A Product Development System using Knowledge-intensive Support Approach

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Abstract: The author is carrying out research studies to explore the applicability of knowledge-based system technologies to today's competitive product design and development, with an emphasis on the design of high quality products at the design stage. A framework of knowledge-intensive support approach for new product concepts is proposed in this paper. Based on the proposed approach and methodologies, a prototype system named KB@Pds, which can assist inexperienced users to perform the process in design and knowledge management. KB@Pds integrates the intelligent design process and knowledge management. This paper presents the underlying concepts of the development and shows the practical application with the prototype system with a case study.

1 INTRODUCTION

The new product development task is a highly iterative process which involves a substantial heuristic knowledge component about areas of customer requirements, product design specifications, production and tooling requirements, etc. Product designers are required to possess a high standard of specific knowledge and experience because design decisions require intensive knowledge and interaction between different parameters. Product design does not result from a sole quantitative analysis but comes within a range of design procedures and decision makings. Individual components of the design may be opened to quantitative analysis, but these do not help the designer to establish the overall aspect of the design, particularly in the conceptual design stage in which the design details are not yet available. The general decision making process required at the conceptual design stage (as shown in Figure 1) for a new product development project.

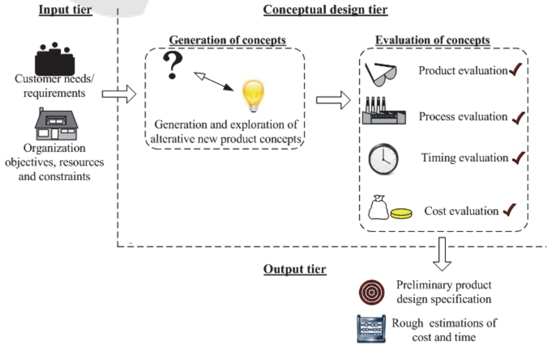

Figure 1: Decision makings in conceptual product design.

The aim of this paper is to discuss knowledge support methodologies and technologies for product design. An integrated modular product design process with knowledge support is explored. This process includes customer requirements modeling, product architecture modeling, product platform establishment, and product assessment. The followings present a knowledge-based assisted product design system, KB@Pds, to support inexperienced users to perform the product analysis and making evaluation decision at the conceptual product design stage. The organization of this paper is as follows. Section 2 describes an analysis of the product design process based on the product designer's perspective. Section 3 outlines the framework of a knowledge-based assisted product design system. Section 4 addresses the relevant

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issues and technologies for implementing the knowledge-intensive support approach for product design. Section 5 summarizes the paper and point out the future work.

2 REQUIREMENTS OF THE PRODUCT DESIGN PROCESS

To develop a good product design process, an analysis of ‘what they have’ and ‘what they want’ needs to be performed. First of all, what they have: (1) the customer’s requirements for the product. This includes the detailed geometry and dimension requirements of the product; (2) an existing product design library. This library covers the standard or previously designed components and assemblies of the product design; (3) n expert knowledge in product design. Expert knowledge for product design is obtained mainly from experienced product designers. Such knowledge includes material selection, geometry suggestion, alternative design evaluation and others. What they want: (1) an intelligent and interactive product design environment. Product design is often composed of a series of design procedures. These procedures usually require certain parts to be created and existing parts to be assembled. An intelligent and interactive environment will be a good choice to integrate some useful automation algorithms, heuristic knowledge and on-line interaction by the experienced product designer; (2) standard/previous designed components/assemblies (product-independent parts) management. Apart from the parts that are similar in structure and geometrical shape that can be used in other product designs. These parts are independent of the products. They are mostly standard components that can be reused in different product designs; (3) useful tools (including solid design and analysis calculation) in product-dependent parts design. Geometrical shapes and the sizes of the component system are determined directly by the product. All components in such a system are product dependent. Also, these parts are the critical components in the product design. Their geometrical requirements may be complicated. Thus, some tools developed to design the component based on partial automation and partial interaction can be quite useful; (4) design for assembly. In conventional CAD/CAM systems, components are represented and stored as a complete geometric and topological solid model. However, this form is not appropriate for tasks that require decision-making based on high-level information about product geometric entities and their relationships. Product designers prefer a design for assembly environment instead of a simple solid model environment (Desai and Mital, 2010); (5) a design for manufacture. A complete product design development can be composed of the design and manufacturing process. To integrate CAD/CAM into the product design, the manufacturing features on the component should be abstracted and analysed for the specific fabrication.

Based on the above analysis, the research focus is to develop techniques to represent ‘what they have’ and ‘what they want’. Representing ‘what they want’ is actually the representation of the knowledge and product object. Developing ‘what they want’ means to integrate the representation with intelligent and interactive tools for the product design into a completed design environment. Therefore, a KB@Pds is proposed for product designers to realize the above two requirements.

3 FRAMEWORK OF PRODUCT DESIGN

3.1 Knowledge Support Scheme and Key Items

Figure 2 shows the process of product concept development, which is composed of several phases – generation of concept, development and evaluation, as well as concepts filtering. Knowledge-based assisted systems are proposed to support decision-making throughout the whole process of concept development. In the phase of concept generation, a customer requirements review is conducted based on customer inputs. After confirming the customer requirements, the design features and specifications will be formulated as the inputs to the next step of conceptual development process. In the phase of development and evaluation, two knowledge-based modules are proposed. A knowledge-based system of product information determines the most appropriate elements, e.g. components, material, and tool, etc., based on the product concept and requirements. Another knowledge-based system of process planning decides the process plan for the product in manufacturing. With these outputs, the alternative product concepts will be compared with the aid of a decision support system to confirm the most suitable option.

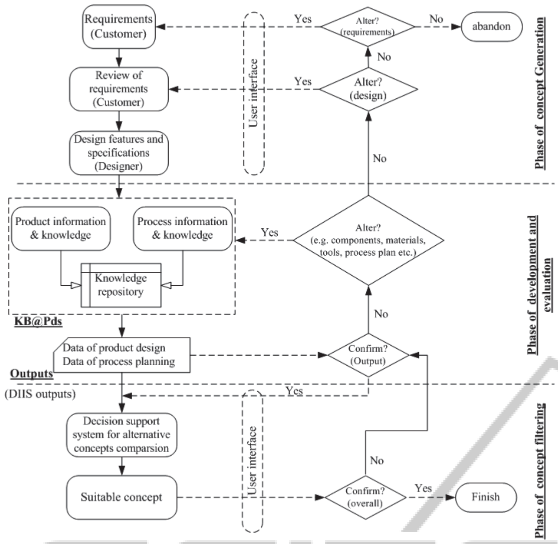


Figure 2: Framework of proposed product development system.

3.2 Product Design Knowledge Modelling and Support

According to the above knowledge support scheme, the implementation of knowledge-based assisted product design can be achieved through two steps: (1) knowledge modeling; (2) the knowledge support process, which are described in this section.

3.2.1 Product Design Knowledge Modeling

Fig. 3(*a*) illustrates the aspects related to product design knowledge modeling, which include design knowledge capture, classification, representation, organization and management. The approach to modeling information and knowledge for product architecture and platform in terms of the semantics used in platform product development is shown in Fig. 4(*b*). The product structure and components of the generic information platform are represented in the physical domain of axiomatic design and configuration rules and mappings are represented as criteria and mappings between the functional, physical, and process domains. It contains modeling constructs for representing alternatives, configuration rules and many other aspects of product platforms. The purpose to adapt the conceptual model to a standard: (1) provide functionally and detailed information models; (2) support the exchange of information between applications and users (Sivard, 2001; Zheng, 2006). With assistance of the product platform, customers' requirements are satisfied either by standard models or customer models configured from standard or custom modules and/or components in knowledge-based configuration systems.

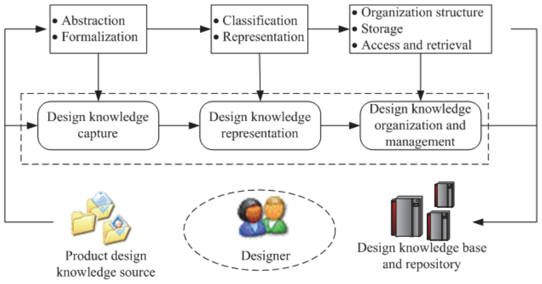


Figure 3(*a*): Knowledge modeling in product design.

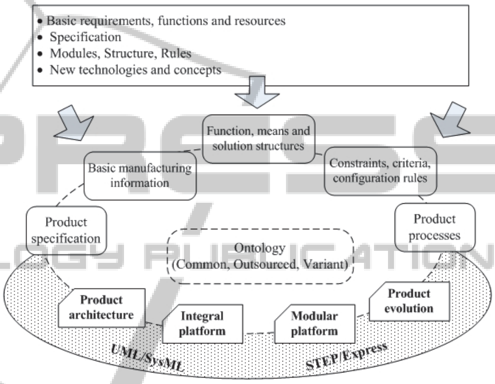


Figure 3(*b*): Generic platform information model.

3.2.2 Knowledge Modelling and Representation for Product Design

Following the requirements of designing product with a high degree of commonality around reusable components, there are two main items of the architecture are: (1) generic product specifications and (2) reusable solution libraries. Product architectures and component architecture are treated in a similar way, enabling a hierarchical structure of structures. Thus, components may be selected from the solution library and integrated into the framework.

Figure 4 shows the construction process of product platform (**Step *I*** – **Step *IV***) and the reuse for domain-specific applications (**Step *V***). Hence, a multi-level hybrid representation schema, e.g. meta tier, conceptual tier, instance tier, geometric tier, is adopted to represent the product design process knowledge in different design stages at different tiers, based on a combination of elements of semantic relationships with the object-oriented data model. To effectively manage and utilize design knowledge, a generalized design knowledge matrix is proposed, in which all tasks in the design process are listed in column while all information and design knowledge is categorized in rows. The contents of design knowledge for each task are recorded in the corresponding cell of the matrix with appropriate representations. Meanwhile, the object-oriented knowledge representation is based on a mixed representation method and object-oriented programming techniques (Liang, 2010), and allows designers to look at the design problem as a collection of objects or sub-problems linked together by rules. If a designer can break the design problem into the form of well-defined, clearly manipulative chunks with their own self-containing information, which is interrelated through a series of rules and constraints, then the problem can be easily solved. The class of an object and its instances are depicted by the module structure. An object-oriented module is composed of several kinds of clusters: attribute, relation, method, and rule: (i) Cluster *attribute* is used for depicting the static attributes (parameters) of design object; (ii) Cluster *relation* is applied for expressing the static relations among objects. According to the relation of classification, the design object can be defined as a hierarchical structure. The hierarchical structure of object-oriented knowledge representation is formed; (iii) Cluster *method* is defined for storing the methods of design, sending messages and performing procedural control and numerical calculation; (iv) Cluster *rule* is used for keeping sets of production rules. The rules can be categorized in accordance with the differences among objects being treated and stored respectively.

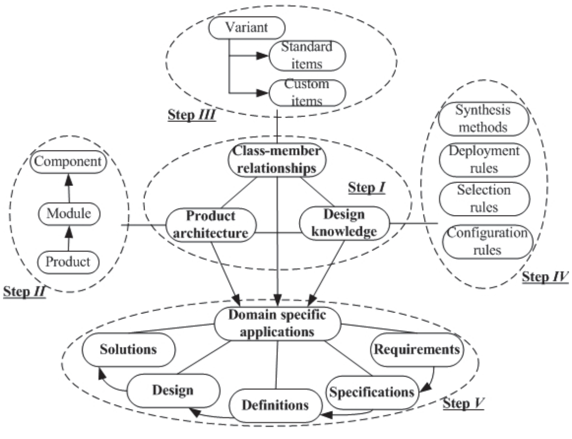


Figure 4: Diagram for product platform construction process.

The integrated knowledge representation scheme realizes the advantages of both object-oriented representation and rule-based representation. For example, an object-oriented representation instance for 3D polarized glasses suit and its parameterized module information (e.g. bond and hinge modules) are described. The modular design is proposed (Liang, 2010), i.e., it is a collection of interchangeable modules that can be assembled into many different types and configurations. The model presented above is being incorporated and fit into the core product model (Szykman and Sriram, 2006) developed recently at US National Institute of Standards and Technology. In this connection, we define a platform product represented by Class ***Platform_Product*** in the Package ***Platform***. Information about differences between the product members can be used for the development of an extensible architecture of the common core assets, and two processes may be involved: platform/component construction and platform/component evolution. ***CCM_Product*** (component construction model) and ***CEM_Product*** (component evolution model) are subclass of ***Platform_Product*** and ***Product***, representing product platform (component) to be constructed and evolved. These packages can support component design for customization.

3.2.3 Knowledge Support Process for Module Product Design

Once the design knowledge repository is built up, the user or designer can utilize the knowledge in it to solve problems in product design. Product variety can be implemented at different layers within the product architecture. A modular architecture has clearly benefits in the areas of cost, product performance and development.

Consequently, the procedure for developing a modular product design can be outlined as follows: (i) decompose products into their representative functions; (ii) build modules with correspondence with functions; (iii) organize common functional modules into a product platform; and (iv) standardize interfaces to facilitate addition, removal and substitution of modules. The fundamental issues underlying the product design include product information modeling, product component architecture, product platform and variety, modularity and commonality, product generation, and product assessment and customization. Incorporating the above stages, the whole knowledge supported modular product design process can be fulfilled.

The knowledge support process in product design evaluation for customization experiences the elimination of unacceptable alternatives, the evaluation of candidates, and the final decision-making under the customers' requirements and design constraints (Mohamed and Celik, 2002). The knowledge resources utilized in the process include differentiating features, customers' requirements, assimilability, manufacturability, and heuristic knowledge (e.g. production rules), etc. In applying the above knowledge support scheme for modular product design, the following should be noted: (i) The first step, system requirement modeling and analysis, should be considered in development of a modular product design; (ii) A system and structured approach is a mandatory for development of a modular product design; (iii) A new product is developed through functional analysis, rather than modifying existing ones; (iv) Complex products or systems have a considerable amount of constraints that limit the product design.

3.2.4 Assessment of Product Design

Figure 5 illustrates an overall view of the proposed fuzzy assessment model with design failure mode and effective analysis (DFMEA), in which there are three major stages to implement the assessment: fuzzification, rule evaluation, and defuzzification (Diaz-Hermida et al., 2005; Li et al., 2005). The model firstly uses linguistic variables to depict the severity, frequency of occurrence, and detectability of the failure. These inputs are then fuzzified to determine the degree of membership in each input group. The resulting 'fuzzy inputs' are evaluated using a linguistic rule base and fuzzy logic operations to create a classification of the riskiness of the failure mode and an associated degree of membership in the risk group. This 'fuzzy output' is then defuzzified to give the prioritization level for the failure mode. The fuzzification process, using crisp gradings, converts the severity, occurrence, and detectability inputs into the fuzzy representations that can then be matched with the premises of the rules in the rule base (Diaz-Hermida et al., 2005; Li et al., 2005). The rule base depicts the riskiness of each combination of input variables. It is composed of the expert knowledge about the interactions between various failure modes and effect that is represented in the form of fuzzy 'IF-THEN' rules. There are two parts included: an antecedent that is compared to the inputs and a consequence that is the result. For example, 'IF t is P THEN u is Q' where P and Q are linguistic values defined by fuzzy sets on the ranges t and u respectively. The portion IF of the rule 't is P' is called the antecedent or premise, while the portion THEN of the rule 'u is Q' is called the consequence or conclusion. The antecedent is an interpretation that returns a single number between 0 and 1, whereas the consequence is an assignment that assigns the entire fuzzy set Q to output variable u.

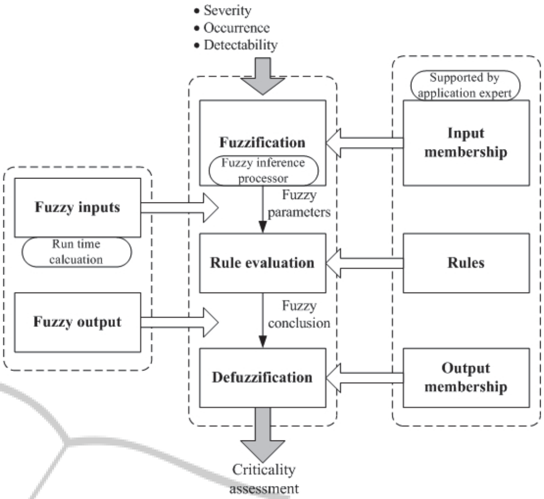


Figure 5: Diagram of a fuzzy criticality assessment model.

The importance of fuzzy 'IF-THEN' rules stems from the fact that human expertise and knowledge can often be represented in the form of fuzzy rules. For the fuzzy criticality analysis, the system expresses the seriousness of a failure through its severity, the failure probability through its occurrence and how easy a failure can be detected through its detectability. The fuzzy inference process uses min-max inferencing to estimate the rule conclusions base on the system input values (Ladneer et al., 2003). The result of this process is called the fuzzy conclusion. The applicability of a rule is determined from the conjunction of the rule antecedents. The defuzzification process builds a crisp grading from the fuzzy conclusion set to express the riskiness of the design so that corrective actions and design revisions can be prioritized. The defuzzification process is required to figure out the meaning of the fuzzy conclusions and their membership values, and resolve conflicts between different results, which may have been triggered during the rule evaluation. Several defuzzification algorithms have been developed (Li et al., 2005; Roychowdhury and Pedrycz, 2001). One of the widely used algorithms, center of gravity, is applied as it gives the average, weighted by their degree of truth, of the support values at which all the membership functions that apply reach their maximum value.

The design decision support subsystem (DIIS) consists of several main units: attributes input, criticality assessment, exploring and grading, and graphical user interaction. These units are supported by a knowledge base and a material database. The operational procedure is described in the following with reference to Figure 6(*a*). The initiatory lists created in a product analytical hierarchical structure from the design requirement review (as illustrated in Figure 6(*b*)), is input into the DIIS. Then, DIIS will conduct the fuzzy criticality assessment on the proposed components. The subsystem applies linguistic variables to depict the severity, frequency of occurrence, and detectability of the failure. All these information in design failure mode effective analysis can be represented by the commonly used triangular membership function (Novák, 2005). The evaluation criteria and fuzzy set definitions for severity, occurrence, detectability, and risk are shown in Table 1(*a*), 1(*b*), 1(*c*), and 1(*d*) respectively. DIIS finally generates the risk priority numbers to prioritize the risk of each component. The results will be screened out for components (materials) selection.

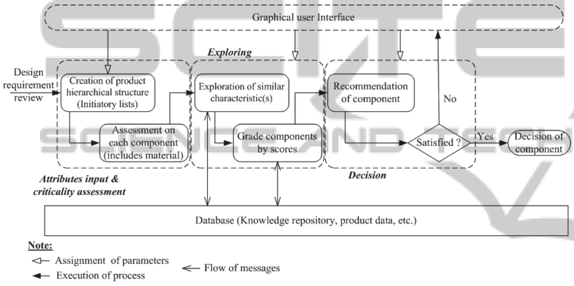


Figure 6(*a*): The architecture of design support decision.

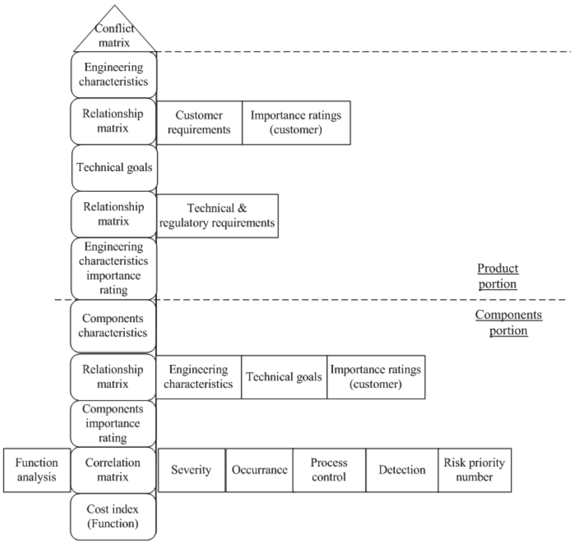


Figure 6(*b*): Check list of product and its components design review.

DIIS will then search appropriate components (materials) based on the input information. Utilizing the searching algorithm, the appropriate components (materials) are listed with grading by scores. The

Table 1(*a*): Evaluation criteria of 3D polarized glasses suit – severity.

Grade	Severity effect	Description
1	none	No effect.
2	low	Fit / tighten item does not conform. Defect noticed by most customers. Item operable, but comfort/convenience item(s) operable at reduced level of performance. Customer experiences some dissatisfaction.
3	moderate	Item operable, but comfort/convenience item(s) inoperable. Customer experiences discomfort.
4	high	Item operable, but at reduced level of performance. Customer dissatisfied.
5	very high	Item operable, with loss of primary function.

Table 1(*b*): Evaluation criteria of 3D polarized glasses suit – frequency of occurrence.

Grade	Occurrence	Description	Probability (%)	Process capability
1	seldom	Unlikely	≅ 0	≧2.00
2	low	Few	10	≧1.58
3	moderate	Occasional	25	≧1.00
4	high	Repeated	30	≧0.75
5	very high	Inevitable	≧50	≧0.51

Table 1(*c*): Evaluation criteria of 3D polarized glasses suit – detectability.

Grade	Detectability	Description
1	definite	A potential cause is definitely detected.
2	high	A potential cause is detected in high chance.
3	moderate	A potential cause is detected in moderate chance.
4	low	A potential cause is detected in low chance.
5	none	A potential cause cannot be detected, or There is no design control.

Table 1(*d*): Evaluation criteria of 3D polarized glasses suit – risk.

Grade	Risk	Description (to take the subsequent actions)
1	not important	It's not important
2	low	It's low priority
3	moderate	Moderate priority
4	important	It's important
5	very important	It's very important

objective of the grading is to prioritize alternative materials, relative to the order of importance of their attributes to the designers. A quantitative scoring system is applied for the grading process.

$R_{st} = C_{rs}+C_{cs}+C_{re}$

R_{st}: the summation of risk, cost and reliability of component (material)

C_{rs}: risk of the component (material)

in which the risk is rated from 0 to 5 with 0 is equal to ‘not important’ and 5 is equal to ‘very important’ that is determined in the fuzzy criticality assessment stage.

C_{cs}: score of cost of component (material)

that the score of cost is rated from 0 to 5 with 0 is equal to the most expensive and 5 is equal to the most inexpensive.

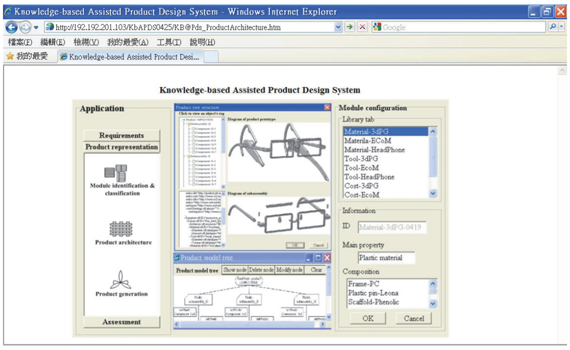
C_{re}: score of reliability of the component (material)

in which the score of reliability is rated from 0 to 1 with 0 is equal to the lowest reliability and 1 is equal to the highest reliability.

The appropriate component (materials) can then be selected by the product designer based on this information. Finally, a proposed bill of material can be created after all the components (materials) have been selected and reviewed.

4 PROTOTYPE SYSTEM

To demonstrate the operations of the prototype system, a case study on a 3D polarized glasses suit for commercial entertainment application has been conducted by using KB@Pds. Figure 7 gives a screen snapshot of the prototype system used for product design.



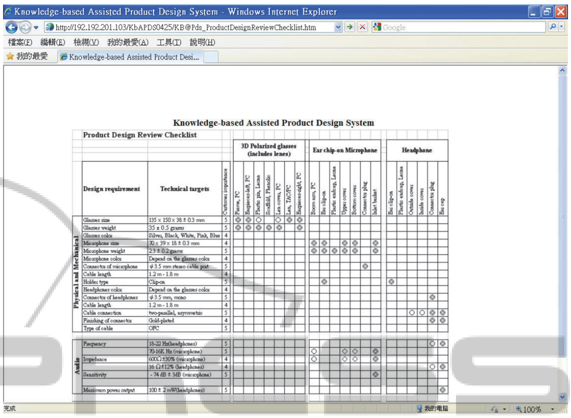
ID: Material-3dPG-0419

Main property: Plastic material

Composition: Frame-PC, Plastic pin-Leona, Scaffold-Phenolic

Figure 7: Screen snapshot of knowledge-based assisted product design system.

The 3D polarized glasses suit is applied to watch the 3D films, view 3D photos, play 3D interactive games. After input the qualitative customer requirements and product features to the phase of concept generation (Chin et al., 2005), the initiatory list was generated in design requirement review as shown in Figure 8(*a*). According to the initiatory list, the model type of the 3D polarized glasses suit was proposed to be in 3dPG215EM and the level of the product hierarchy structure was also constructed as illustrated in Figure 8(*b*).



Knowledge-based Assisted Product Design System

Product Design Review Checklist

				3D Polarized glasses (includes lenes)							Ear chip-on Microphone							Headphone					
	Design requirement	Technical targets	Customer importance	Frame, PC	Earpieces-left, PC	Plastic pin, Leona	Scaffold, Phenolic	Len cover, PC	Len, TAC/PC	Earpieces-right, PC	Boom arm, PC	Ear clip-on	Plastic endcap, Leona	Upper cover	Bottom cover	Connector plug	Inlet basket	Ear clip-on	Plastic endcap, Leona	Outside cover	Inside cover	Connector plug	Ear cap
Physical and Mechanical	Glasses size	135 x 150 x 38 ± 0.3 mm	5	◎	◎	○		○	◎	◎													
	Glasses weight	35 ± 0.5 grams	5	◎	◎	◎	◎	◎		◎													
	Glasses color	Silver, Black, White, Pink, Blue	4																				
	Microphone size	70 x 39 x 18 ± 0.3 mm	4								◎	◎		◎	◎		◎						
	Microphone weight	2.3 ± 0.2 grams	5								◎	◎	◎	◎	◎		◎						
	Microphone color	Depend on the glasses color	4																				
	Connector of microphone	ϕ 3.5 mm stereo cable port	5													◎							
	Cable length	1.2 m - 1.8 m	4																				
	Holder type	Clip-on	5									◎						◎					
	Headphones color	Depend on the glasses color	4																				
	Connector of headphones	ϕ 3.5 mm, mono	5																			◎	
	Cable length	1.2 m - 1.8 m	4																				
	Cable connection	two-parallel, asymmetric	5																	○	○	◎	◎
	Finishing of connector	Gold-plated	4																			◎	◎
	Type of cable	OFC	5																				
Audio	Frequency	18-22 Hz(headphones)	5																			○	◎
		70-16K Hz (microphone)	5								○			◇	◇		◎						
	Impedance	600Ω±30% (microphone)	4								○			◇	◇		◎						
		16 Ω±12% (headphones)	4																			○	◎
	Sensitivity	- 74 dB ± 3dB (microphone)	5														◎						
	Maximum power output	100 ± 2 mW(headphones)	5																				◎

Figure 8(*a*): Output table of design requirement review checklist.

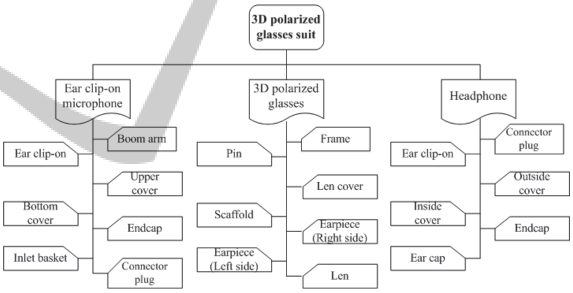
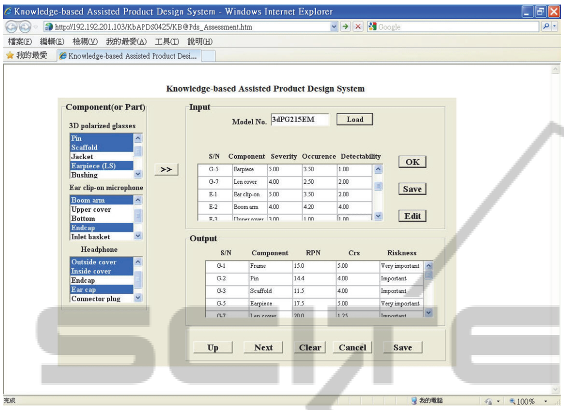


Figure 8(*b*): Hierarchical structure of 3D polarized glasses suit in model (No. 3dPG215EM).

The product designer determined the initiatory list of the proposed 3D polarized glasses suit and triggered the option boxes which next to the item list of components by processing the graphical user interface. After pressing the ‘Import’ button, the value of severity, occurrence and detectability of each component was shown on the DFMEA inferencing interface, the product design then adjusted the these values to get a more accurate input. The next step is to prioritize the risk of each component by DFMEA inferencing process with fuzzy logic grading approach. To assist the fuzzy DFMEA evaluation, a rule base is generated in the form of rule matrix of the riskiness for DFMEA analysis, is built in the prototype system (KB@Pds). The graphical user interface of DIIS was as illustrated in Figure 9(*a*). In the DFMEA inferencing process, the risk of each component was prioritized automatically with fuzzy logic grading algorithm according to the potential failure, effect, cause, and the grading of severity, occurrence and detectability of each component. Finally, the bill of components of the robustness product design was generated after completing the alternative components selection by means of DIIS through press the 'Finish' button. It is shown in the form of a spreadsheet in Figure 9(*b*).



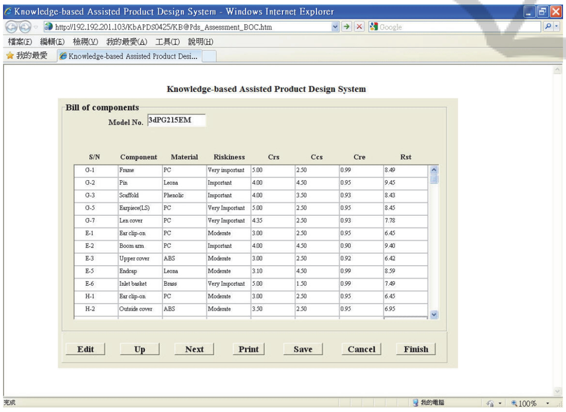
Knowledge-based Assisted Product Design System

Model No. 3dPG215EM

S/N	Component	Severity	Occurence	Detectability
G-5	Earpiece	5.00	3.50	1.00
G-7	Len cover	4.00	2.50	2.00
E-1	Ear clip-on	5.00	3.50	2.00
E-2	Boom arm	4.00	4.20	4.00
E-3	Upper cover	3.00	1.00	1.00

S/N	Component	RPN	Crs	Riskness
G-1	Frame	15.0	5.00	Very important
G-2	Pin	14.4	4.00	Important
G-3	Scaffold	11.5	4.00	Important
G-5	Earpiece	17.5	5.00	Very important
G-7	Len cover	20.0	1.25	Important

Figure 9(*a*): Fuzzy DFMEA assessment of 3D polarized glasses suit.



Knowledge-based Assisted Product Design System

Model No. 3dPG215EM

S/N	Component	Material	Riskiness	Crs	Ccs	Cre	Rst
G-1	Frame	PC	Very important	5.00	2.50	0.99	8.49
G-2	Pin	Leona	Important	4.00	4.50	0.95	9.45
G-3	Scaffold	Phenolic	Important	4.00	3.50	0.93	8.43
G-5	Earpiece(LS)	PC	Very Important	5.00	2.50	0.95	8.45
G-7	Len cover	PC	Very Important	4.35	2.50	0.93	7.78
E-1	Ear clip-on	PC	Moderate	3.00	2.50	0.95	6.45
E-2	Boom arm	PC	Important	4.00	4.50	0.90	9.40
E-3	Upper cover	ABS	Moderate	3.00	2.50	0.92	6.42
E-5	Endcap	Leona	Moderate	3.10	4.50	0.99	8.59
E-6	Inlet basket	Brass	Very Important	5.00	1.50	0.99	7.49
H-1	Ear clip-on	PC	Moderate	3.00	2.50	0.95	6.45
H-2	Outside cover	ABS	Moderate	3.50	2.50	0.95	6.95

Figure 9(*b*): Recommended bill of components for proposed 3D polarized glasses suit.

5 CONCLUSIONS

This paper has proposed a knowledge-intensive support approach and framework for knowledge-based assisted product design and development. An integrated modular platform-based product design scheme is presented with knowledge assistance for customer requirements' modeling, product architecture modeling, product platform establishment, product generation, and product variant assessment. The developed approach and framework can be applied for capturing, representing, and managing product design knowledge and provide support in the design process. Finally, the issues related to the implementation of the knowledge support framework are addressed.

The system is expected to help to optimize product quality and reliability and costs and to reduce the iterations of redesign so as to shorten the development lead time. On the basis of the current decision-making models used in the industry, the KB@Pds has a modular structure to facilitate access to the knowledge bases and to ensure its future development and extension. A case study on a 3D polarized glasses suit has been conducted by using KB@Pds to illustrate the feasibility of the proposed system. However, the current system only focuses on the generation of simple product or component design. For complex product, the framework could be modified to cater the assembly operations.

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