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ORIGINAL ARTICLE

Development of a fuzzy FMEA based product design system

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Abstract The demand for high-quality and low-cost products with short development time in the dynamic global market has forced researchers and industries to focus on various effective product development strategies. The authors are carrying out research studies to explore the applicability of fuzzy logic and knowledge-based systems technologies to today's competitive product design and development, with an emphasis on the design of high quality products at the conceptual design stage. A framework of a fuzzy FMEA (failure modes and rffects analysis) based evaluation approach for new product concepts is proposed in this paper. Based on the proposed approach and methodologies, a prototype system named EPDS-1, which can assist inexperienced users to perform FMEA analysis for quality and reliability improvement, alternative design evaluation, materials selection, and cost assessment, thus helping to enhance robustness of new products at the conceptual design stage. This paper presents the underlying concepts of the development and shows the practical application with the prototype system with a case study.

Keywords Product design · Failure mode and effect analysis FMEA) · Fuzzy logic · Knowledge-based system

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1 Introduction

Manufacturing competitiveness means sustained growth and earnings through building customer loyalty by creating high value products in a very dynamic global market. In order to remain competitive, companies are compelled to produce low-cost and high-quality products in nowadays highly competitive environment. The new product design and development task is a highly iterative process which involves a substantial heuristic knowledge component (practical knowledge) 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 elements of the design may be opened to quantitative analysis, but these do not help the designer to establish the overall form of the design, particularly in the conceptual design stage in which the design details are not yet available. Mathematical calculations are thus limited to empirical rules. Figure 1 shows the general decision making process required at the conceptual design stage of a new product development project.

In traditional practice, the design of new products depends largely on the human expertise of product designers, tool designers, manufacturing engineers, who need to possess thorough and broad specific knowledge and experience. Unfortunately, there is always a shortage of these experienced designers and engineers to cope with the growing demand in the industries. It is thus quite often that many product design changes are inevitable during the

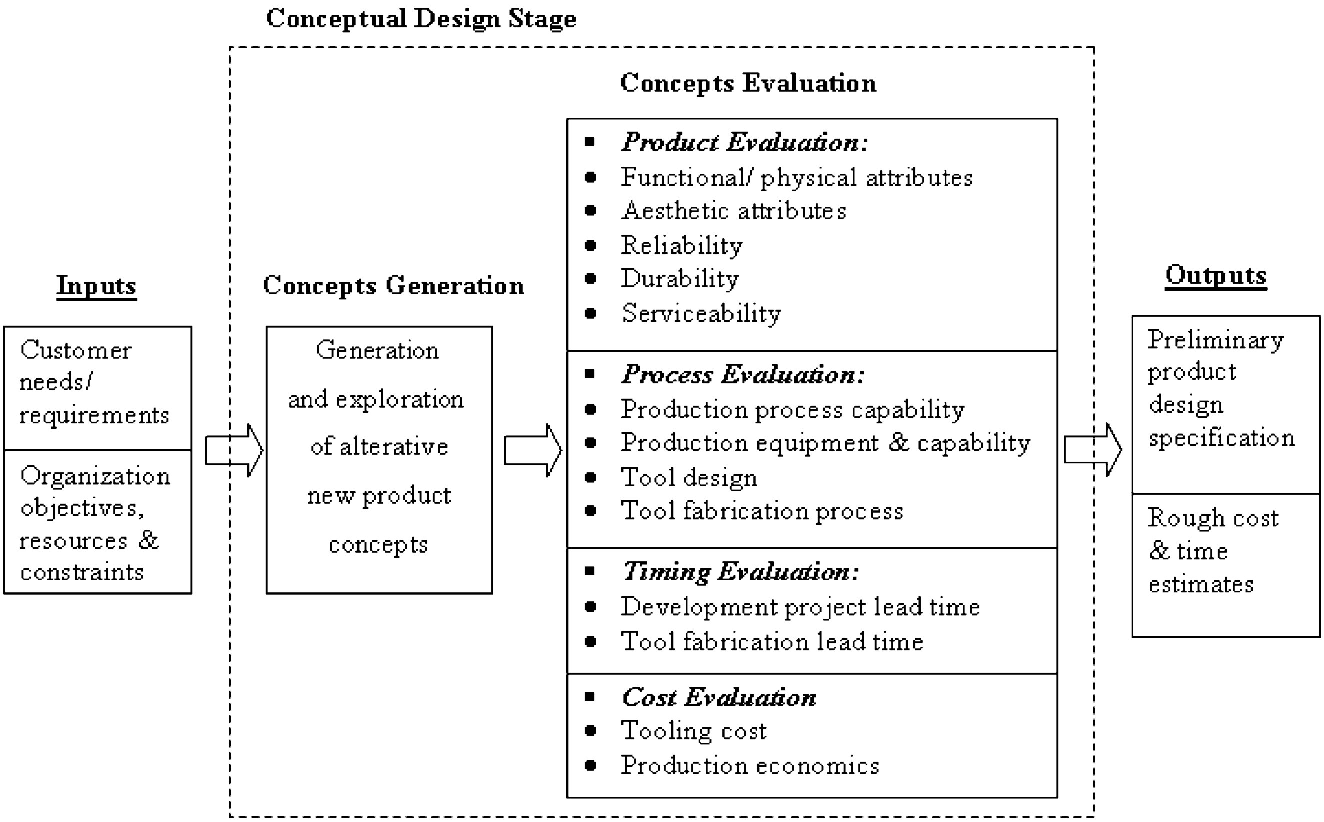


Fig. 1 Decision makings in conceptual product design

stages of tool design, tool making and production in order to meet tool manufacturability requirements as well as production economics. These problems inevitably lead to long lead times and high cost of changes. To succeed in today's global and rapidly changing marketplace, companies must develop low-cost but high-quality products that must be reliable during the product life cycle [5, 23, 35, 40]. Companies must address quality, costs and reliability in their product development process.

Quality and reliability of products are absolutely critical to the functional performance of the final products. In order to meet product reliability requirements, the technique failure mode and effects analysis (FMEA) [21, 35, 42, 44, 53] is used in the early stage of product design. FMEA is increasingly adopted by manufacturers of high-end products like the automotive industry in order to identify and evaluate the potential failures of a product or process as well as their effects, which will initiate actions that could eliminate or reduce the chance of the potential failures occurring. It is a formalized analytical technique which lists all potential sources of failure and then allocates a weighted score according to the severity of the consequences of failure. It is used to ensure that all design failure modes have been considered and assessed with an aim to reduction and even elimination. Nevertheless, difficulties are usually encountered in dealing with the interrelationships among various failure modes with limited uncertain and imprecise information when FMEA is conducted in conceptual design stage [8, 18, 19, 26, 43, 53].

To optimize the product design process in terms of product quality, cost and reliability, the authors consider a potential to utilize the evolving knowledge-based system technology and fuzzy set theory to support the FMEA analysis so as to assist designers to solve the conceptual design problems. The followings present the authors' recent work in this aspect and the development of a knowledge-based product design system, EPDS-1, to assist inexperienced users to perform the FMEA analysis and making evaluation decision at the conceptual product design stage.

2 Related work

2.1 Knowledge based design

Researchers have started to adopt knowledge-based system approach to solve engineering design problems in recent years. Dixon [15] presented a general review of knowledge based systems for engineering design. IMPARD [45] is an knowledge based system developed for injection moulded part design. ICAD [12], CADFEED [32], IKMOULD [30], etc., were developed for injection mould design. Chin [9] addressed the conceptual design development of plastic parts. They developed a prototype knowledge-based system which could select the appropriate plastic material and generate the major injection mould design features. Shin [39] developed an knowledge-based system based pneumatic design system, PNEUDES (PNEUmatic Design Expert System), that enables users to obtain optimal design of pneumatic system. Tam [41] developed a hybrid artificial intelligent (AI) system for optical lens design with case base reasoning (CBR) and genetic algorithm (GA). Myint [31] presented the framework and development of an knowledge-based system to generate alternative product designs based on the information of customers' needs and existing products derived from their product realization model. The generation of alternative products is based on the combination of primitive parts stored in the database, rules developed from the knowledge-based system and the weights of the customers' needs. Ong [33] developed a knowledge-based system called DKB (Domain Knowledge Based) Search Advisor to support the problem solving in design stage. Sapuan [38] reviewed various work on the development of computerized material selection system and studied knowledge-based system approach in material selection in an engineering design process. Kanoglu [22] developed an integrated automation system to aid the design/build firms in managing the design phase of construction projects, though the current version is of limited practical use.

At the conceptual design stage, product designers usually face lots of uncertainties in product attributes and requirements such as features, sizes, materials, and functional performance. The decisions made at this stage of design have significant impact on overall cost [9, 22]. Antonsson [4] reviewed and compared methods for incorporating imprecision in engineering design decision making. Mohamed [29] also developed a knowledge-based system for alternative design, cost estimating and scheduling. It provides a single but rapid analysis on design alternatives and cost analysis of different types of building material at the design stage. Du [16] used probability distribution to model uncertainty of input design parameters. Venter [46] used fuzzy set theory to model the uncertainty in aircraft design and found that fuzzy set based design is superior when compared with traditional deterministic design that uses a safety factor to account for the uncertainty. Xu [48] presented a fuzzy-logic-based method to address the issue of interdependencies among various failure modes with uncertain and imprecise information in FMEA analysis. Wang [47] described an interactive evolutionary approach to synthesize component-based preliminary engineering design problems with

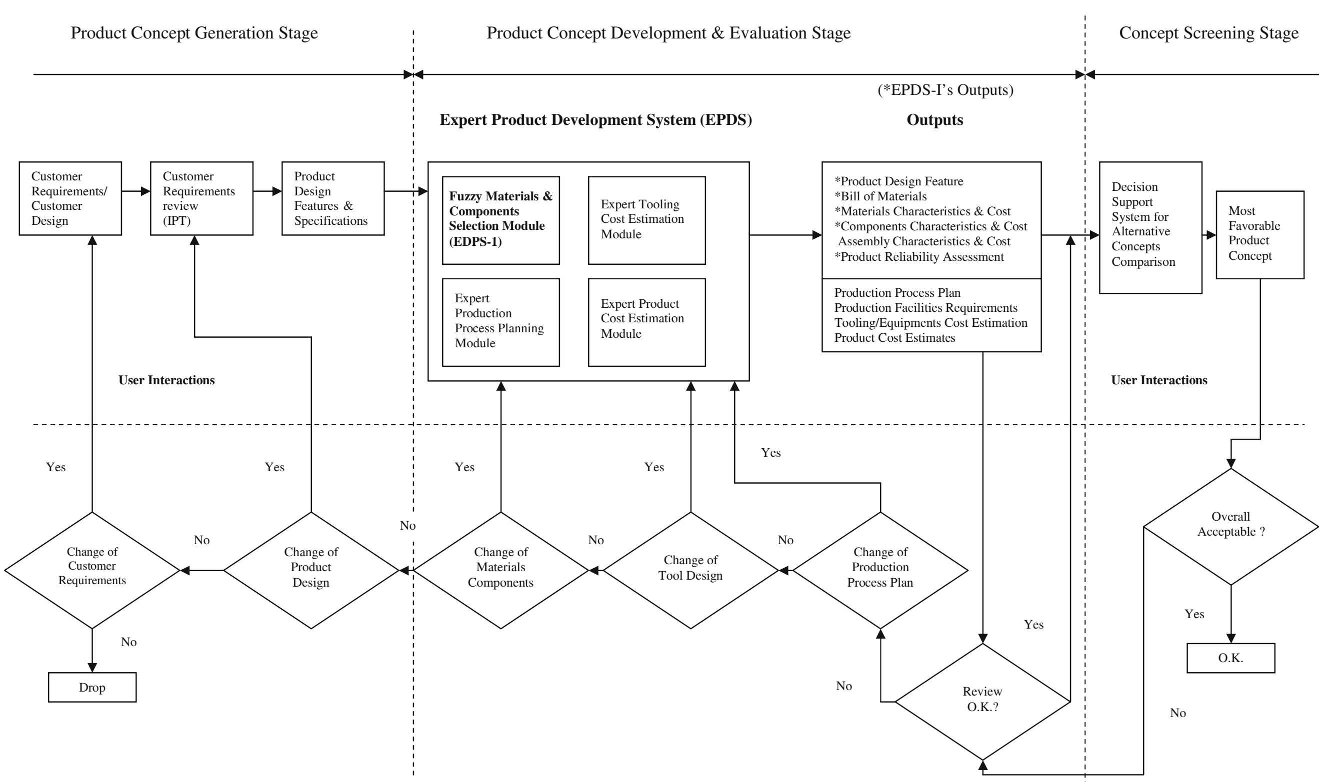


Fig. 2 Proposed expert product development system framework

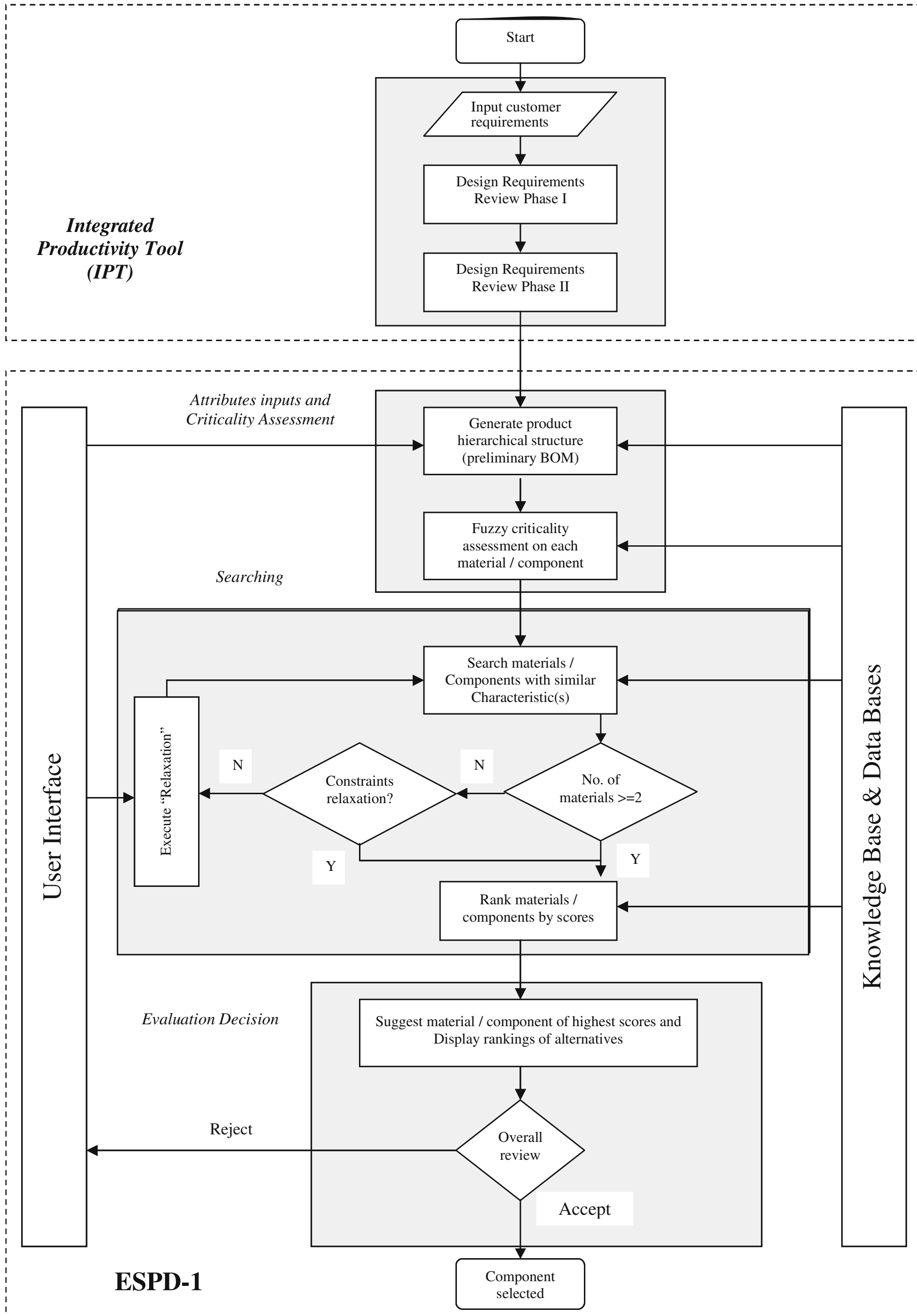


Fig. 3 The system structure of EPDS-1

the needs for human-computer interaction in a changing environment caused by uncertainty and imprecision inherent in the early design stages. It combines an agent-based hierarchical design representation, set-based design generation, fuzzy design trade-off strategy and interactive design adaptation into evolutionary synthesis to gradually refine and reduce the search space while maintaining solution diversity to accommodate future changes. Zha [52], Ratchev [35] and Metaxiotis [28] have also researched into the development of knowledge-based decision support system for product design, in the areas of requirements engineering and collaborative design engineering. Fay [17] and Ammar [3] have developed fuzzy knowledge-based systems in controlling railway traffic and assessing finance of public schools, respectively. Their researches are not related to product design and development but provide some insights into the development of fuzzy knowledge-based system.

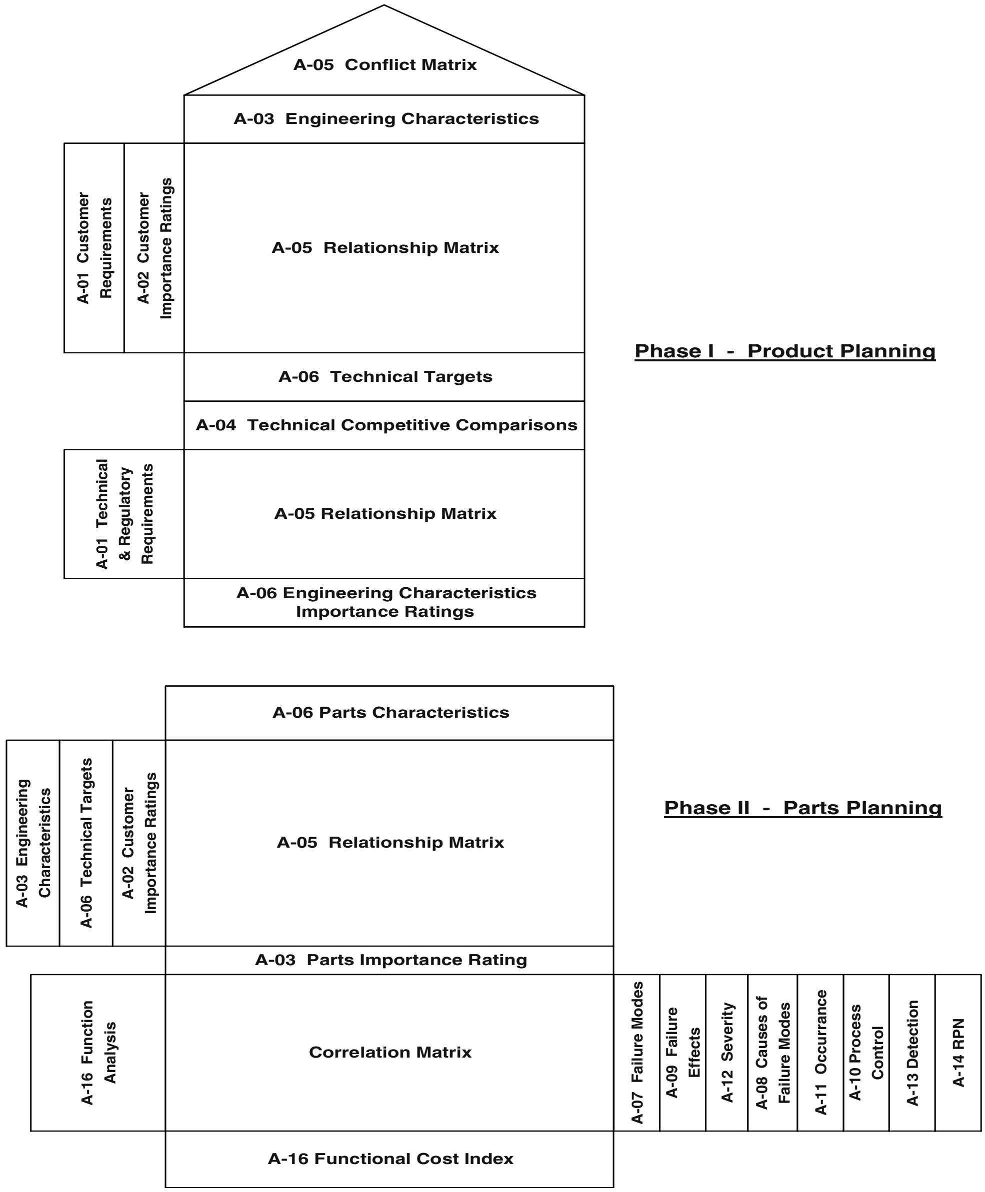


Fig. 4 The design review check lists - phases I and II

2.2 FMEA

Failure mode and effect analysis (FMEA) provides a framework for cause and effect analysis of potential product failures. It requires a cross-functional team which is formed by specialists from various functions (e.g., design, process, production and quality) to thoroughly examine and quantify the relationships among failure modes, effects, causes, current controls, and recommended actions. Each failure mode will be assessed in three parameters, namely, severity, likelihood of occurrence, and difficulty of detection of the failure mode. A typical evaluation system gives a number between 1 and 10 (with 1 being the best and 10 being the worst case) for each of the three parameters. By multiplying the values for severity (S), occurrence (O), and detectability (D), the team obtains a risk priority number (RPN), which is $RPN = S \times O \times D$. These risk priority numbers helps the team to identify the parts or processes that need the priority actions for improvement. Depending on the company policy, different criteria are used to trigger the improvement actions. For instance, action could be required if one of the individual numbers, or the overall RPN, exceeds a predefined threshold, or for the highest RPN regardless of a threshold.

When performing FMEA, it may be difficult or even impossible to precisely determine the probability of failure events [8, 26, 44]. Much information of FMEA is expressed in linguistically, such as 'likely', 'important' or 'very high' etc. In addition, most components or systems degrade over time and have multiple states. An assessment on these

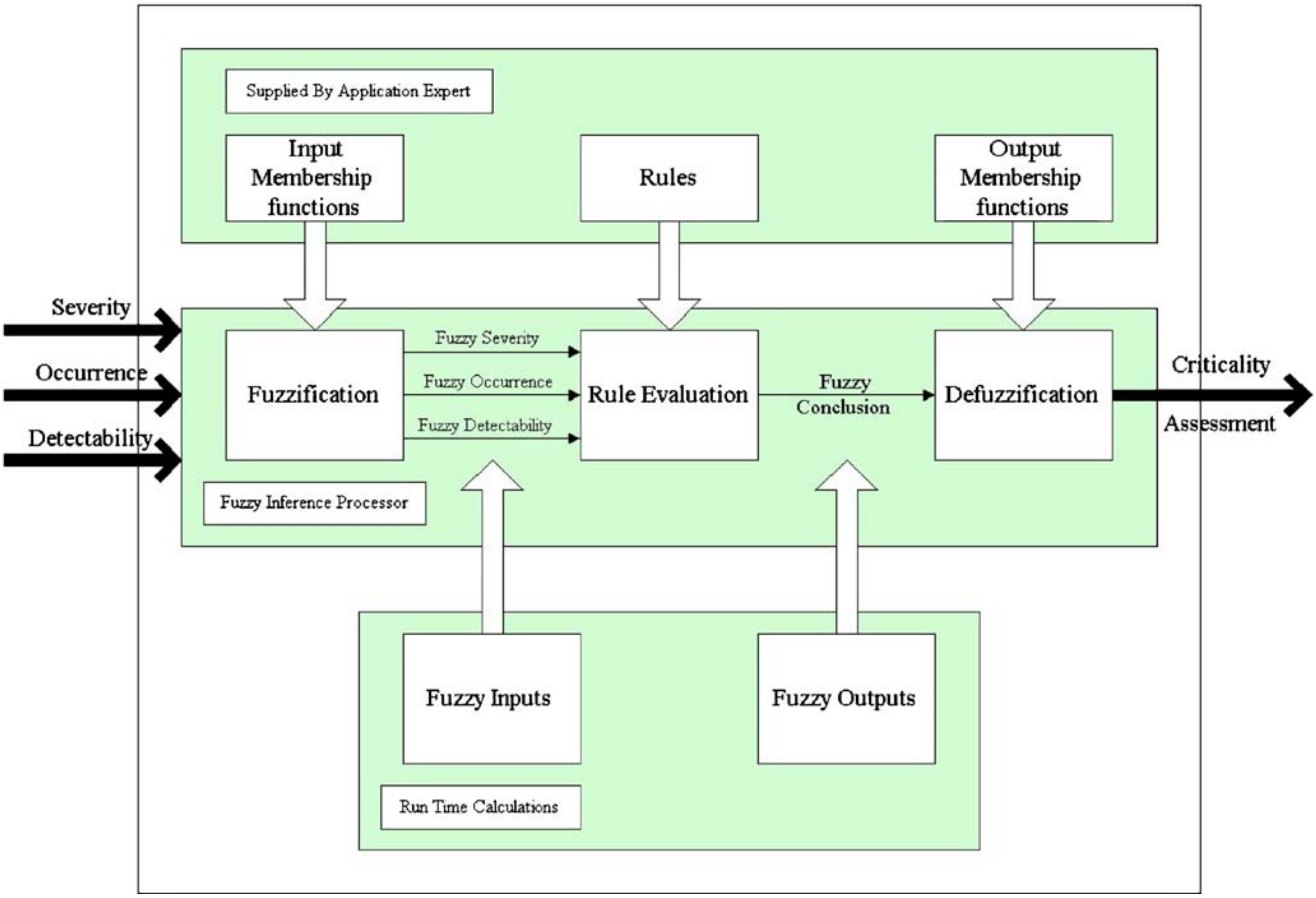


Fig. 5 Overall view of the fuzzy criticality assessment system

states is also often subjective and qualitatively described in natural language such as 'degradation of performance', 'reliability', and 'safety'. It is always difficult to evaluate these linguistic variables objectively. Besides, interdependencies among various failure modes and effects on the same level and different levels of hierarchical structure of a product or engineering system are not taken into account. It is not likely to combine multiple qualitative assessments and is also difficult to obtain the probability distributions that several failure modes occur simultaneously. In traditional FMEA approach, the diversity and ability of the team are the most important considerations, followed by training for the team members. This leads to a high cost. Furthermore, industrial practitioners usually find it hard to share their experience among team members of different background. This indeed prohibits the application of FMEA in a broader scope [18, 19, 26, 48].

Many decision-making and problem-solving tasks are too complex to be understood quantitatively; however, people succeed by using knowledge that is imprecise rather than precise. Fuzzy set theory, originally introduced by Lotfi Zadeh in the 1965 [50], resembles human reasoning in its use of approximate information and uncertainty to generate decisions. Fuzzy logic was developed later from fuzzy set theory to mathematically represent uncertainty and vagueness and provide formalized tools for dealing with the imprecision intrinsic to many problems. By contrast, traditional computing demands precision down to each bit. Since knowledge can be expressed in a more natural way by using fuzzy sets [1, 6, 11, 20, 24]. There is a potential to employ the fuzzy set theory to enhance the performance of FMEA [8, 19, 48].

In this paper the authors explore the applicability of fuzzy logic and knowledge-based approach with the FMEA methodology to today's competitive product design and development. A framework of a fuzzy FMEA-based evaluation system for new product concepts is proposed. Based on the proposed approach and methodologies, a prototype fuzzy knowledge-based system named EPDS-1, which can assist inexperienced users to perform the FMEA analysis for quality and reliability improvement, alternative design evaluation, materials selection, and cost assessment, which could help to enhance robustness of new products at the conceptual design stage.

Table 1 Severity evaluation criteria

Rank	Severity effect	Meaning
9, 10	Hazardous	Very high severity ranking when a potential failure mode affects safe vehicle operation and / or involves noncompliance with government regulation with / without warning.
8	Very high	Vehicle / item inoperable, with loss of primary function.
7	High	Vehicle / item operable, but at reduced level of performance. Customer dissatisfied.
5, 6	Moderate	Vehicle / item operable, but comfort / convenience item(s) inoperable. Customer experiences discomfort.
4	Low	Vehicle / item operable, but comfort / convenience item(s) operable at reduced level of performance. Customer experiences some dissatisfaction.
3	Very low	Fit and finish / squeak & rattle item does not conform. Defect noticed by most customers.
2	Minor	Fit and finish / squeak & rattle item does not conform. Defect noticed by average customer.
1	None	No effect.

3 The proposed knowledge-based product development system framework

The product concept design and development process is outlined in Fig. 2, which consists of three stages, namely, product concept generation, product concept development and evaluation, and concepts screening. Knowledge-based systems are proposed to support decision-making throughout the whole concept development process.

In the product concept generation stage, a customer design requirements review is conducted based on customer inputs. After confirming the customer requirements, the preliminary product design features and specifications will be formulated as the inputs to the next step of conceptual development process, the product concept development and evaluation stage. In the concept development and evaluation stage, four knowledge-based modules are proposed. A knowledge-based system of material and components selection determines the most appropriate material/components which will give optimum product quality and reliability, based on inputs of product concept and requirements. Another knowledge-based system module is for process planning that determines the process plan for the manufacture of the product. Based on these outputs, other two modules for tooling cost and product cost are proposed to generate the cost estimates for tooling and product respectively. With these outputs, the alternative product concepts will be compared with the aid of a decision support system to determine the most favorable option.

Referring to Fig. 2, the authors are currently focusing in the development of the expert product development system (EPDS) for evaluating alternative product design concepts in the areas of material and component selection for robust design, product process planning, tooling cost estimates and product cost estimates. 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 EPDS has a modular structure to facilitate access to the knowledge bases and to ensure its future development and extension. As the first phase of the research work on EPDS, a prototype fuzzy FMEA-based knowledge-based product design system, called EPDS-1, has been developed for the material and component selection by the authors. The research work was supported by a worldwide leading micro-motor manufacturer. The development work of this prototype system is elaborated in the following sections.

Table 2 Frequency of occurrence evaluation criteria

Rank	Occurrence	Meaning	Quantitative failure probability	Process capability (Cpk)
10	Very hgh	Failure is almost inevitable	$\geq$ 1 in 2	$\geq$ 0.33
9	Very high		1 in 3	$\geq$ 0.51
8	High	Repeated failures	1 in 8	$\geq$ 0.67
7	High		1 in 20	$\geq$ 0.83
6	Moderate	Occasional failures	1 in 80	$\geq$ 1.00
5	Moderate		1 in 400	$\geq$ 1.17
4	Moderate		1 in 2000	$\geq$ 1.33
3	Low	Few failures	1 in 15000	$\geq$ 1.50
2	Very low	Relatively few failures	1 in 150000	$\geq$ 1.67
1	Remote	Failure is unlikely	$\leq$ 1 in 1.5×10^6	$\geq$ 2.00

Table 3 Detectability evaluation criteria

Rank	Detectability	Meaning
10	None	Design control will not and / or cannot detect a potential cause / mechanism and subsequent failure mode; or there is no design control.
8, 9	Rare	Rare chance the design control will detect a potential cause / mechanism and subsequent failure mode.
6, 7	Low	Low chance the design control will detect a potential cause / mechanism and subsequent failure mode.
5	Fair	Fair chance the design control will detect a potential cause / mechanism and subsequent failure mode.
4	Moderate	Moderate chance the design control will detect a potential cause / mechanism and subsequent failure mode.
3	High	High chance the design control will detect a potential cause / mechanism and subsequent failure mode.
2	Very-High	Very high chance the design control will detect a potential cause / mechanism and subsequent failure mode.
1	Certain	Design control will certainly detect a potential cause / mechanism and subsequent failure mode.

4 The prototype system: EPDS-1

4.1 The system structure

A prototype fuzzy FMEA based product design system, called EPDS-1, has been recently developed to assist design engineers in selecting material and components in the conceptual design and development stage with special emphasis on the robustness of the design. The system incorporates functions of quality and reliability assessment, alternative design decision support, and materials selection. This system links various functions together under pre-defined bill of materials to acquire, capture, share and distribute knowledge for better optimal product development. The FMEA technique is used to evaluate the quality and reliability of products.

Customer requirements, design information and expert opinion are all vital for the FMEA assessment but they are often uncertain or vague in the conceptual design phase. There are usually no crisp inputs and outputs and the relationships among the failure modes and effects are very complex, subjective and qualitative. In order to further improve the effectiveness in dealing with the interrelationships among various failure modes which have uncertain and imprecise information when conducting FMEA, and in evaluating human heuristic knowledge and empirical knowledge, a fuzzy approach is proposed to improve the traditional FMEA methodologies. A fuzzy based FMEA approach, which will be elaborated in Sect. 4.3, is then adopted to tackle the product design issue in the prototype system EPDS-1. The overall system structure of EPDS-1 is shown in Fig. 3.

4.2 Design requirements review

In the product concept generation stage, design review is conducted based on customer designs and requirements. The first author had developed an integrated productivity tool (IPT) tool to facilitate such a design requirement review [10]. The design requirement review process consists of two phases. Phase I is used to translate the customer requirements into corresponding engineering characteristics, while phase II moves further into the component design and assembly process by translating the engineering characteristics into critical parts characteristics. Figure 4 illustrates the two phases of the approach that structures the design requirement review checklist into two major activities: product planning and part planning. The ability to trace design and part features needs back to customer requirements is formed by taking the design characteristics from the top of the initial matrix and using them as the left-hand side of the next matrix. This waterfall process continues until specific product and part specifications result. Traceability is, therefore, obtained throughout the application.

The matrix approach was originally developed in Japan by Prof. Yoji Akao to create linkages with customer needs and product characteristics. It has been further developed by Bob King of Goal/QPC to a much more structured approach to implementation of quality function deployment

Table 4 Risk evaluation criteria

Rank	Risk	Priority of follow-up actions
9, 10	Very important	Very-important to take the follow-up actions
8	Important	Important to take the follow-up actions
6	Moderate	Moderate priority to take the follow-up actions
4	Low	Low priority to take the follow-up actions
2	Minor	Minor priority to take the follow-up actions
1	Not important	Not-important to take the follow-up actions

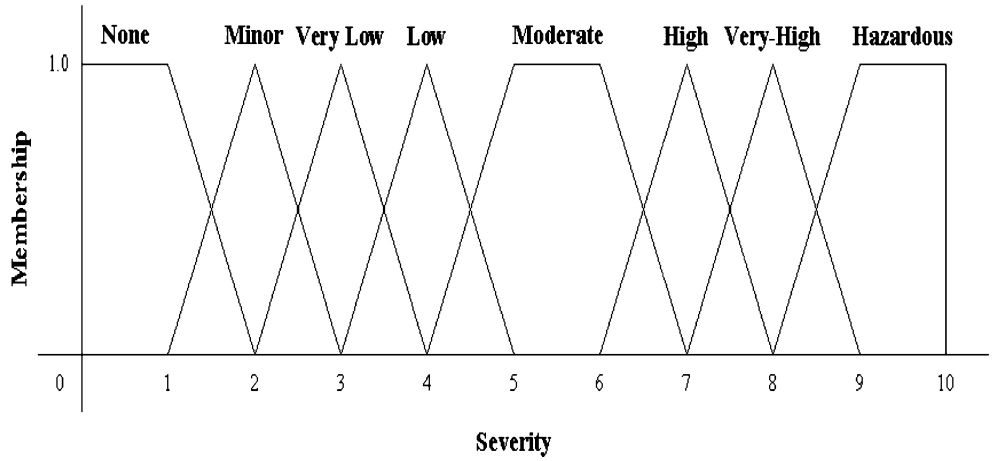


Fig. 6 Fuzzy severity sets definition

(QFD), using a series of QFD charts that are to be completed depending upon the particular analysis of the product [2, 13]. This methodology is always used to map customer needs against product requirements, although it requires a greater commitment of resources and time to understand and implement. It, however, does not help much to map other design activities in a matrix fashion, such as FMEA, value engineering, etc.

As proposed by the authors, phase I of the checklist is used to translate the customer voice into corresponding engineering characteristics. Thus, it provides a way of converting qualitative customer requirements, drawn from market evaluation into specific, quantitative engineering characteristics. Phase II moves one step further back in the component design and assembly process by translating the engineering characteristics into critical parts characteristics. This is accomplished by taking selected design requirements from phase I and brings them onto the phase II chart as WHATs. The HOWs of design deployment are part characteristics. The phase II chart is used to further evaluate the individual part characteristics by cost and reliability deployment. For each part characteristics, corresponding basic functions and supporting functions are described as shown on left-hand side of the checklist. It is so called function analysis process. By extending the function description column towards right-hand side, potential failure modes of each function are listed. Based on the identification of failure modes, it is required to brainstorm what are its effects to customer if the failure mode occurs. Finally, a preliminary risk assessment on each function is obtained by simply multiplying of the severity, occurrence and detectability rating.

4.3 Fuzzy FMEA Assessment

Figure 5 shows an overall view of the proposed fuzzy FMEA assessment system, in which there are three major steps to carry out the assessment, namely, fuzzification, rule evaluation, and defuzzification [7, 14, 25, 27, 34]. The system firstly uses linguistic variables to describe the severity, frequency of occurrence, and detectability of the failure. These inputs are then 'fuzzified' to determine the degree of membership in each input class. The resulting 'fuzzy inputs' are evaluated using a linguistic rule base and fuzzy logic operations to yield a classification of the 'riskiness' of the failure mode and an associated degree of membership in the risk class. This 'fuzzy output' is then 'defuzzified' to give the prioritization level for the failure mode. The details and special considerations for each step of the procedure are discussed as follows.

The fuzzification process, using crisp rankings, converts the severity, occurrence, and detectability inputs into the

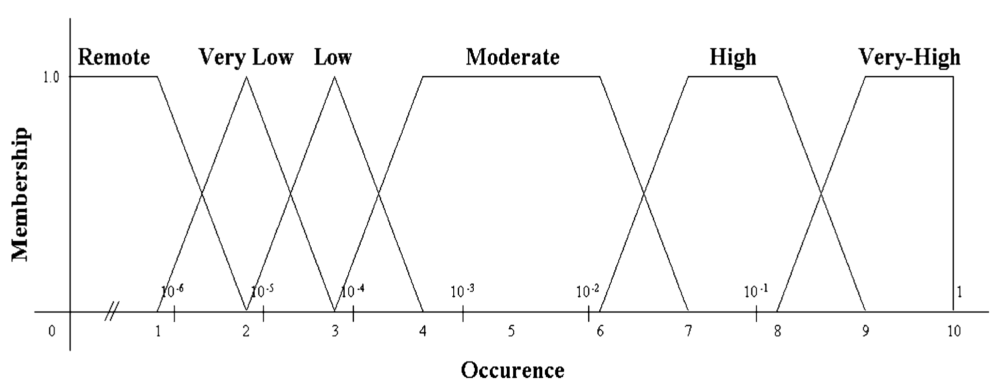
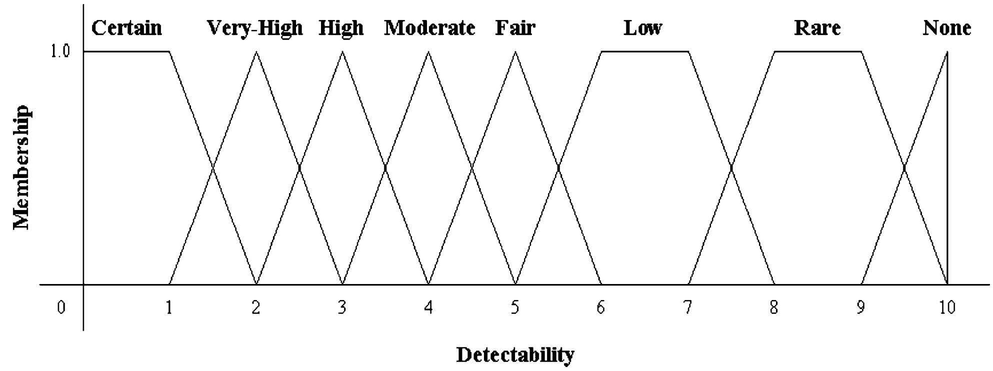


Fig. 7 Fuzzy occurrence sets definition

Fig. 8 Fuzzy detectability sets definition



fuzzy representations that can then be matched with the premises of the rules in the rule base [14, 25]. Using the linguistic variables and their definitions, ranking of severity, occurrence, and detectability for the failure mode can be made in a scale basis. The scales and the membership functions identify the range of input values corresponding to each fuzzy linguistic label.

The rule base describes the riskiness of each combination of input variables. It consists of the expert knowledge about the interactions between various failure modes and effect that is represented in the form of fuzzy 'If–Then' rules. Such rules are usually more conveniently formulated in linguistic terms than in numerical terms, and they are often expressed as 'If–Then' rules which are easily implemented by fuzzy conditional statements. 'If–Then' rules have two parts: an antecedent that is compared to the inputs, and a consequence that is the result. A single fuzzy 'If–Then' rule assumes the form 'If x is A Then Y is B' where A and B are linguistic values defined by fuzzy sets on the ranges (universes of discourse) X and Y, respectively. The If−part of the rule 'x is A' is called the antecedent or premise, while the Then−part of the rule 'Y is B' is called the consequence or conclusion. Note that 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 B to output variable Y.

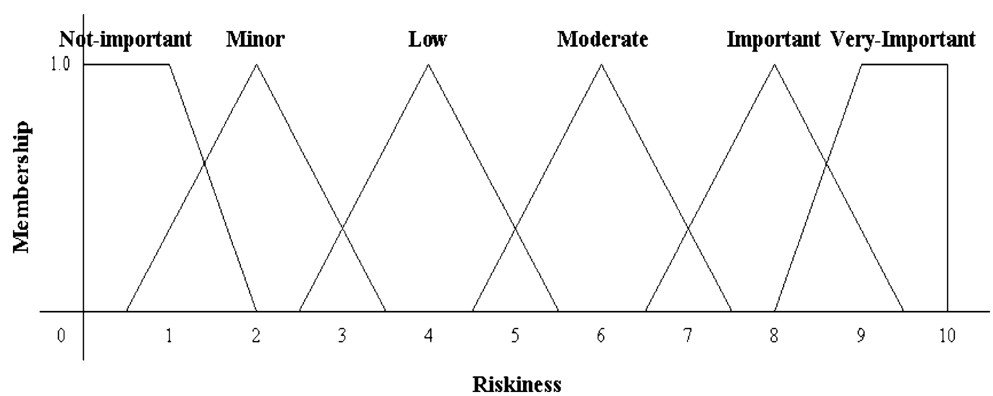
In practical applications, the fuzziness of the antecedents eliminates the need for a precise match with the inputs. All the rules that have any truth in their premises will contribute to the fuzzy conclusion set. If the antecedent is true to some degree of membership, then the consequence is also true to that in same degree. That is, each rule is found to be a function of the degree to which its antecedent matches the input. This point leads a natural way to combine multiple qualitative assessments. Consequently, for FMEA, the fuzzy rules describing the relations between failure modes and effects can be combined in this way. This imprecise matching provides a basis for interpolation between possible input states and serves to minimize the number of rules need to describe the input−output relation. A sample of the rule base as shown in the following is used for the criticality analysis:

If **severity** is '*high*' and **occurrence** is '*moderate*' and **detectability** is '*gair*' then the **risk** is '*very-important*'.

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. Rules based on these types of linguistic variables are more natural and expressive than the numerical RPN ranking and criticality number calculations. The rules also allow quantitative data (such as the failure probability) and qualitative and judgmental data (such as the severity and detectability) to be combined in a uniform manner.

The fuzzy inference process uses 'min-max inferencing' to calculate the rule conclusions based on the system input

Fig. 9 Fuzzy risk sets definition



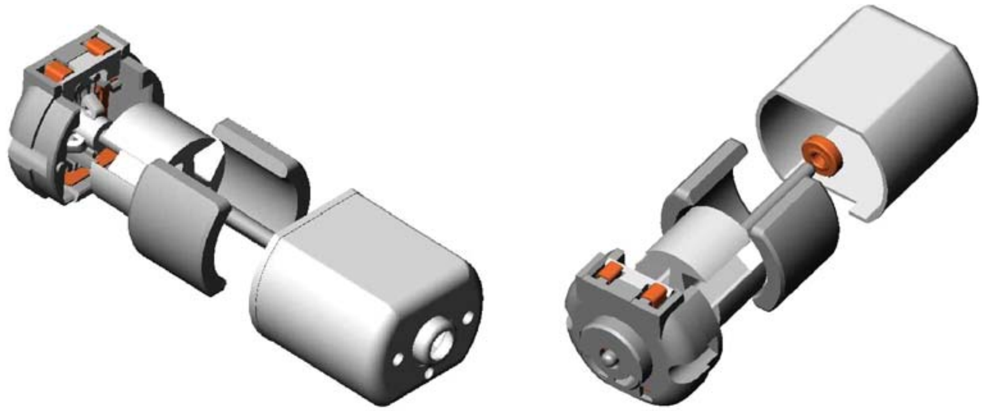


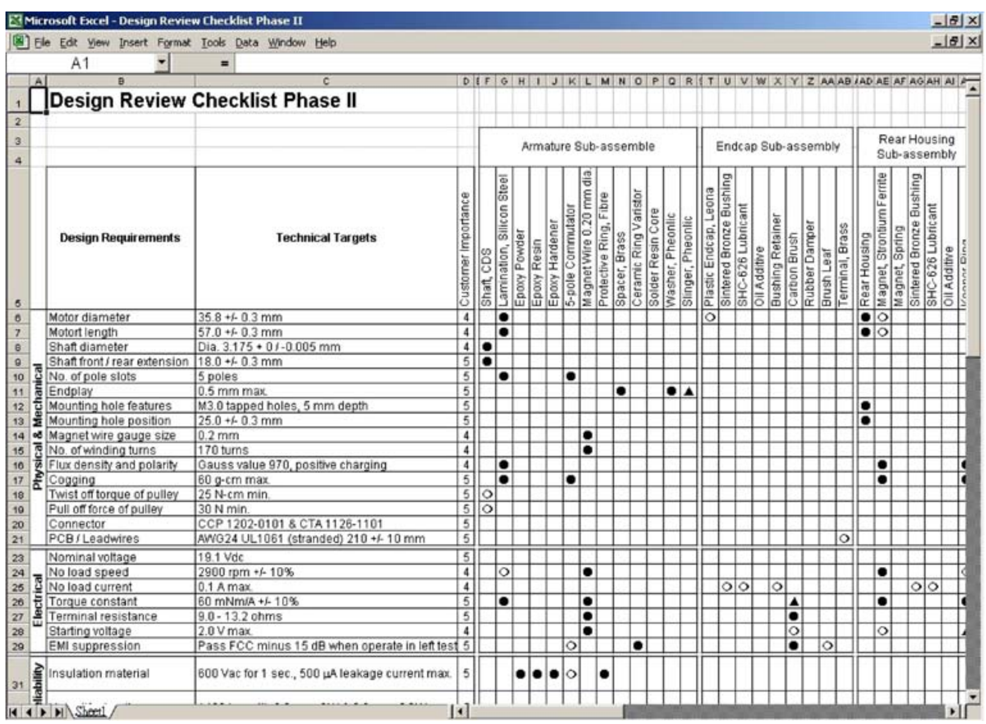
Fig. 10 Explosion drawing of PMDC motor

values. [50, 51]. The result of this process is called the 'fuzzy conclusion'. The applicability, or 'truth value', of a rule is determined from the conjunction of the rule antecedents. With conjunction defined as 'minimum', rule evaluation then consists of determining the smallest (minimum) rule antecedent, which is taken to be the truth value of the rule. This truth value is then applied to all consequences of the rule. If any fuzzy output is a consequence of more than one rule, that output is set to the highest (maximum) truth value of all the rules that include it as a consequence. The result of the rule evaluation is a set of fuzzy conclusions that reflect the effects of all the rules whose truth value are greater than zero.

The defuzzification process creates a crisp ranking 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 decipher 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. In the case of defuzzification to determine a failure mode criticality ranking, the defuzzification strategy should result in a continuous range of criticality rankings, and consider all of the rules fired during the rule evaluation according to the 'degree of truth' of the conclusion.

Several defuzzification algorithms have been developed but there is no single algorithm is best for all applications [27, 34, 36, 37, 49]. The 'center of gravity' algorithms, one of the widely used algorithms, is adopted 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 :

$$Z = \frac{\sum_{i=1}^{N} w_i \cdot x_i}{\sum_{i=1}^{N} w_i}$$



		Design Requirements	Technical Targets	Customer Importance
6	Physical & Mechanical	Motor diameter	35.8 +/- 0.3 mm	4
7		Motort length	57.0 +/- 0.3 mm	4
8		Shaft diameter	Dia. 3.175 + 0 / -0.005 mm	4
9		Shaft front / rear extension	18.0 +/- 0.3 mm	5
10		No. of pole slots	5 poles	5
11		Endplay	0.5 mm max.	5
12		Mounting hole features	M3.0 tapped holes, 5 mm depth	5
13		Mounting hole position	25.0 +/- 0.3 mm	5
14		Magnet wire gauge size	0.2 mm	4
15		No. of winding turns	170 turns	4
16		Flux density and polarity	Gauss value 970, positive charging	4
17		Cogging	60 g-cm max.	5
18		Twist off torque of pulley	25 N-cm min.	5
19		Pull off force of pulley	30 N min.	5
20		Connector	CCP 1202-0101 & CTA 1126-1101	5
21		PCB / Leadwires	AWG24 UL1061 (stranded) 210 +/- 10 mm	5
23	Electrical	Nominal voltage	19.1 Vdc	5
24		No load speed	2900 rpm +/- 10%	4
25		No load current	0.1 A max.	4
26		Torque constant	60 mNm/A +/- 10%	5
27		Terminal resistance	9.0 - 13.2 ohms	5
28		Starting voltage	2.0 V max.	4
29		EMI suppression	Pass FCC minus 15 dB when operate in left test	5
31	Reliability	Insulation material	600 Vac for 1 sec., 500 µA leakage current max.	5

Fig. 11 Outputs of design requirement review II from IPT

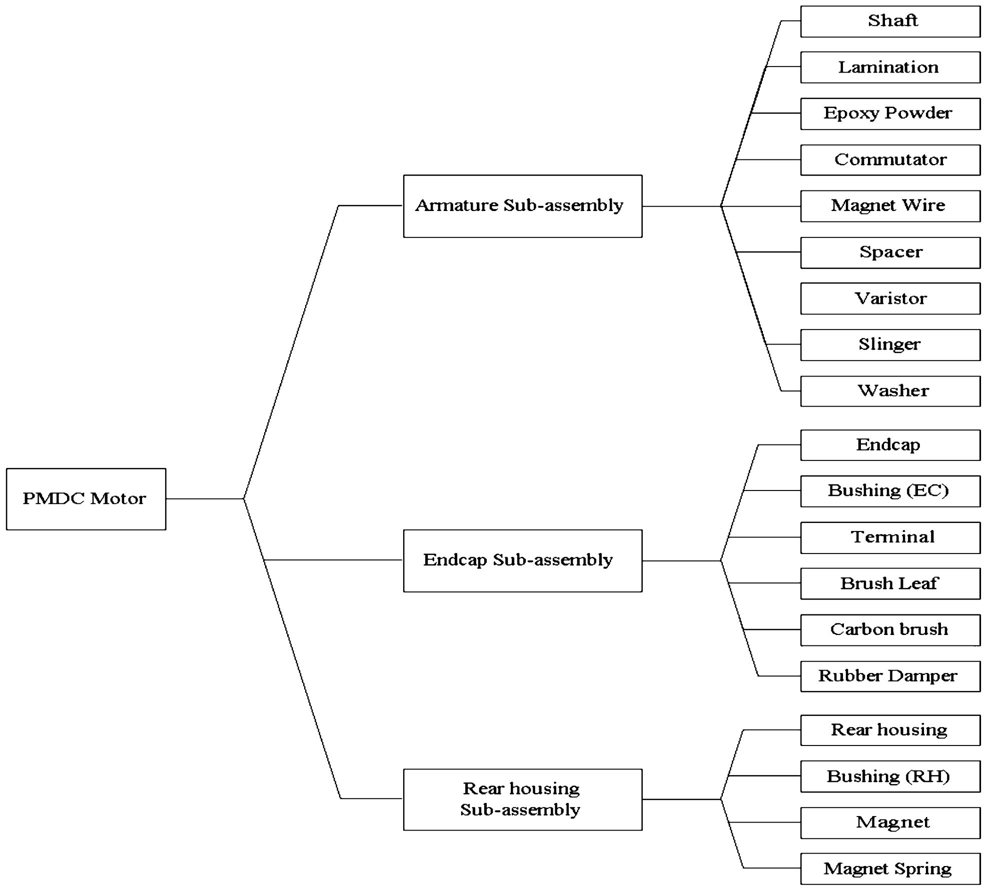


Fig. 12 Hierarchical structure of PMDC motor in model No. HC315MG

Where N= the number of quantized riskiness conclusions, x_i= the support value at which the i th membership function reaches its maximum value (for trapezoidal membership functions it is taken as the center of the maximal range), w_i= the degree of the truth of the i th membership function, and Z= the center of gravity conclusions.

4.4 Operations of EPDS-1

Referring to the EPDS framework, Fig. 2, preliminary product design features and specifications can be obtained via the design review after inputting the product concept requirements which are initiated by the external customers or internal development. The design decisions demand knowledge of the mutual influences among the areas including the part design requirements, potential failure modes and RPN, material/components selection and materials cost, which interact with each other. The EPDS-1 is then developed to support the decision-making of the conceptual design development process. The EPDS-1 consists of three main mechanisms namely, 'attributes input and criticality assessment', 'searching & ranking' and 'user Interaction'. These mechanisms are supported by a knowledge base and a material database. The operations of EPDS-1 are described in the followings with reference to Fig. 3.

A preliminary BOM generated in a product analytical hierarchical structure from the design requirement review II of IPT, as shown in Fig. 4, is input into the EPDS-1. Then, EPDS-1 will conduct the fuzzy criticality assessment on the proposed parts and components. The system uses linguistic variables to describe the severity, frequency of occurrence, and detectability of the failure. As described in section 4.3, these inputs are then 'fuzzified' to determine the degree of membership in each input class. The resulting 'fuzzy inputs' are evaluated using a linguistic rule base and fuzzy logic operations to yield a classification of the 'risk' of the failure mode and an associated degree of membership in the risk class. This 'fuzzy output' is then 'defuzzified' to give the prioritization level for the failure mode. All these information in FMEA can be represented by the commonly used triangular membership function [54]. The evaluation criteria and fuzzy set definitions for 'severity', 'occurrence', 'detectability' and 'risk' are shown in Tables 1, 2, 3, 4 and Figs. 6, 7, 8, 9, respectively. EPDS-1 finally generates the risk priority numbers to prioritize the risk of each part and component. The risk of parts and components in the categories of 'important' and 'very important' will be screened out for materials or components selection.

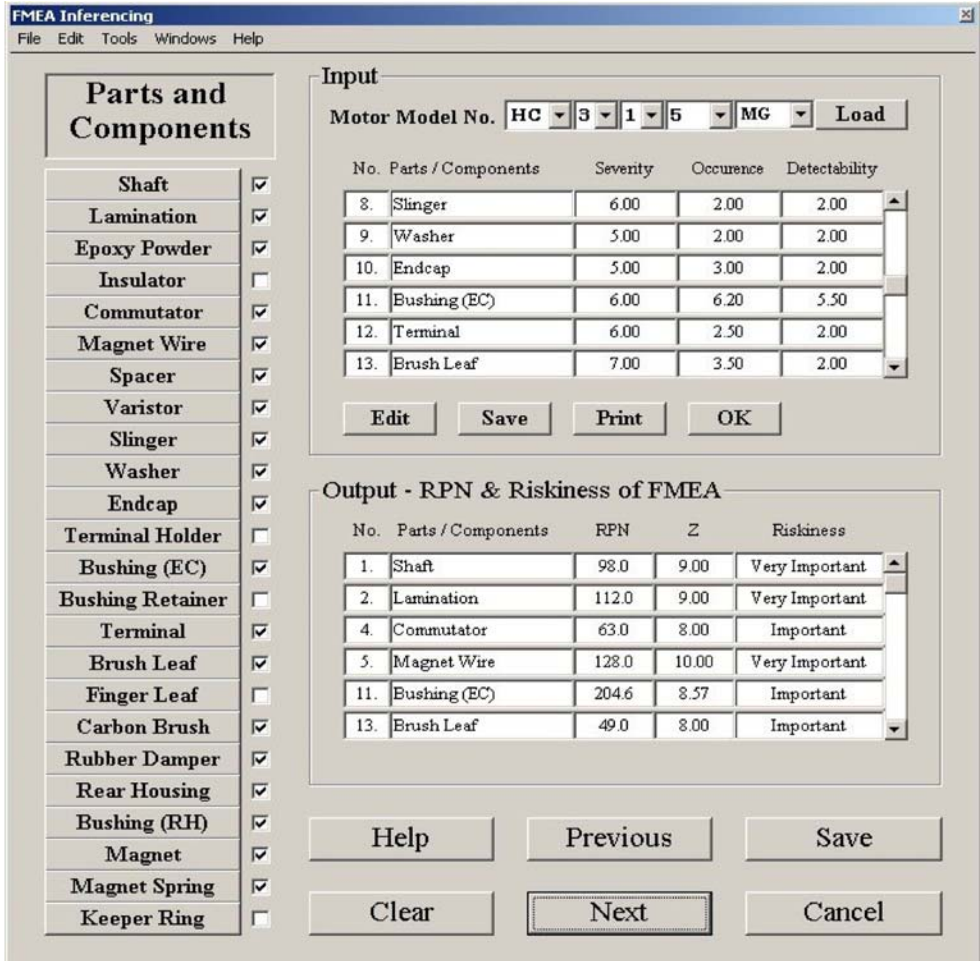


Fig. 13 Fuzzy FMEA assessment of PMDC motor

EPDS-1 will then search appropriate materials and components according to the input information. Utilizing the searching algorithm, the appropriate materials and components are listed with rankings by scores. In case that is insufficient material selected in the first searching exercise, or the selected materials are not favored by users, the system will do 'constraint relaxation' to seek alternative materials. For example, if the number of alternative materials selected is less than a predetermined number, say 2, the system will do 'relaxation' until sufficient materials are found, or the 'relaxation' process is ended by the product designer. The objective of the ranking is to prioritize alternative materials, relative to the order of importance of their attributes to the designers. It combines multiple attributes into a single measure, and ranks the candidate materials by this measure. The following quantitative scoring system is used for the ranking process.

$$S_T = Z + C + R$$

in which the total score S_T is the summation of the risk, score of cost and reliability of material or component.

Z = Risk of the material/component

in which the risk of the material is rated from 0 to 10 with 0 is equal to 'not important' and 10 is equal to 'very important' which is determined in the fuzzy criticality assessment stage.

C = Score of cost of the material/component

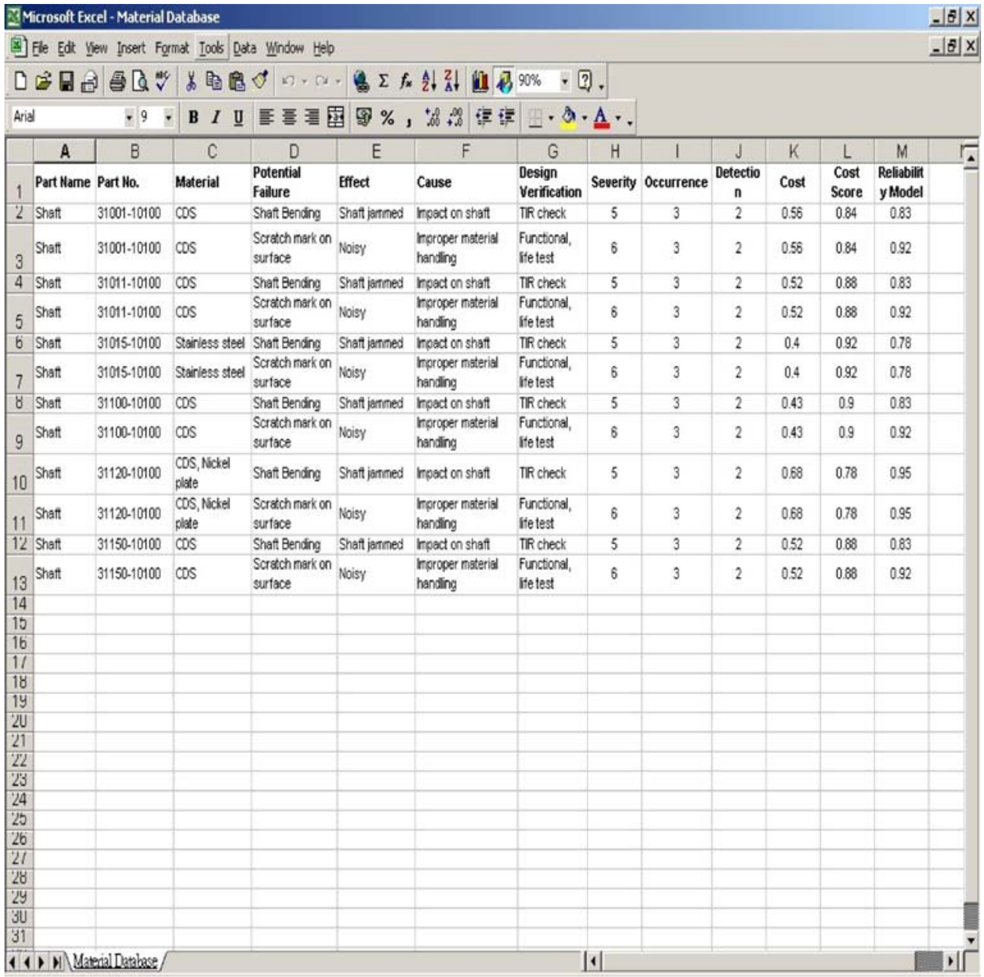
in which the score of cost is rated from 0 to 10 with 0 is equal to the most expensive and 10 is equal to the most inexpensive.

R = Score of reliability of the material/component

in which the score of reliability is rated from 0 to 10 with 0 is equal to the lowest reliability and 10 is equal to the highest reliability.

The appropriate materials and components can then be selected by the product designer based on this information. Finally, a proposed BOM can be generated after all the materials and components have been selected and reviewed.

The user interface of EPDS-1 is developed with the aim of satisfying multiple users, representing a wide range of experience in the industry. With the aid of the edit facilities provided by the EPDS-1, the editing of instances, classes



Part Name	Part No.	Material	Potential Failure	Effect	Cause	Design Verification	Severity	Occurrence	Detection	Cost	Cost Score	Reliability Model
Shaft	31001-10100	CDS	Shaft Bending	Shaft jammed	Impact on shaft	TIR check	5	3	2	0.56	0.84	0.83
Shaft	31001-10100	CDS	Scratch mark on surface	Noisy	Improper material handling	Functional, life test	6	3	2	0.56	0.84	0.92
Shaft	31011-10100	CDS	Shaft Bending	Shaft jammed	Impact on shaft	TIR check	5	3	2	0.52	0.88	0.83
Shaft	31011-10100	CDS	Scratch mark on surface	Noisy	Improper material handling	Functional, life test	6	3	2	0.52	0.88	0.92
Shaft	31015-10100	Stainless steel	Shaft Bending	Shaft jammed	Impact on shaft	TIR check	5	3	2	0.4	0.92	0.78
Shaft	31015-10100	Stainless steel	Scratch mark on surface	Noisy	Improper material handling	Functional, life test	6	3	2	0.4	0.92	0.78
Shaft	31100-10100	CDS	Shaft Bending	Shaft jammed	Impact on shaft	TIR check	5	3	2	0.43	0.9	0.83
Shaft	31100-10100	CDS	Scratch mark on surface	Noisy	Improper material handling	Functional, life test	6	3	2	0.43	0.9	0.92
Shaft	31120-10100	CDS, Nickel plate	Shaft Bending	Shaft jammed	Impact on shaft	TIR check	5	3	2	0.68	0.78	0.95
Shaft	31120-10100	CDS, Nickel plate	Scratch mark on surface	Noisy	Improper material handling	Functional, life test	6	3	2	0.68	0.78	0.95
Shaft	31150-10100	CDS	Shaft Bending	Shaft jammed	Impact on shaft	TIR check	5	3	2	0.52	0.88	0.83
Shaft	31150-10100	CDS	Scratch mark on surface	Noisy	Improper material handling	Functional, life test	6	3	2	0.52	0.88	0.92

Fig. 14 Material database worksheet

and rules in the EPDS-1, as well as the supporting databases, is very user-friendly. At the beginning of the execution of EPDS-1, a list of parts and components is posed to collect the inputs of product features in accordance with the product hierarchical structure from the designers. A 'help' menu to explain the glossary, and quick access to the properties of particular materials, are provided in the system to assist the users for making material selection. The search results are shown to the designers by not only suggesting the material with the highest score, but also displaying the ranking of other alternative materials. A score list of alternatives is displayed for users' consideration. On top of the built-in heuristics, user intervention, including the constraint relaxation, is allowed in various areas during the system execution for experienced users who have some special preference related to their particular design problems. The material database in EPDS-1 can be established from data obtained from supplier's information and in-house data. The technical data of the properties of particular material can be accessed and displayed to the product designers at any time, upon the designers' request.

5 Case study

To demonstrate the operations of the prototype system, a case study on a permanent magnet direct current (PMDC) micro-motor development project for printer carriage drive application has been conducted by using EPDS-1. The PMDC motor (Fig. 10) is used to drive the printer carriage to perform printing. The motor is running in bi-directional rotation and controlled by a pulse-width modulation controller. The printer application limits Electromagnetic Interference (EMI) level induced from motor according to the office equipment regulation in Federal Communication Commission (FCC) so that motor designer has to consider adding suppression components such as varistor, choke and capacitor on motor. In general, ripple movement caused by motor cogging torque need to be minimized as low as possible to avoid affecting printing quality. Pulley, pinion or worm gear is required to fit to motor shaft to transmit motor output torque to belt drive. Specialized mounting features and electrical connections are also required to adopt the modularized assembly in printer manufacture.

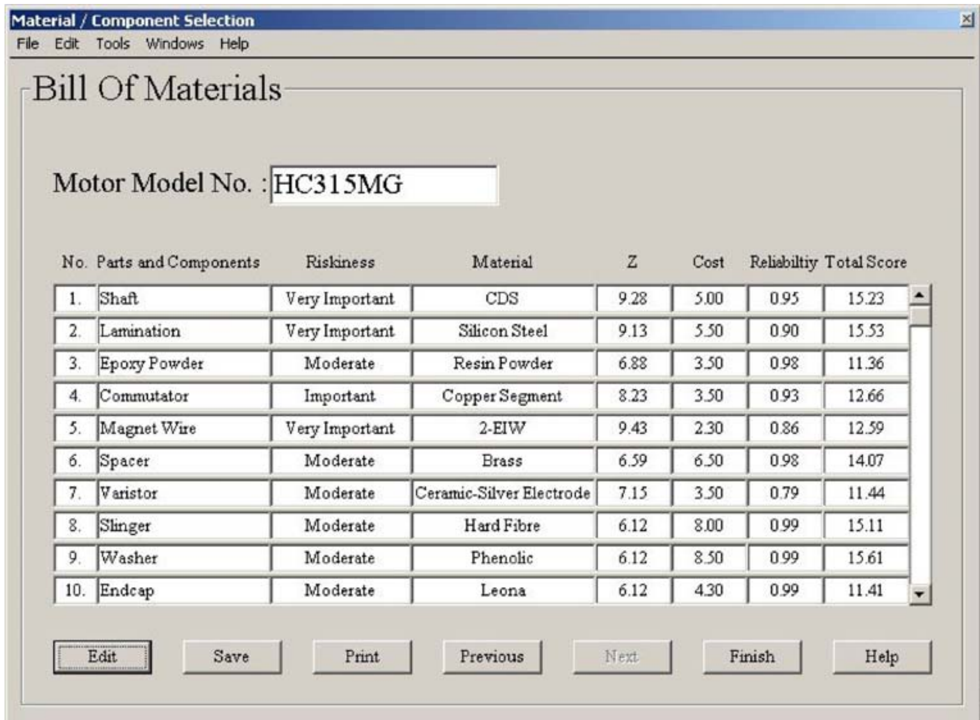


Fig. 15 Recommended bill of materials for proposed PMDC motor

After input the qualitative customer requirements and product features to the IPT [10], the preliminary BOM was generated in design requirement review checklist II as shown in Fig. 11. According to the preliminary BOM, the model type of the motor was proposed to be in HC315MG and the level of the product hierarchy structure was also constructed as shown in Fig. 12.

In accordance with the hierarchical structure of PMDC motor in Fig. 12, the product designer determined the preliminary BOM of the proposed motor and trigger the option boxes which next to the item list of parts and components by processing the user interface.

After pressing the 'Load' command button, the data value of severity (S), occurrence (O) and detectability (D) of each part or component was shown on the FMEA inferencing interface, the product designer then revised the data value of S, O, and D of a specific part or component to obtain a more accurate input. The next step is to prioritize the risk of each part or component by FMEA inferencing process with fuzzy logic approach. To support the fuzzy FMEA evaluation, a rule base consists of 384 rules, which are developed in the form of rule matrix of the riskiness for FMEA analysis, is built in the prototype system. It could help the product designers to screen out the risk of parts or components in the categories of 'important' and 'very important'. The user interface of EPDS-1 was as shown in Fig. 13.

If the product designer wants to retrieve the parts and components information from the material database, he can press the button of the 'Parts and Components Name' to access the material database information. In this case, the product designer retrieves the shaft material information, by pressing the 'Shaft' button first and clicking to retrieve the detailed material information in the form of a 'EXCEL' format as shown in the Fig. 14.

In the FMEA inferencing process, the risk of each component was prioritized automatically with fuzzy logic algorithm according to the potential failure, effect, cause, and the rating of severity, occurrence and detectability of each component. Finally, after completing the alternative materials or components selection via the EPDS-1 by press the 'Finish' command button, the bill of materials (BOM) of the robustness product design was generated in the form of a spreadsheet as shown in Fig. 15.

6 Conclusion and future work

This paper has proposed a fuzzy knowledge-based evaluation system for product development at the conceptual design stage. The work attempts to automate the planning and evaluation intelligently, by integrating multiple domains. The functions of the proposed framework, called the expert product development system (EPDS), can be summarized as evaluating alternative product design concepts in the areas of material and component selection for robust design, product process planning, tooling cost estimates and product cost estimates. 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 EPDS has a modular structure to facilitate access to the knowledge bases and to ensure its future development and extension. However, the current system only focuses on the development of simple product or part/component design. For complex product, the framework could be modified to cater the assembly operations. This work is under the authors' current research.

As the first phase of the research work on EPDS, a prototype fuzzy expert system 'EPDS-1', was developed to help design engineers in selecting material and components with reference to product requirements, robustness of design and cost. The FMEA technique is used to evaluate the quality and reliability of products. Having considered difficulties encountered in dealing with the interrelationships among various failure modes which have uncertain and imprecise information, in FMEA, a fuzzy-based knowledge-based system approach is used in developing this prototype system. Human heuristic knowledge and empirical knowledge can be incorporated for effective automation of the FMEA assessment.

The development work was supported by a worldwide leading micro-motor manufacturer. A case study on a permanent magnet direct current (PMDC) micro-motor development project for printer carriage drive application has been conducted by using EPDS-1 to illustrate the feasibility of the proposed system. The prototype has demonstrated that fuzzy set theory and knowledge-based technology are valuable tools for design and planning applications. The future direction of this research is of two folds, namely: enhancing the 'intelligence' of EPDS-1 by enriching the knowledge, and continuing the development works of knowledge bases of the product process planning, tooling cost estimates and product cost estimates of the outlined expert product development system (EPDS).

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References

1. Adenso-Diaz B, Gonzalez I, Tuya J (2004) Incorporating fuzzy approaches for production planning in complex industrial environments: the roll shop case. Eng Appl Artif Intell 17:73–81
2. Akao Y (1990) Quality function deployment: integrating customer requirements into product design. Productivity Press, Cambridge Press
3. Ammar S, Duncombe W, Jump B, Wright R (2004) Constructing a fuzzy knowledge-based system: an application for assessing the financial condition of public schools. Expert Syst Appl 27:349–364
4. Antonsson EK, Otto KN (1995) Imprecision in engineering design. ASME J Mech Des 17(2):25–32
5. Biren P (1996) Concurrent engineering fundamentals: integrated product and process organization. Prentice Hall, Englewood Cliffs, NJ
6. Bovea MD, Wang B (2003) Identifying environment improvement options by combining life cycle assessment and fuzzy set theory. Int J Prod Res 41(3):593–609
7. Bowles JB, Peláez CE (1995) Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. Reliability Engineering and System Safety 50:203–213
8. Braglia M, Frosolini M, Montannari R (2003) Fuzzy criticality assessment model for failure modes and effect analysis. Int J Qual Reliab Manage 20(4):503–524
9. Chin KS, Wong TN (1996) Knowledge-based evaluation for the conceptual design development of injection moulding parts. Eng Appl Artif Intell 9(4):359–376
10. Chin KS, Lam J, Chan JKF, Poon PKK, Yang JB (2005) A CIM-OSA presentation of an integrated product design review framework. Int J Comput Integr Manuf 84(4):260–278, June
11. Chiu YC, Shyu JZ, Tzeng GH (2004) Fuzzy MCDM for Evaluating the E-commerce Strategy. Int J Comput Appl Technol 19(1):12–22
12. Cinquegrana DA (1990) Knowledge-based injection mold design automation, PhD Thesis, University of Lowell
13. Cohen L (1995) Quality function deployment. Addison-Wesley, Reading, Massachusetts
14. Diaz-Hermida F, Losada DE, Bugarin A, Barro S (2005) A probabilistic quantifier fuzzification mechanism: the model and its evaluation for information retrieval. IEEE Trans Fuzzy Syst 13 (5):688–700
15. Dixon JR (1995) Knowledge-based systems for design. J Mech Des 117:11–16
16. Du X, Chen W (2000) Concurrent subsystem uncertainty analysis in multidisciplinary design. 8th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, AIAA, AIAA-00–4928 pp 82–89
17. Fay A (2000) A fuzzy knowledge-based system for railway traffic control. Eng Appl Artif Intell 13:719–729
18. Franceschini F, Galetto M (2001) A new approach for evaluation of risk priorities of failure modes in FMEA. Int J Prod Res 39 (13):2991–3002
19. Garcia AA, Schirru R, Melo PF (2005) A fuzzy DEA approach for FMEA. Profess in Nuclear Energy 46(3–4):359–373
20. Gien D, Jacqmart S, Seklouli A, Barad M (2003) An approach based on fuzzy sets for manufacturing system design. Int J Prod Res 41(2):315–335
21. Hawkins PG, Woollons DJ (1998) Failure mode and effects analysis of complex engineering systems using functional models. Artificial Intelligence Engineering. 12:375–397
22. Knoglu A, Arditi D (2004) An integrated automation system for design/build organizations. Int J Comp Appl Technol 20(1–3):3–14
23. Lalla TRM, Lewis WG, Pun KF, Chin KS, Lau HCW (2003) Manufacturing strategy, total quality management and performance measurement: an integrated model. Int J Manuf Technol Manag 5(5/6):414–427
24. Lau HCW, Wong CWY, Lau PKH, Pun KF, Chin KS, Jiang B (2003) A fuzzy multi-criteria decision support procedure for enhancing information delivery in extended enterprise networks. Eng Appl Artif Intell 16:1–9
25. Li DC, Wu CS, Chang FMM (2005) Using data-fuzzification technology in small data set learning to improve FMS scheduling accuracy. Int J Adv Manuf Technol 27(3–4):321–328

26. Liao TW (2004) An investigation of a hybrid CBR method for failure mechanisms identification. Eng Appl Artif Intell 17:123–134
27. Mendil B, Benmahammed K (2001) Activation and defuzzification methods for fuzzy rule-based systems. J Intell Robot Syst 32 (4):437–444
28. Metaxiotis K, Ergazakis K, Samouilidis E, Psarras J (2004) Decision support through knowledge management: the role of artificial intelligence. Int J Comp Appl Technol 19(2):101–112
29. Mohamed A, Celik T (2002) Knowledge-based system for alternative design, cost estimating and scheduling. Knowl-Based Syst 15:177–188
30. Mok CK, Chin KS, Ho JKL (2001) An interactive knowledge-based CAD system for mould design in injection moulding processes. Int J Adv Manuf Technol 17:27–38
31. Myint S, Tabucannon MT (1998) The framework for an expert system to generate alternative products in concurrent engineering design. Comput Ind 37(2):125–134
32. Ong SK, Prombanpong S, Lee KS (1995) An object-oriented approach to computer-aided design of a plastic injection mould. J Intell Manuf 6:1–10
33. Ong YS, Keane AJ (2002) A domain knowledge based search advisor for design problem solving environments. Eng Appl Artif Intell 15:105–116
34. Opricovic S, Tzeng GH (2003) Defuzzification within a multi-criteria decision model. Int J Uncertain Fuzziness Knowl-based Syst 11(5):635–652
35. Ratchev S, Urwin E, Muller D, Pawar KS, Moulek I (2003) Knowledge based requirement engineering for one-of-a-kind complex systems. Knowl-Based Syst 16:1–5
36. Roychowdhury S, Pedrycz W (2001) A survey of defuzzification strategies. Int J Intell Sys 16(6):679–695
37. Saade JJ, Diab HB (2000) Defuzzification techniques for fuzzy controllers. IEEE Trans Syst Man Cybern, Part B, Cybern 30 (1):223–229
38. Sapuan SM (2001) A knowledge-based system for materials selection in mechanical engineering design. Materials and Design 22:687–695
39. Shin HY, Lee JW (1998) An expert system for pneumatic design. AI EDAM 12(1):3–11
40. Takahashi I (1996) Product design review. Productivity Press, USA pp 3–13
41. Tam SM, Kwong CK, Ip WH (2000) A hybrid artificial intelligence system for optical lens design. Int J Comput Appl Technol 13(3/4/5):229–236
42. Teng SH, Ho SY (1996) Failure mode and effects analysis: an integrated approach for product design and process control. Int J Qual Reliab Manage 13(5):8–26
43. Teoh PC, Case K (2004) FMEA through knowledge modeling. J Mater Process Technol 153:253–260
44. Teoh PC, Case K (2005) An evaluation of failure modes and effect analysis generating method for conceptual design. Int J Comput Integr Manuf 18(4):279–293
45. Vaghul M (1985) Expert systems in CAD environment: injection molding part as an example in computer in engineering, Proceedings of 1985 ASME Design Conference, New York, USA, Vol. 2, pp 77–82
46. Venter G, Haftka RT (1998) Using response surface methodology in fuzzy set based design optimization, 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA, AIAA, AIAA-98–1776, pp 641–652, 1998
47. Wang JC, Terpenny J (2003) Interactive evolutionary solution synthesis in fuzzy set-based preliminary engineering design. J Intell Manuf 14(2):153–167
48. Xu K, Tang LC, Xie M, Ho SL, Zhu ML (2002) Fuzzy assessment of FMEA for engine systems. Reliab Eng Syst Saf 75(1):17–29
49. Yager RR, Filev DP (1993) On the issue of defuzzifiztion and selection based on fuzzy set. Fuzzy Sets Syst 55:255–271
50. Zadeh L (1965) ‘Fuzzy sets’, Inf Control 8:338–353
51. Zadeh L (1992) The calculus of fuzzy if-then rules. AI Expert 7:23–27
52. Zha XF (2002) A knowledge intensive multi-agent framework for cooperative/collaborative design modeling and decision support of assemblies. Knowl-Based Sys 15:493–506
53. Zheng LY, Chin KS, Wei L (2002) Knowledge-enriched process FMEA model for process planning. The Asian Journal on Quality 3(1):12–27, June
54. Zimmerman HJ (1990) Fuzzy sets and systems: theory and applications. Kluwer Academic Publishers, Boston, USA