in the system whenever the design team wants to determine whether the customer requirements comply with the directives.

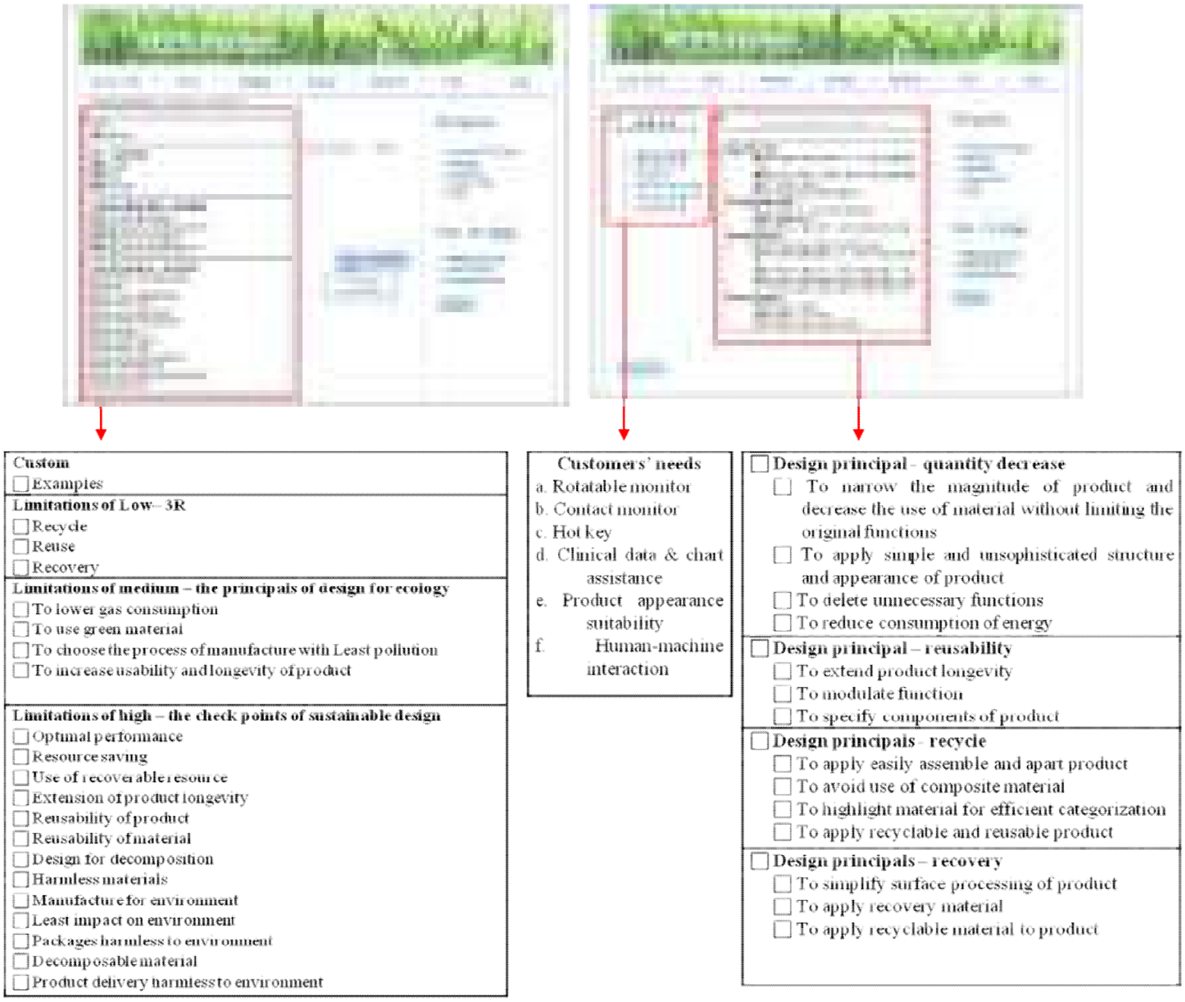


Fig. 6: The first block shows the directives with three kinds of levels or users defined. The second block shows the customer requirements. The third block is the sustainability derivatives which have been chosen from block 1.

Evaluation: After all the requirements have been defined, the system provides the PM a convenient mechanism to manage and fill in the requirements. Then, developers depend on their expertise to evaluate the relationship between customer requirements, design and engineering, and sustainability requirements and fill them in QFD.

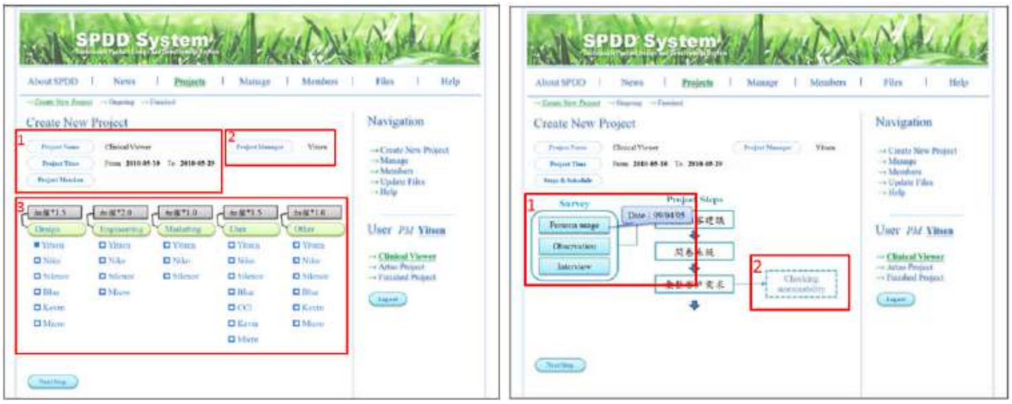
Analysis: After the requirements and relationship weights have been chosen and filled in, the system automatically analyzes the weight, the importance, and the percentage in green QFD for further consideration.

2.2.5 Assistant design module

The assistant design module (ADM) provides three integrated functions to help the design team. The E-mail and bulletin board functions support asynchronous communication among the PM, developers, clients, and customers. In addition, a human resources management function helps the design team to review and look for suitable members joining the design process. When invited people agree to involve this design process, automatic E-mails will inform the PM whether they have interesting in participation after the PM chose his/her team members.

3 THE CASE STUDY

In order to test the SPDD system, we applied it to design and develop a clinical viewer. We cooperated with a company and held the study with doctors in the Chang Gung Medical Foundation in Taiwan. The following is the procedure of product design and development based on the SPDD system to show how the system works. According to the process of SPDD, first, customer requirements need to be defined. The PM started the new project and recorded the project name, project profile, and starting and finishing dates in the system. After the preliminary information was set, the PM represented all the members with different expertise in the system so that he could choose and assemble efficiently the required designers, engineers, and manufacturers. Fig. 7 (a) shows the personnel management module. The PM (block 2) has already set the essential data of the project (block 1) and the developers who could be chosen were separated into different domains depending on expertise (block 3). Furthermore, the PM also set the weight of each domain to decide which options of the domain are more important. All the participants will be informed by e-mail automatically because of ADM.



(a) (b)

Fig. 7: (a) Preliminary settings and project members choosing and weight. (b) The problems could be saved in different folders to facilitate their management.

In this case, we visited a clinical room and applied observation and interview techniques to collect problems which doctors might encounter while diagnosing. Fig. 7 (b) shows that all the problems which we collected from observation and interview were imported into the system (block 1), and the first sustainability checking was done (block 2). The system will automatically order and list the sustainability directives for the design team to easily and conveniently choose and delete the customer requirements if they do not comply with the sustainability demands (shown in Fig. 6). Therefore, the potential requirements have been summarized and shown in Tab. 1.

Customer	Design & engineering	Sustainability
Convenience of diagnosis	*Marketing*:	Energy consumption
Direct manipulation	Essential functions	Product material reduction
Simple usage	The specifications	Product volume reduction
Clinical data & chart assistance	*Engineering*:	Modulisation
Product appearance suitability	Water & dust proof	Simple structure
Human-machine interaction	Control key for setting	Unnecessary functions deleting
	PACS system	Usage life prolonging
	Display supports	Assemble simplification
	Heat dissipation	Manufacture simplification
	Design:	
	Appearance	
	Scenario:	
	Rotatable display	
	Contact display	

Tab. 1: The potential requirements in clinical room.

In the second stage of the design process, the design team has to define the design and engineering requirements depending on the MEDS analysis:

Marketing analysis: We collected the relative product made by other companies and identified the essential functions such as high number of pixels, high contrast, high luminous flux, etc. On the other hand, the specifications of a clinical liquid crystal display (LCD) are much stricter than those of a normal LCD. For example, clinical devices need to comply with the three class regulations [18].

Engineering and design analysis: In addition to complying with the essential functions and specifications, the systems needed to include a picture archiving and communication system (PACS). PACS is a system to manage digitalized clinical images such as X-ray and MRI images. However, doctors who apply the system to download clinical images for diagnosis often use functions such as zoom in and out, drag, and simple measurement by mouse which can be achieved instead by contact display for efficient and direct manipulation. Furthermore, according to the customer requirements and engineering considerations, display supports are the key to achieve convenience of diagnosis. Heat dissipation is also an essential function for a display to operate for a long time. On the other hand, based on product appearance suitability from the requirements, we emphasized that the appearance of the clinical viewer needed to be designed to match the environment of the clinical room.

Scenario analysis: We simulated the clinical routine when the doctor diagnoses the patient and grouped three scenario analyses. One is a medical examination by interview and touch, the other is diagnosis by watching the viewer, and still another is a clinical report key-in. An example of the scenario analyses is as follows:

After the doctor downloaded the clinical images such as X-ray or MRI from PACS and showed them on the traditional CRT or LCD, the doctor explained the symptoms and diagnosis. During the examination, the patient only listened to the doctor and usually imagined the illness conditions by himself. After finishing the examination, the doctor keyed in the clinical report and printed it out for further examination.

In the scenario analysis, some possible problems that doctors may encounter are apparent. First, the doctor explained the symptoms to the patient but the patient can only imagine the illness conditions. Second, the doctor needs to key in clinical report, which means there are some techniques for the doctor to describe symptoms more clearly. Therefore, the analysis identified a rotatable contact display as a requirement. Finally, the sustainability requirements were defined by the design team who referred to the directives set by the PM. The requirements also were shown in Tab. 1. All the requirements including customer weight need to be uploaded to the system for management and for analysis of green QFD. Fig. 8 shows the environment of the green QFD in the system to set the relationship score.

4 RESULT AND DISCUSSION

After observation, interview, MEDS analysis and two times of sustainability checking, the requirements have been introduced into the green QFD. All the data were collected and accumulated from the relevant domain, clients, and media. Therefore, after setting the preliminary score relationship of each requirement, the system calculated the final importance, percentage, and weight. Thus, green QFD could be completed and showed the rated techniques and sustainability importance and rated customer requirements weight in Fig. 9. According to the importance and weight, the top three priorities of customer requirements are direct manipulation, human–machine interaction, and simple usage. Therefore, the corresponding techniques are contact LCD and control key for setting. Then, considering the sustainability requirements, we applied the CAD software-Pro/E-to sketch the prototype of the clinical viewer model. The prototype, shown in Fig. 10 (a), allows the doctor to show the clinical images to the patient directly without moving the display, or to print out clinical reports because of the rotatable LCD. Furthermore, the clinical viewer also allows the doctor to directly manipulate the images by hand through the monitor; he or she can even use a pen to write down symptoms and give a prescription through the monitor, in order to express the diagnosis clearly. All the feedback and questionnaire data regarding the doctor can be collected by the marketing module.

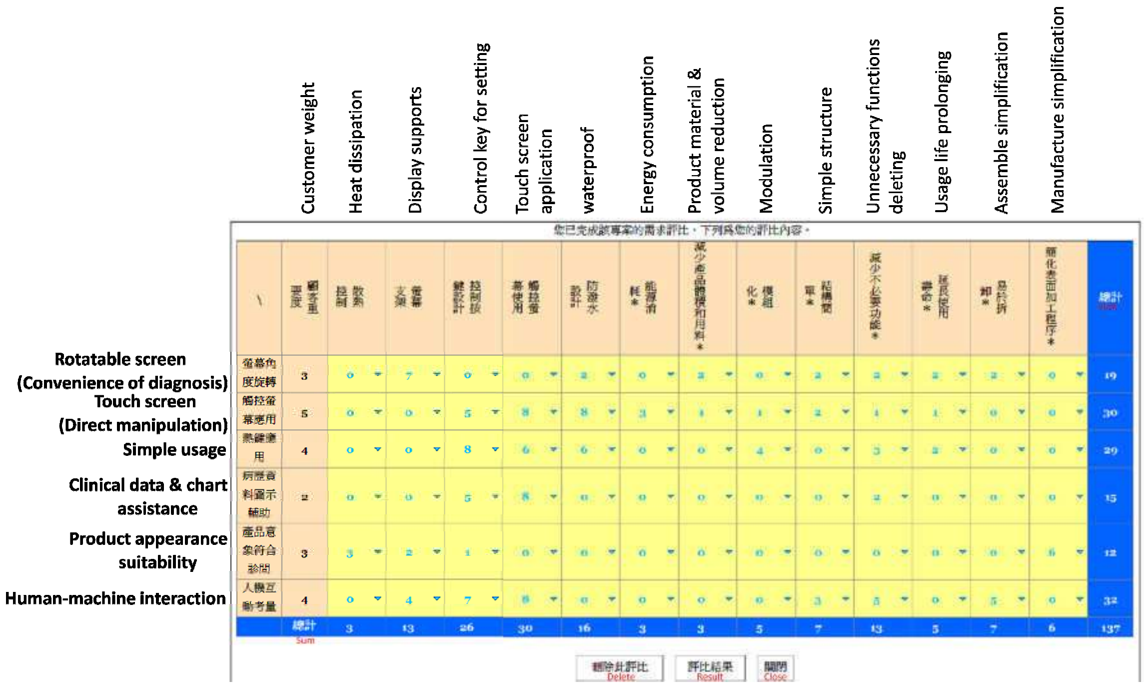


Fig. 8: Green QFD of clinical viewer before analyzing.

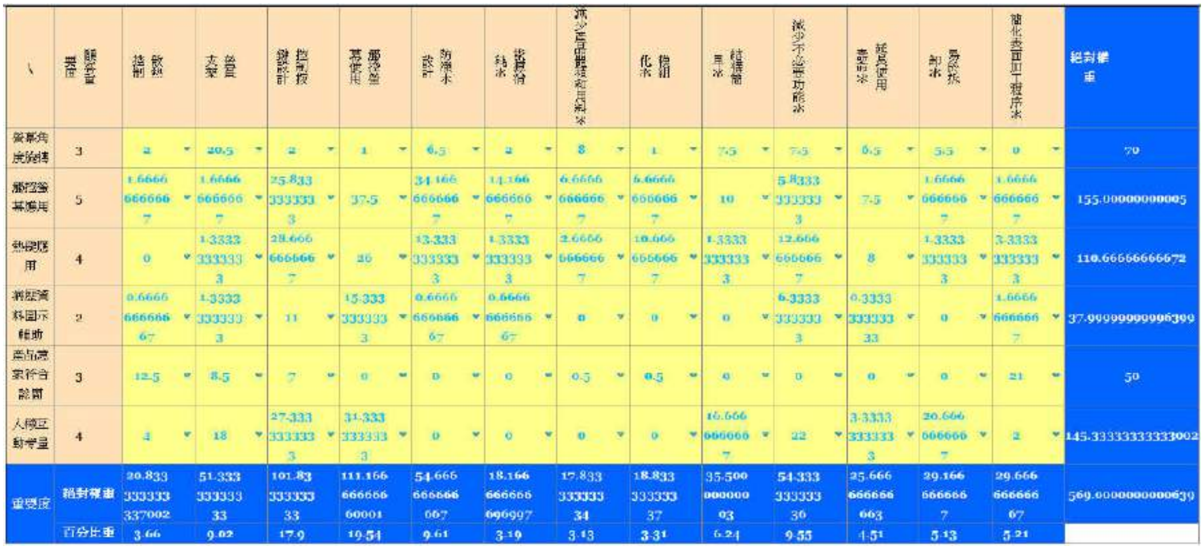


Fig. 9: Green QFD of clinical viewer after analyzing.

In the traditional process of diagnosis, a doctor normally uses a “light box” which is just next to him or her to light up clinical images to diagnose symptoms, and the patient sits in front of or next to the doctor (see Figure 10 (b)). This arrangement prevents the patient from seeing the clinical image directly. Therefore, applying the clinical viewer, the doctor can adjust the LCD to let the patient view the symptoms and manipulate the images to assist the patient’s understanding. Furthermore, removing the light box will increase the space in the clinical room.

On the other hand, comparing with PLM system including CAD toolkits, the salient advantages of the proposed system are revealed. First, some conventional PLM process sets CAD at late development stage after collection of information has been finished. For instance, Ding et al. [20] proposed a framework for product lifecycle which enhance interaction between different departments of a design team and information sharing throughout design process. Second, most literatures of product design and development do not include the considerations of sustainability and cannot efficiently help designers develop ideas at early stage. For example, Sudarsan et al. [21] described a new approach to seamlessly interoperate each domain in design team with all information during design phases because of the problems that are relative to information cohesion and traceability, CAD modelling at early stage, and changes of modelling based on latest information. Kiritsis et al. [22] developed an information tracking and flow management system in order to enhance the information flow at the late product lifecycle stages. However, the proposed system assists a design team to develop concepts at early stage because the system provides a mechanism for sustainability selection which is incorporated in concept development at first stage. Except sustainability of directives, the system could also include industrial standards such as ISO standards for designers, engineers, and manufacturers to avoid potential problems at the early stage as future works.

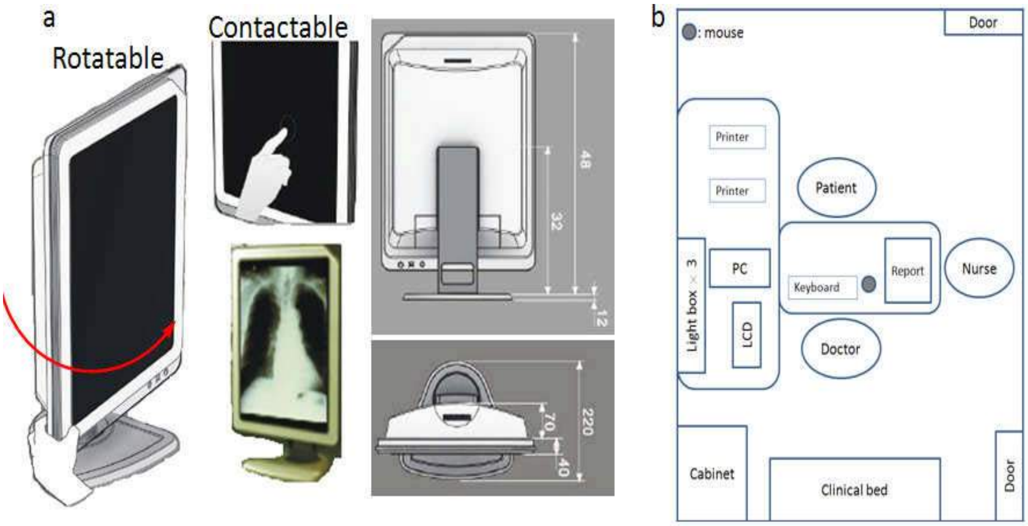


Fig. 10: (a) Prototype of the clinical viewer; (b) furniture of clinical room.

5 CONCLUSION

We have presented a significant SPDD system included a generative and managing mechanism to help designers consider sustainability in the early design conceptual development stage. The advantages of the system are, first, the emphasis of the SPDD design process helps users consider sustainability in the early design stage, which can bring many benefits. Second, users won't be limited by time and distance because of the system's web-based structure. Third, sustainable directives have been imported into the system in order of users' convenience and comparison between the three kinds of requirements. Fourth, the generative and managing mechanism helps designers manage requirements.

In the case study, according to the opinions of doctors and patients, we discovered factors contributing to dissatisfaction with the examination process. Therefore, we applied the SPDD system to design and develop a clinical viewer and proposed the improved clinical viewer to help the situation. However, customer requirements obtained by observation and interview may include designers' subjective viewpoints. Therefore, in the future, we will incorporate more vigorous and objective analysis such as the analytical Kano model [20] into the system in order to provide more robust and comprehensive analysis of customer requirements.

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