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RESEARCH ARTICLE - MECHANICAL ENGINEERING

Nuclear Product Design Knowledge System Based on FMEA Method in New Product Development

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Abstract Nuclear power product manufactories are continually striving to reduce both the amount and the cost of product maintenance, whilst at the same time ensuring that the nuclear power product safety, reliability, and integrity are not compromised. The demand for high-quality and low-cost products with short development time, especially for complex nuclear power products, e.g., nuclear power reheat valve, has forced the product development team to focus on the various effective product development strategies. In this paper, authors explore the applicability of knowledge-based technologies to competitive new reheat valve product design and development. Based on the proposed approach and methodologies, a web-based and service-oriented system supporting new reheat valve product design has been developed, which can assist inexperienced users to perform failure modes and effects analysis (FMEA) analysis,and most important, to get knowledge stored in database for future quality and reliability improvement. The system will help to enhance new reheat valve product stability at the stage of product conceptual design. A framework of system based on FMEA approach for new reheat valve product design is proposed in this paper.

Keywords New product development · Failure mode and effect analysis · Design supported system · Collaborative design

Mathematics Subject Classification 68T35 · 93B51

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الخلاصة

تسعى المصانع المنتجة للطاقة النووية استمرار للحد من كمية وتكلفة صيانة المنتج، بينما في الوقت نفسه تريد ضمان عدم المساس بسلامة منتج الطاقة النووية والموثوقية والنزاهة. والطلب على منتجات ذات جودة عالية ومنخفضة التكلفة مع قصر الوقت اللازم للتطوير، أما بالنسبة لمنتجات الطاقة النووية المعقدة، مثل صمام إعادة التسخين للطاقة النووية فقد أجبر فريق تطوير المنتج على التركيز على مختلف استراتيجيات تنمية المنتج الفعالة. وفي هذه الورقة العلمية يكتشف المؤلفون إمكانية تطبيق التكنولوجيات القائمة على المعرفة من أجل منافسة تصميم وتطوير منتجات صمام التسخين الجديدة. وبالاستناد إلى النهج والمنهجيات المقترحة، تم تطوير نظام معتمد على شبكة الإنترنت وخدمة المنحى الداعم لتصميم منتجات صمام التسخين الجديدة التي يمكن أن تساعد المستخدمين عديمي الخبرة لإجراء تحليل FMEA، والأهم من ذلك، للحصول على المعرفة المخزنة في قاعدة البيانات للحصول على جودة المستقبل وتحسين الاعتمادية. وسيقوم النظام بالمساعدة في تعزيز استقرار منتج صمام التسخين الجديد في مرحلة تصميم المنتج الافتراضي ، لذلك اقتُرح إطار نظام يقوم على وسائط الفشل ونهج آثار التحليل (FMEA) في تصميم منتجات صمام التسخين الجديدة في هذه الورقة العلمية.

1 Introduction

Nuclear energy has become an important energy for human beings although the Fukushima nuclear power accident occurred in Japan. Although nuclear power valve is an attachment in the nuclear power equipment, it is essential to the security of nuclear power plant. And reheat valve is an impartment part in nuclear power components. The security requirements of valves for nuclear power are higher than conventional coal-fired power.

At present, the demand for nuclear power reheat valve is much higher than the same level of power plant capacity in China. With a capacity of 80 million KW of nuclear power plants, for example, the demand of reheat valve whose diameter is DN25–1,000 mm is 2–3 times that of same level of power plant capacity. The reheat valve maintenance costs take more than 50 % of the total maintenance costs per year in a nuclear power plant which nuclear power units are 1 million KW, and the cost is about 150 million in China. Therefore, if the designers can fully consider the possible failure in product design stage, they will greatly help to reduce costs in maintenance stage.

Nuclear 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. Nuclear product design comes within a range of design procedures and decision makings. A knowledge-based system of the nuclear product 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. To optimize the nuclear product design process in terms of product quality, cost and reliability, the authors consider a Failure mode and effect analysis (FMEA) analysis knowledge-based system to assist designers to solve the conceptual design problems.

Currently, the reheat valve product design and development for nuclear power plant projects lack of FMEA in China. The design quality depends entirely on the individual experience and skill level of engineers. Serious defects often begin in design flaws, but they will be found until the product is used. It also brings some negative impact on corporate reputation and brand.

Failure mode and effect analysis is a very powerful and effective analytical tool to examine possible failure modes and eliminate potential failure during product design. As time going on, the information about design failures and product maintenance are accumulated, this information can provide a very valuable knowledge for future product and product design. The paper built a system in this project, which integrates in FMEA process, to reuse the design and maintenance information and knowledge in reheat valve product development. In this paper, the paper analyzes the failure mode of reheat valve in nuclear power plant, design and develop the FMEA system to support new reheat valve design. In the meantime, traditional FMEA is made by addressing problems according to an order from the biggest risk priority number (RPN) to the smallest ones. However, one disadvantage of this approach is that it ignores the fact that three factors severity (S), occurrence (O), and detectability (D) have the different weights in practice rather than equality. For example, reasonable weights for factors S, O are higher than the weight of D sometimes. The authors also consider this factor to characterize the importance of the failure causes within the system.

At present, a few researchers study on the FMEA method and system for nuclear power product in China. This paper mainly focuses on building the design supported system for new reheat valve development. Therefore, in this paper, authors propose an approach to construct reheat valve hierarchical structure and dependence relation models. Based on the proposed approach and methodologies, a design supported system is built, which can assist inexperienced users to perform the FMEA analysis for quality and reliability improvement, and could help to enhance stability of new products at the design stage.

2 Literature Review

Although the new product development (NPD) has been a significant part of the industry for some 50 years, at the same time, designing a product which reduces cost in maintenance stage is becoming more difficult than ever [1]. Many new products fail because they have been not fully considered when the product is designed. Therefore, a right product design can increase the probability of success, and reduces both the probability of failure and the uncertainty of achieving the organization’s overall objectives.

2.1 FMEA Review

The FMEA tool was first proposed by National Aeronautics and Space Administration (NASA) from their studies in 1963, and then it was implemented to the automobile industry for detecting possible potential failures at the design stage [2]. Many professional societies published certain procedures to perform the FMEA analysis during 1960s–1970s. In the early 1980s, automobile industries started applying FMEA into their product development process. Moreover, the characteristics of FMEA analysis are implemented rapidly to the different application areas such as aerospace, machinery, electronic and other manufacturing industries.

When performing FMEA, it may be difficult or even impossible to precisely determine the probability of failure events [3–5]. Many people give their understanding about the purposes of FMEA. Russomanno et al. [6] noted that FMEA allowed a team to analyze the effect of each failure on system operation. Most components or systems degrade over time and have multiple states. Barkai [7] stated that an FMEA is designed to find the sources of the failures of a system. Kennedy [8] noted that the risk priority number is computed using the probability of occurrence of the failure mode, the severity of the effect of the failure mode, and the probability of detection of the failure mode through manufacturing. Loch pointed out that FMEA could provide a prioritized list of potential failures [9]. Pries noted that FMEA documents should be under formal document control [10]. 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 [4,11–13]. In this paper, the authors propose and explore the applicability of knowledge-based approach in NPD with the FMEA methodology to todays competitive product design and development.

2.2 New Product Development Review

Although NPD has played an indispensable part in all kinds of fields, there may be some failure in the design stage when people develop a new product. In order to improve the qualities of a new product, doing some reliability analysis during the new product developing process is necessary and analysis results can transform knowledge for next generation of products. Among the numerous methods of reliability analysis, FMEA has proved to be one of the most effective methods to improve the reliability in product design stage.

The knowledge is a very important resource for developing new product, solving emergency problems and creating core competences for both individual and organizations now and in the future [14]. People can exchange data through a platform built on the information and communication technology infrastructure, in addition, they can also coordinate activities, share information, emerge private and public sectors, and support globalization commerce [15]. Expert systems are knowledge-intensive computer programs that capture the human expertise in limited domains of knowledge [16]. Database technology is a collection of data organized to efficiently serve many applications by centralizing the data and minimizing redundant data [17].

In recent years, researchers have started to adopt knowledge-based system approach to solve engineering design problems. Dixon [18] presented a general review of knowledge-based systems for engineering design. Tam [19] developed a hybrid artificial intelligent system for optical lens design with case base reasoning and genetic algorithm. Ong [20] developed a knowledge-based system called DKB (domain knowledge based) search advisor to support the problem solving in design stage. Kanoglu [21] 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. Kwai-Sanga [22] developed 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.

3 Application Scenario of Design FMEA in New Reheat Valve Development

Failure mode, effects, and criticality analysis (FMECA) is an extension of FMEA. FMEA is a bottom-up, inductive analytical method which may be performed at either the functional or piece-part level. FMECA extends FMEA by including a criticality analysis, which is used to chart the probability of failure modes against the severity of their consequences. The result highlights failure modes with relatively high probability and severity of consequences, allowing remedial effort to be directed where it will produce the greatest value. In order to perform FMECA, analysts must perform FMEA followed by critical analysis (CA). FMEA identifies failure modes of a product or process and their effects, while CA ranks those failure modes in order of importance, according to failure rate and severity of failure. CA does not add information to FMEA. What it does, in fact, is limit the scope of FMECA to the failure modes identified by FMEA as requiring reliability centered maintenance. FMECA tends to be preferred over FMEA in space and military applications, while various forms of FMEA predominate in other industries. The reheat valve product in this paper is an industry product, the authors chose FMEA method to solve the problem in this project.

Through the implementation of FMEA in nuclear power reheat valve design, we can analyze its main failure modes and causes. According to the failure modes, product developers take certain preventive measures while developing new generation of products next time. A successful FMEA activity helps the product development team to identify potential failure modes based on past experience with similar products or processes, enabling the team to design those failures out of the system with the minimum of effort and resource expenditure, thereby reducing development time and costs. The process of FMEA is presented in Fig. 1.

The process for conducting FMEA in nuclear power reheat valve design is summarized as follows:

- Describe the product or process.
- Define functions.
- Identify potential failure modes.
- Describe effect of failures.
- Determine causes.
- Direction methods or current controls.
- Calculate risks.
- Take actions.
- Assess results.

3.1 Bill of Material (BOM) of Reheat Valve

Before starting the actual FMEA, a worksheet needs to be created, which contains important information about the valve, such as the names of the components. On this worksheet, all the items or functions of the subject should be listed in a logical manner.

A bill of materials (sometimes bill of material or BOM) is a list of the raw materials, sub-assemblies, intermediate

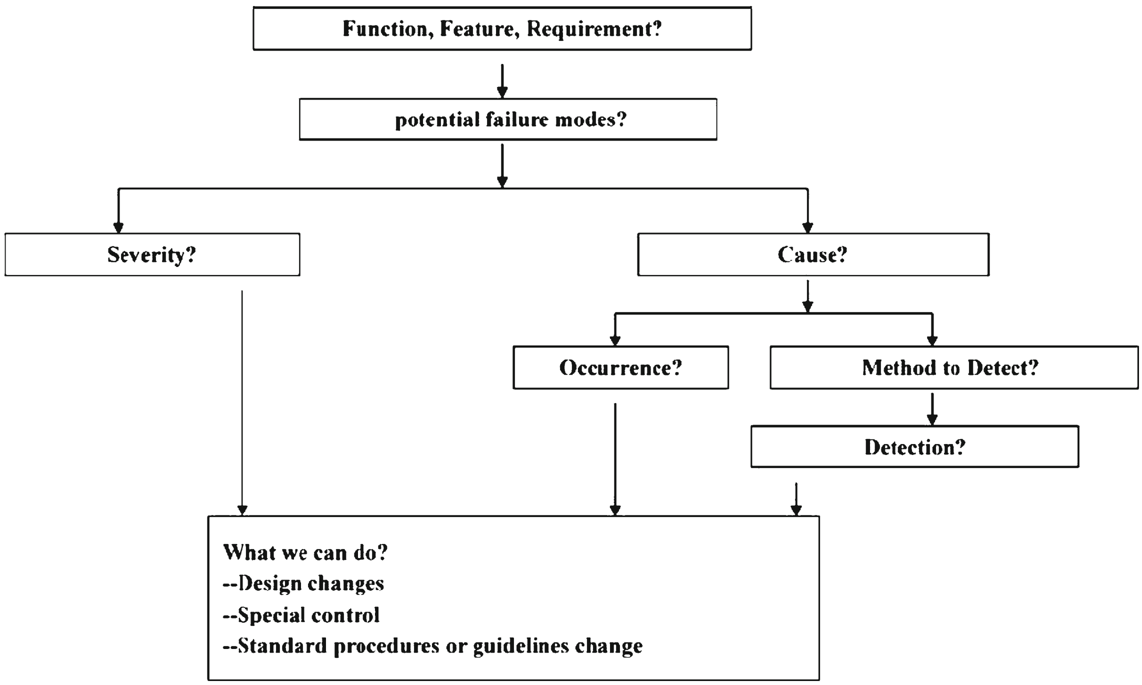

Fig. 1 Process of FMEA

assemblies, sub-components, components, parts and the quantities of each needed to manufacture an end product [16]. The reheat valve in this project is divided into three levels according to product function: main systems, sub-systems, and parts. The BOM structure is showed as Fig. 2.

3.2 Failure Modes and Effects Analysis for Reheat Valve

3.2.1 Block Diagram of Reheat Valve

Under consideration of structural and functional aspects, the presented design of the reheat valve ensures interruption of the steam supply to the LP turbine sections (stop valve) or throttling of the steam flow from the reheater in the event of load rejection to the extent that run up of the turbine to quick closing speed is prevented (control valve).

Then, a block diagram of the valve needs to be created. This diagram gives an overview of the major components or process steps and how they are related. These are called logical relations around which the FMEA can be developed. It is useful to create a coding system to identify the different system elements. The block diagram should always be included in FMEA. Every item shown in Figs. 3, 4 are diagram and block diagram of reheat valve, and at the same time, its the key component whose failure rises most possibly. Therefore the authors divide the valve by the function of each part.

3.2.2 The Failure Mode of Reheat Valve

In order to analyze the reheat valve failure modes and effects, the authors take brainstorming, reference method or list the failure modes through product life-cycle dimension. Then the authors get the Severity, Occurrence, and Detection numerical scale. The Severity, Occurrence and Detection factors are individually rated using a numerical scale, typically ranging from 1 to 10. However, for all FMEA standards, a high value represents a poor score. Once a standard is selected it must be used throughout the FMEA. In this paper, the criteria are used but with some amendment, and these modifications are necessary to make the FMEA methodology more appropriate to our project [23,24].

The modified Severity scale and criteria are shown in Table 1. The original scale of 1–3 is maintained, but changes were made to the category criteria definitions to emphasize their implications.

The modified Occurrence scale and criteria are tabulated in Table 2. There are four levels that consist of extremely unlikely, remote, occasional and frequent.

The level of Detection is shown in Table 3. The number 1 represents level 1—means almost certain; numbers 2, 3, 4 represent level 2—means high; numbers 5, 6, 7 represent level 3—means low; numbers 8, 9, 10 represent level 4—means almost impossible.

Then there can be concluded that the minimum RPN for any cause is 1 and the maximum is 1,000. As long as the rating scales of a selected FMEA procedure remain fixed, it can be used for the comparison of alternative designs and

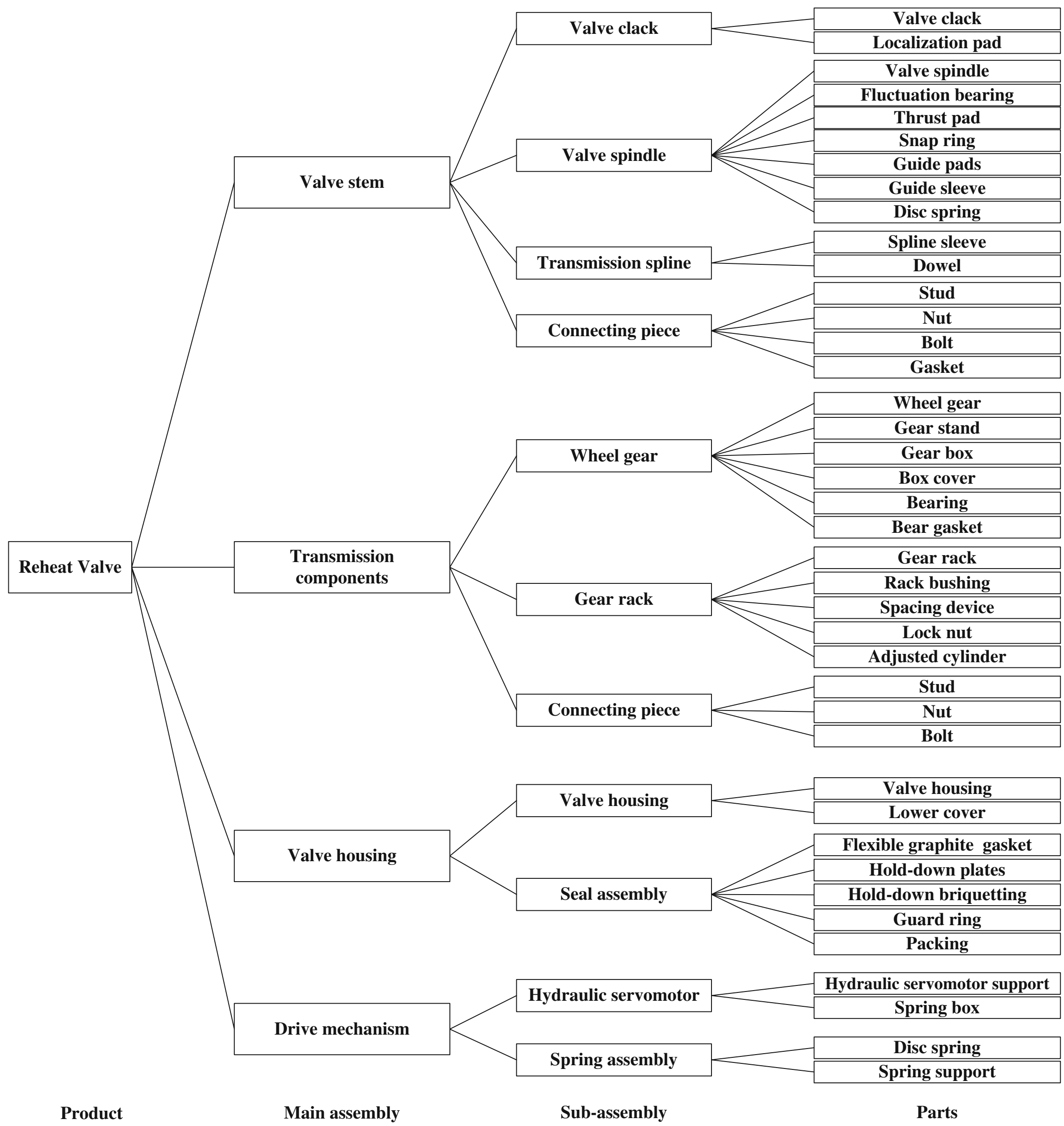

Fig. 2 Structure of the nuclear power valve

identification of critical assemblies. Defining these three criteria tables based on standard of MIL-STD-1629A [25] is the first step in performing an FMEA. As mentioned before the basic principles of an FMEA using different standards are similar and simple [26];

- The system to be studied must be broken down into its assemblies.
- Then for each assembly all possible failure modes must be determined.
- The causes of each failure mode must be determined for each assembly.
- The end effects of each failure modes must be assigned a level of Severity, and every root cause must be assigned a level of Occurrence, and Detection.
- Levels of Severity, Occurrence, and Detection are multiplied to produce the RPN.

Therefore, the first stage in the FMEA procedure is: obtaining a comprehensive understanding of the valve system and its main assemblies.

3.3 Process Model for Product Design Integration with FMEA

During product design, a detailed process model needs to be designed for FMEA service. The process model is shown in Fig. 5. Therefore, there are three activities which are impor-

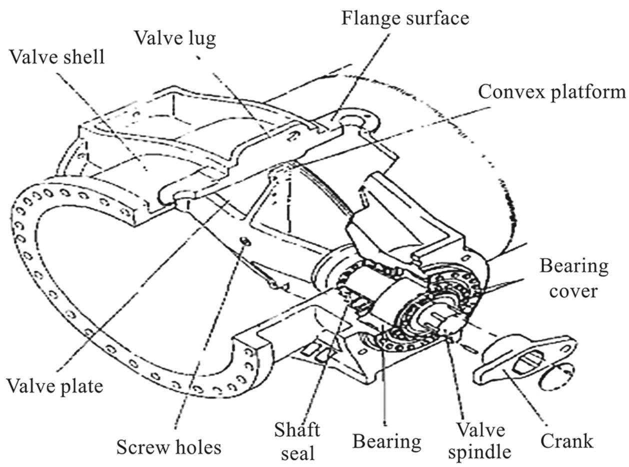

Fig. 3 Diagram of Reheat valve

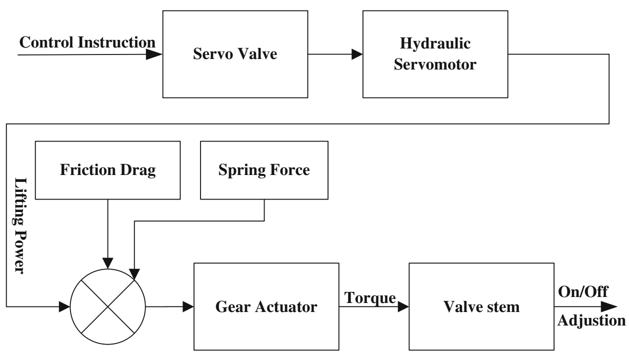

Fig. 4 Block diagram of Reheat valve

Table 1 Severity evaluation criteria

Rank	Severity effect	Criteria
8, 9, 10	Hazardous	Electricity can be generated but urgent repair is required
4, 5, 6, 7	Critical	Loss of ability to generate electricity
1, 2, 3	Minor	Major damage to the Turbine as a capital installation

Table 2 Frequency of occurrence evaluation criteria

Rank	Occurrence	Criteria
9, 10	Frequent	Failure is almost inevitable
7, 8	High	Repeated failures
4, 5, 6	Occasional	Occasional failures
1, 2, 3	Remote	Few failures or failure is unlikely

tant because one can use FMEA knowledge while performing their tasks. The process model includes following steps:

Step 1: Product designers create product model as per the product requirements and product specifications;

Table 3 Detectability evaluation criteria

Rank	Detectability	Criteria
8, 9, 10	Almost impossible	Current monitoring methods almost always will detect the failure
5, 6, 7	Low	Good likelihood current monitoring methods will detect the failure
2, 3, 4	High	Low likelihood current monitoring methods will detect the failure
1	Almost certain	No known monitoring methods available to detect the failure

Step 2: The product development team consists of product designers and quality engineers, and they work together for FMEA;

Step 3: With the initial product model as product requirements and product specifications, product development team has possible failure modes and failure problems. These problems will be input to software to search for historical and similar data, information or knowledge from the design FMEA knowledge base. The system will feed back results from any similar failure problem to product development team. If the feedbacks from system are adopted to revise the product model, then the new information will be generated and input to a new product object. This will be store to the knowledge base as new information.

It can be seen from this process model that the system can be used to serve three tasks during product design by providing FMEA knowledge fault data/information, failure analysis, and design improvement.

4 Design of FMEA System

4.1 Functional Framework of FMEA System

A functional framework about how the product development team works in the FMEA system supporting new reheat valve product design is presented in Fig. 6. The framework is a five layer Java-based system framework, which was developed to satisfy these technical requirements, and composed of portal, FMEA process data management, enterprise application platform, knowledge base and infrastructure.

Users have their own portal to access the system. The design FMEA process framework and models are implemented in the layer of FMEA process data management. Enterprise application layer contains two platforms: product life-cycle management and product development. Knowledge base stores the product failure data and information

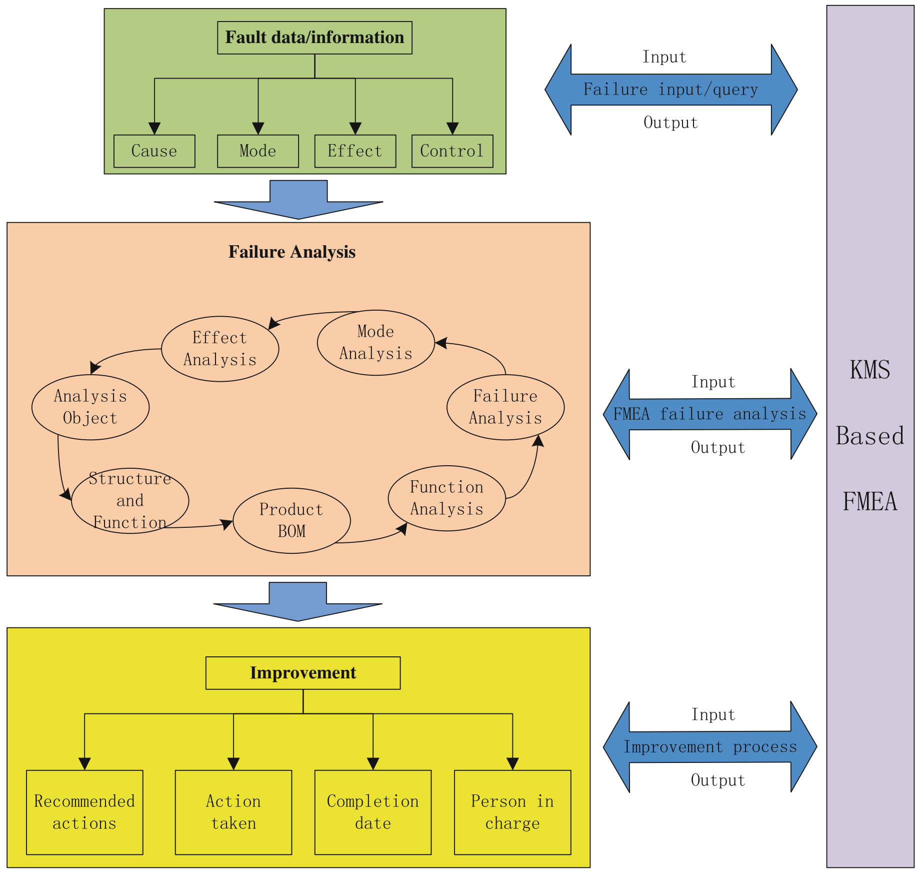

Fig. 5 Process model for product design integration with FMEA

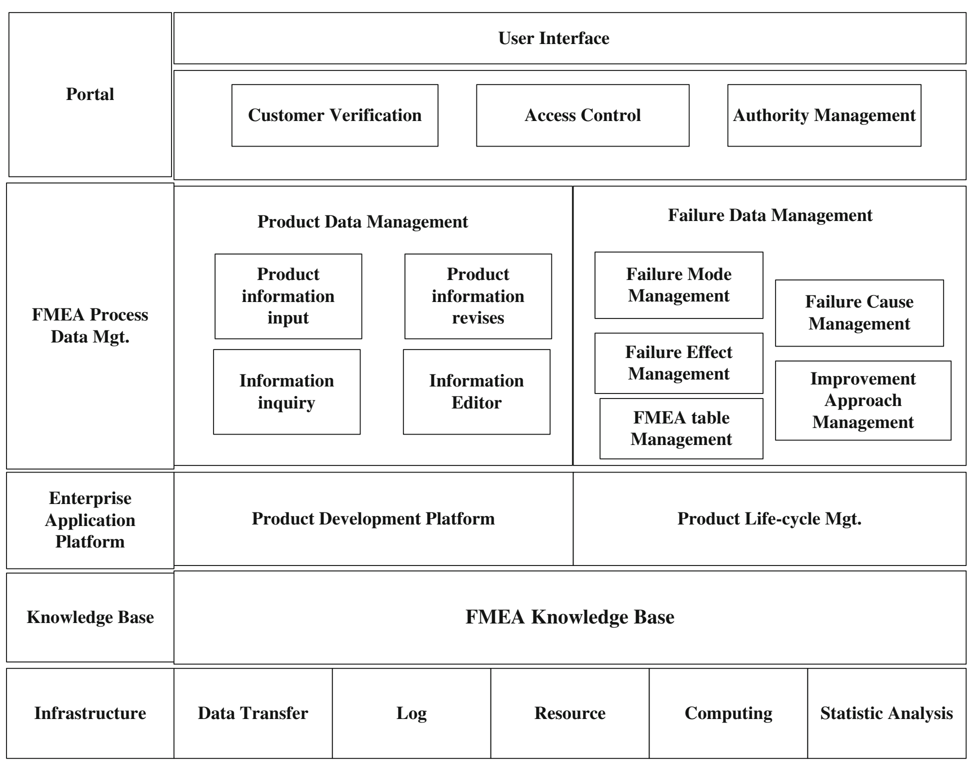

Fig. 6 Functional framework of FMEA system

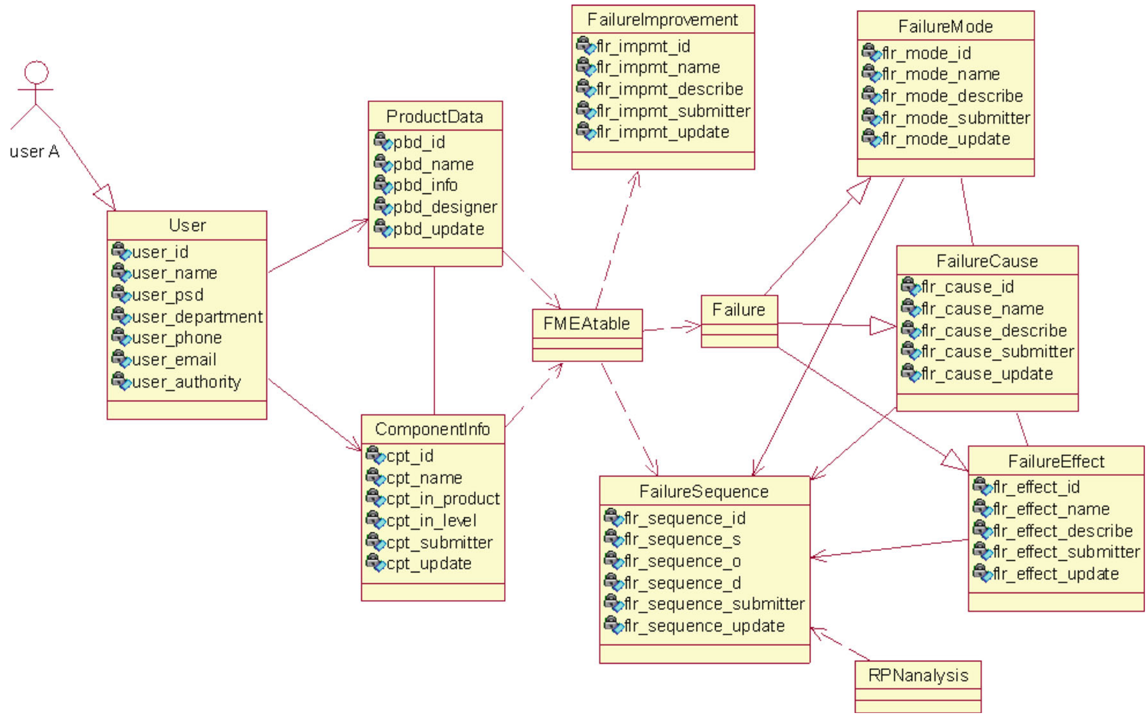

Fig. 7 Information model of product design with FMEA

mostly used by designers. The infrastructure layer is responsible for maintenance and system administration.

4.2 Information Model

The information model presented below shows how FMEA knowledge links to the product or resource. The information model is shown in Fig. 7. The information model represents the data exchange required between product development team and knowledge base system. It consists of the FMEA knowledge model, product model, and engineering document.

In this information model, FMEA data structure consists of product type, part/component type, failure mode, failure cause, failure effect, improvement action. These data, which are product type, part/component type, failure mode, are sent to FMEA knowledge base as a data set. The product design FMEA knowledge base system provides the corresponding causes and actions for each product design. With this cause and action, product development team can improve the efficiency of product development.

4.3 Function Collaboration

The function collaboration depicts the interactive processes between the system and user. It includes the processes to search failure data from users, failure data with knowledge base, update product failure to the system, data transfer process in knowledge base, engineering document links to or associates with the product and resource, as shown in Fig. 8.

5 System Implementation and Demonstration

5.1 Three-tier Architecture of the FMEA System

The structure of the FMEA system, as shown in Fig. 9, is divided into three parts: browser for users, web server design knowledge system, and database server design knowledge base. The user can access the system using Browser through Internet or Intranet, and get the information or knowledge they need. The developed design supported system, which is web-based, is running on a web server. The system mainly consists of customer verification, access control, authority management, product data management, failure data management, and settings management. The customer verification helps to reduce risk by allowing only customers who have registered to login and view the information stored in system. The function of access control is used to control which principals have access to certain resources in the system and what files they can read, which programs they can execute, how they share data with other principals, and so on. Authority management is the formal authority specified in a

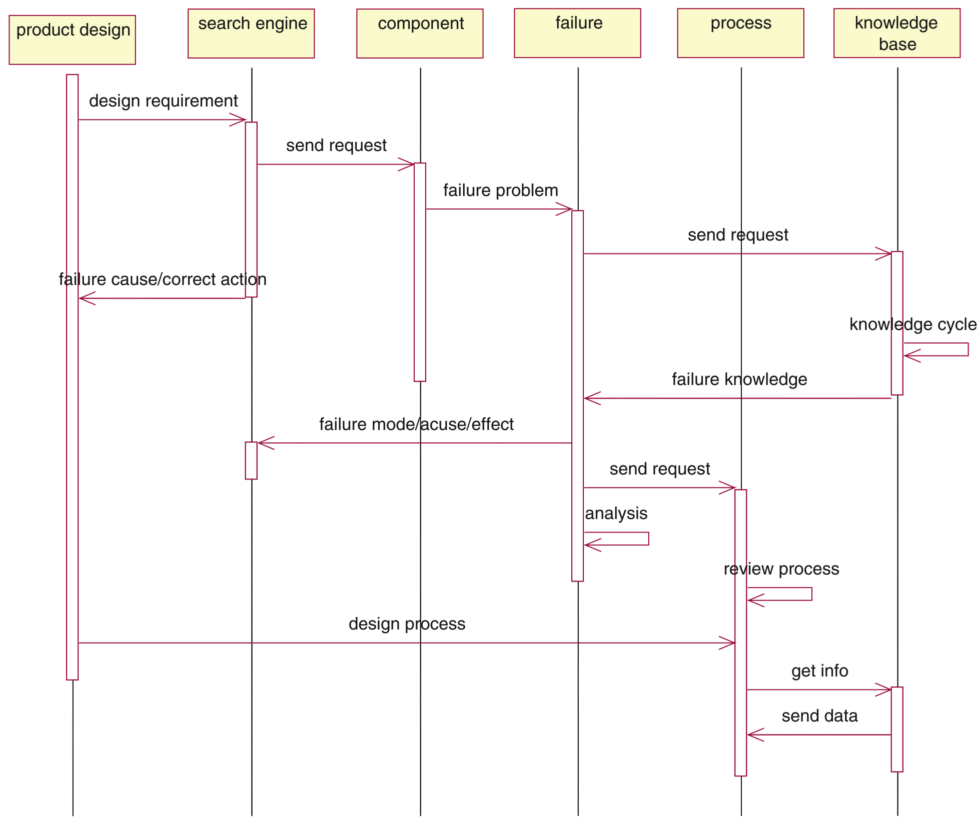

Fig. 8 Function collaboration of product design with FMEA

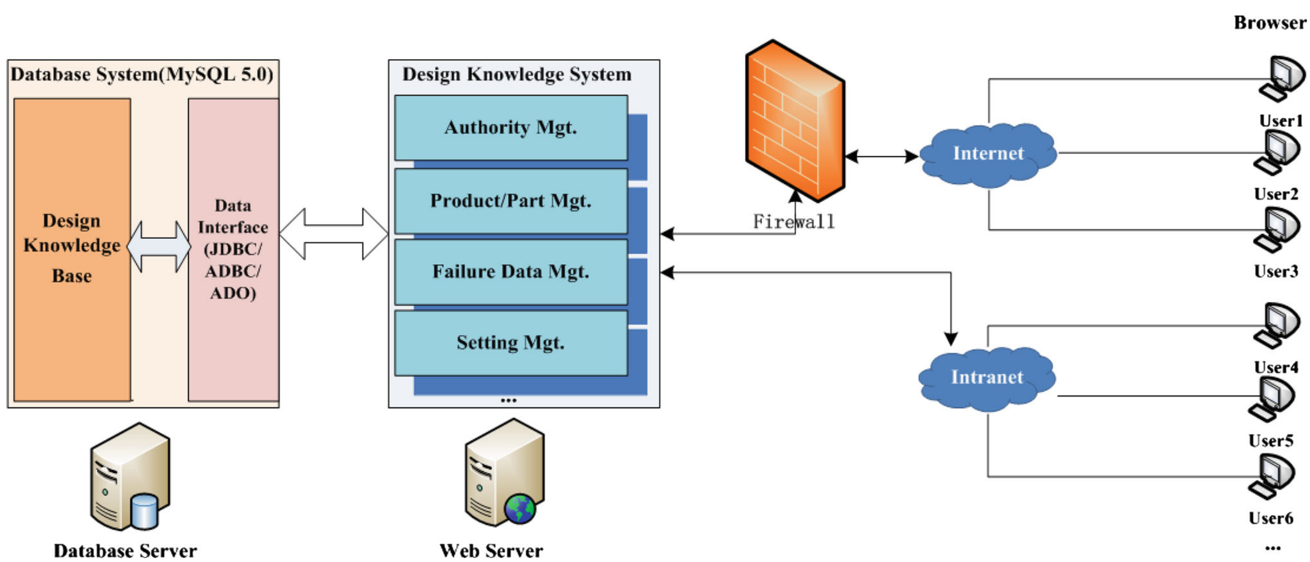

Fig. 9 Three-tier architecture of the FMEA system

system that gives a visitor the authority to view or modify data in the system. Product data management in this paper consists of product information input, product information revises, information inquiry, and information editor. Failure data management in this paper consists of failure mode management, failure cause management, failure effect management, improving measures management, and FMEA table management. Setting management is responsible for setting option values for common parameters or options involved with FMEA. All product data and failure data are stored by the database management system which is MySQL on the database server.

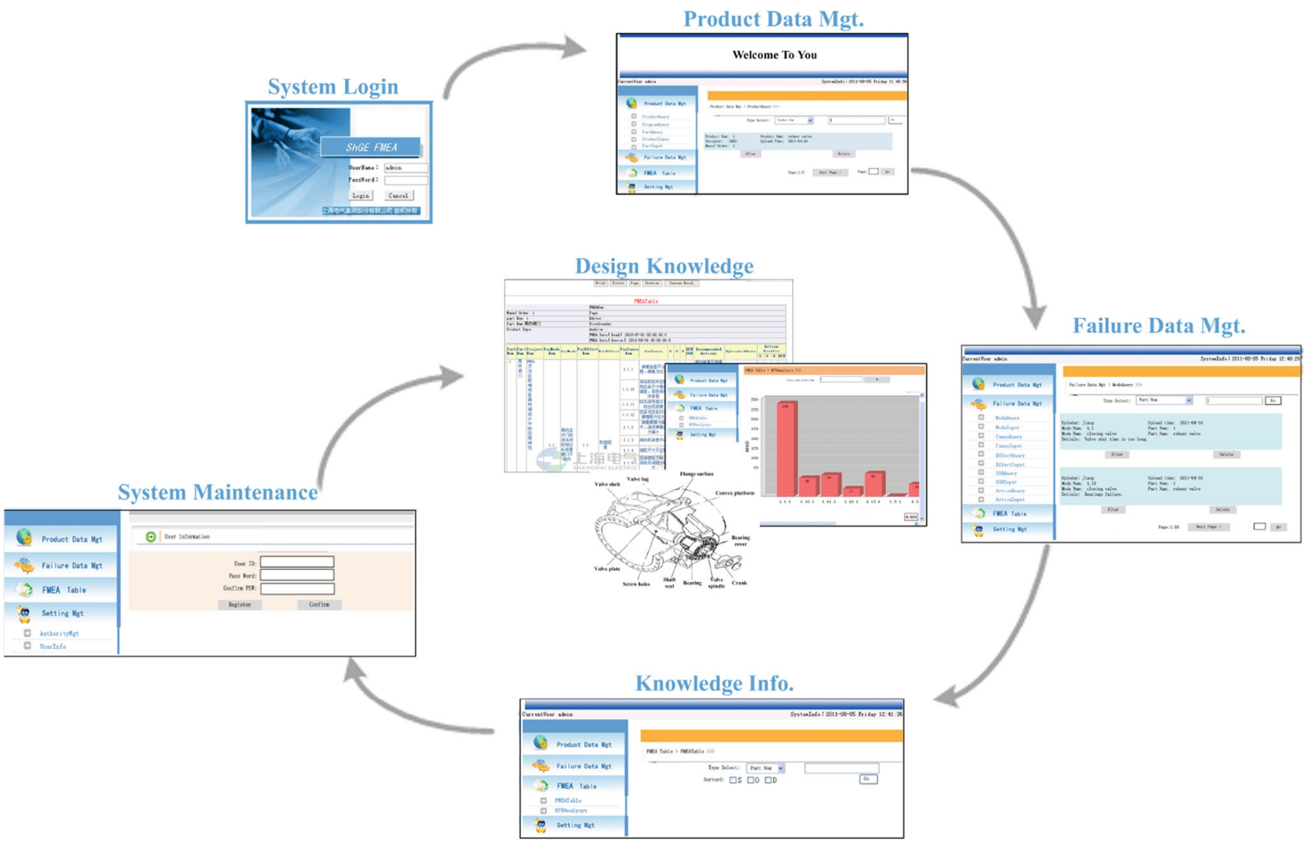

Fig. 10 Illustration of FMEA system for reheat valve product development

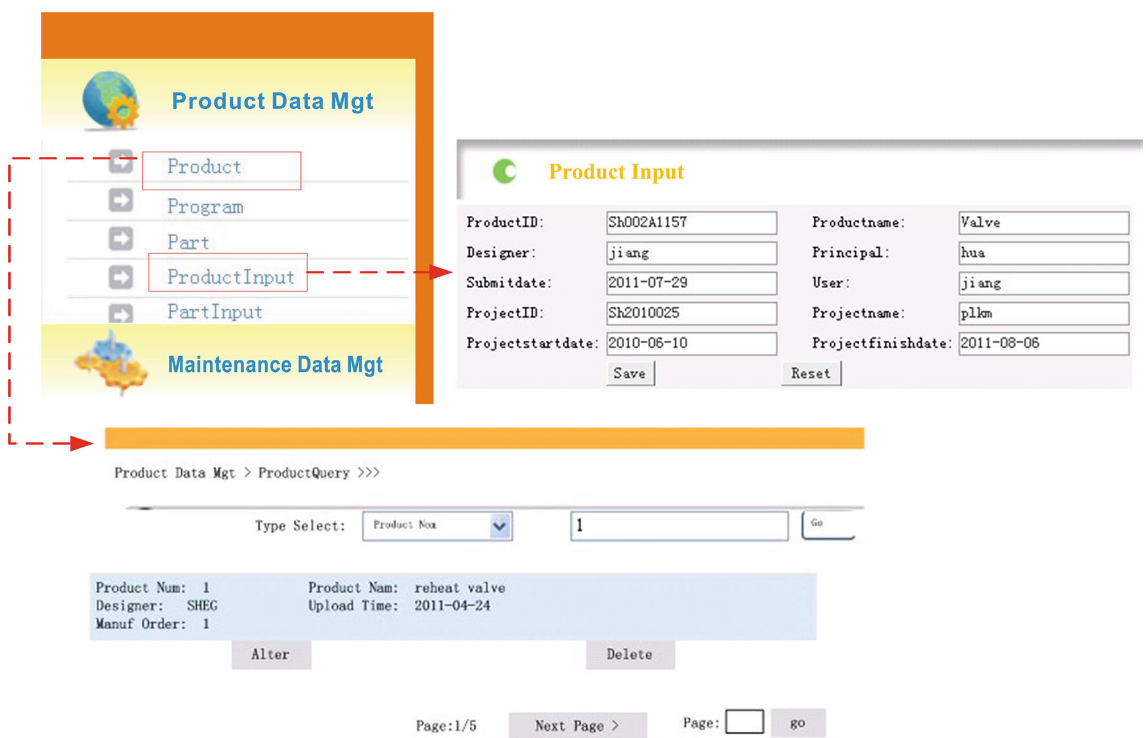

Fig. 11 Product data management for FMEA system

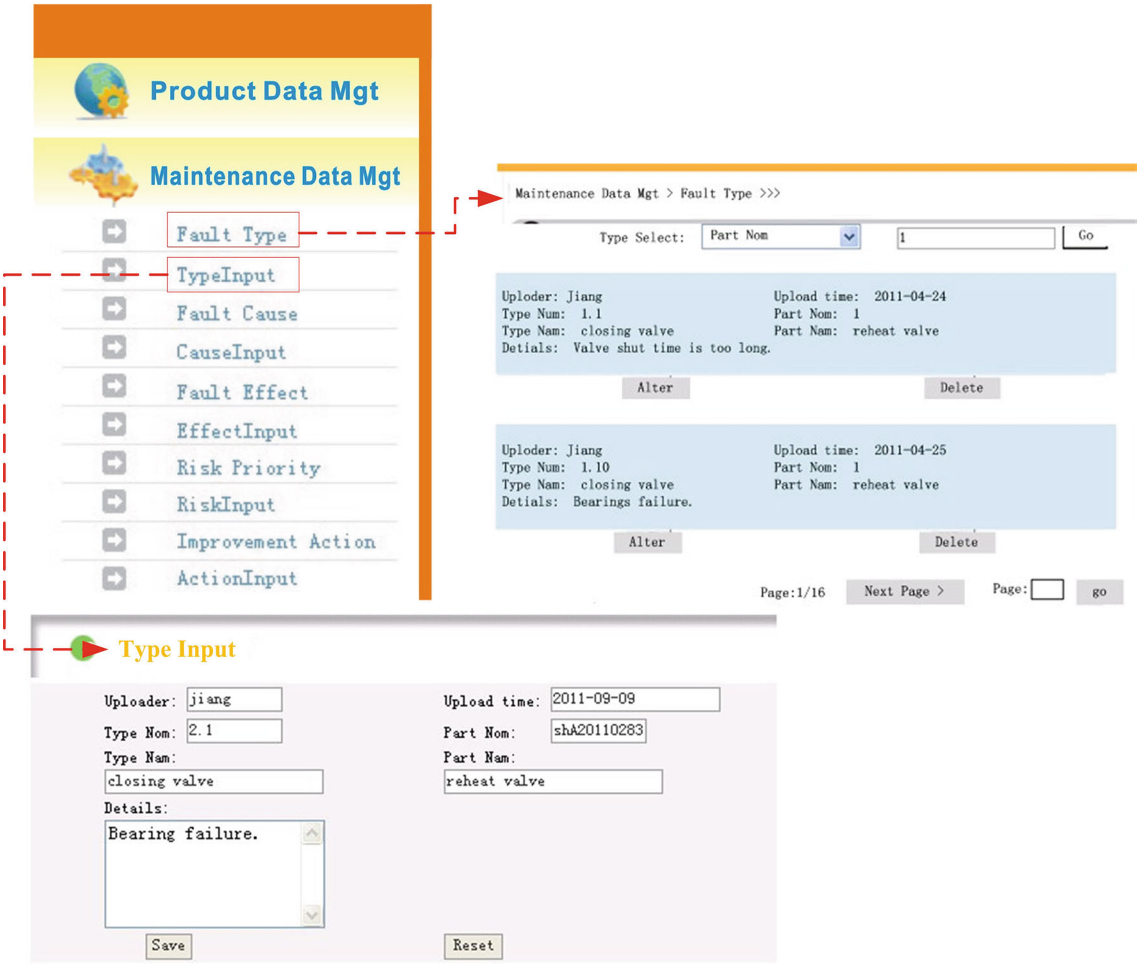

Fig. 12 Failure data management for FMEA system

5.2 System Implementation and Application Example

5.2.1 Demonstration of the System

An application system was developed to demonstrate the approaches proposed in this study. Figure 10 is the shortcut of this system. This system was developed on the four layer browser/server infrastructure based on J2EE architecture. These four layers consist of resource management, data management, application collaboration, and device-independent presentation layer.

5.2.2 Application Example

This section shows how to integrate FMEA method with reheat valve producibility analysis. The details of the FMEA system for new reheat valve production development are shown in Figs. 11, 12, and 13 as follows:

1. *Product data management* The relation information of the product is included in this module such as program information, part information. After clicking 'Product' button there will be a menu in which user can search the product property information, and in 'Product Input' menu user can type data into system such as product ID, product name, designer, principal, submit date, user, project ID, project name, project start date, and project finish date as shown in Fig. 11.
2. *Failure data management* The relation data of product failure are included in this module such as fault type of product, fault cause, fault effect, risk priority of product/part, improvement action. The reheat valve consists some of sub-assembly and part, each sub-assembly or part may have many types of fault, and each type of fault have fault cause and effect itself. For example, on clicking the 'Fault Type' button there will be a menu in which user can search the product fault type information as part number or project number. In the same way, user can input data in 'Type Input' menu as shown in Fig. 12. Due to limited space, the other menu is not depicted here.
3. *Fault analysis* The relation operations of fault analysis menu consist of FMEA analysis and RPN analysis

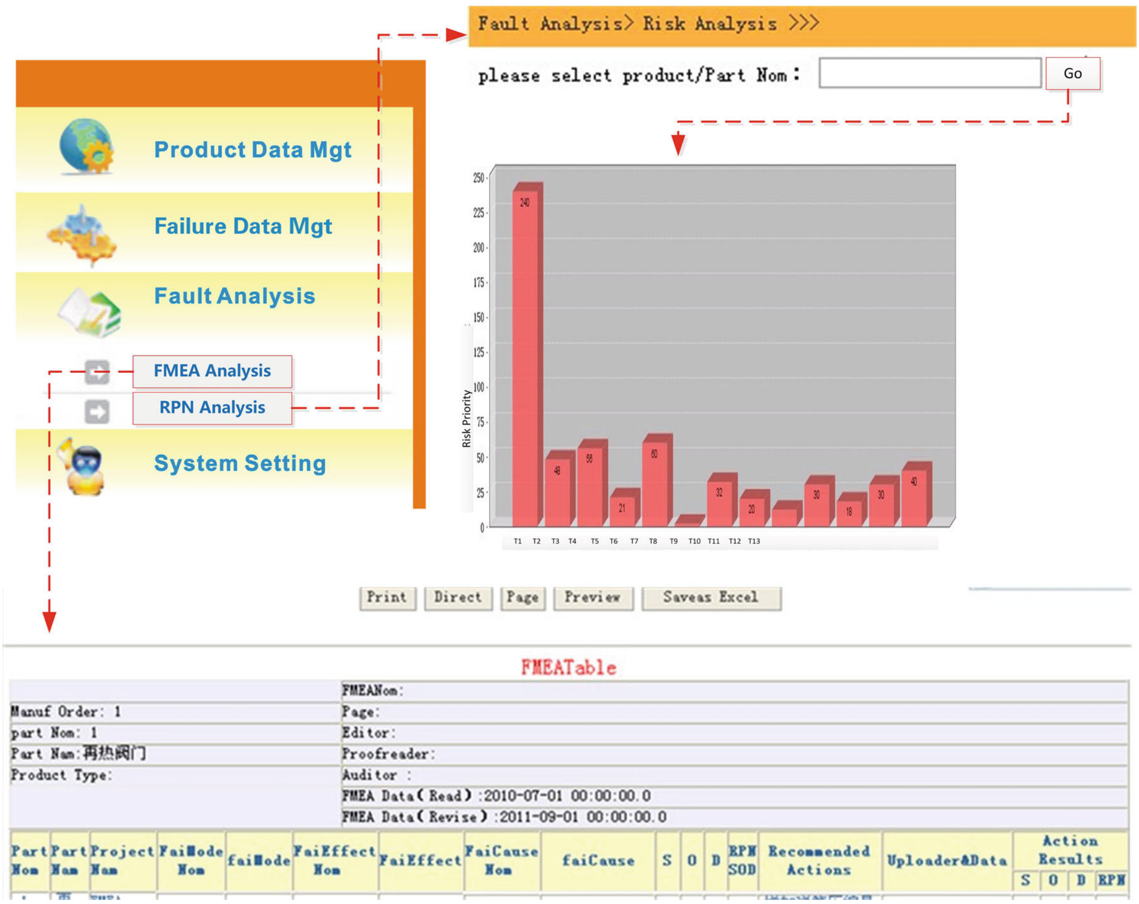

Fig. 13 Fault analyses for FMEA system

shown in Fig. 13. User can analyze the failure data of sub-assembly or part through 'FMEA Analysis' menu. 'RPN Analysis' is used to analyze risk priority about sub-assembly or part of reheat valve, and then user can get the maximum value. Hence, the designer must prove this fault first.

5.3 Technical Advantages and Potential Industrial Benefits

This paper proposes a FMEA method and new framework that integrates knowledge model for new reheat design. This new approach intends to deal with design knowledge reuse for nuclear power product development. The aim is that designers can avoid as many potential failures as possible by identifying them and taking appropriate mitigating actions in all stages of product development. By through theoretical analysis and real practical verification, the proposed approach has the following features:

- The web-based design supported system has been developed to provide a timely FMEA knowledge service for feasibility analysis and new reheat valve product development.
- The approach provides a support to collaboration design through network.
- Design supported system constructed in this paper is standardized and can be easily reused in other projects.
- Engineer's ability of product design and development is promoted with the help of the system proposed in paper.
- Enterprise R&D knowledge is accumulated and core competence is enhanced through this IT platform.

6 Conclusion and Future Perspectives

This paper has proposed a design supported system for new reheat valve product development at the product design stage. A web-based design supported system has been developed to provide a timely FMEA information or knowledge service for activities including feasibility analysis, failure mode, failure cause, and recommend action during new reheat product development. The proposed methodology and tools improve the quality and shorten the development lead time.

The development work was supported by a famous leading steam turbine manufacturer. The case study on a reheat valve development project for nuclear power plants has been conducted using this system to improve the quality and shorten the development lead time. The system proposed in this paper has demonstrated that design FMEA method is a valuable tool for new product design.

Future research works will be carried out based on the above results to tackle the further challenges as follows:

- Enhancing the reliability of data in knowledge base by enriching the data and information, and continuing the development works of knowledge bases of the product quality analysis, product maintenance data. This is because that product maintenance data is important knowledge to product development and design.
- Deeper collaboration needs stronger IT-based techniques. For the knowledge sharing and intellectual properties, this is not easy to do. It is a technology challenge on the one hand, but a management challenge on the other. New product developer can improve the quality of product development through the use of FMEA system. But there is also much tacit knowledge in product designers' brain, and this part of knowledge is more important. How to mine the tacit knowledge is our research focus in next stage.

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