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A Closed-loop Based Framework for Design Requirement Management

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Abstract. Requirement management plays a crucial role in determining a successful engineering design project. The focus of current requirement research is on the development of requirement elicitation, analysis and formalization methods and tools. Moreover, the existing requirement research often pays attention to the fuzzy front end of product design process. In fact, there exists more needs for requirement knowledge at each stage of a product lifecycle and requirement also has its own lifecycle. However, the research in the field of engineering design lack of a framework to support requirement management from product lifecycle, and requirement and requirement management lifecycle views. This paper highlights the importance of requirement lifecycle management and aims at closing the requirement information loop in product lifecycle. Then, it addresses the requirement management in engineering design field with focusing on the dynamics nature and incomplete nature of requirements. Finally, a closed-loop based framework is proposed for requirement management in engineering design.

Keywords. Requirement management, requirement lifecycle, closed-loop, engineering design

Introduction

Requirement management (RM) plays a key role in determining a successful product development [1], which is a wide research field involving marketing research, business studies, psychological studies, human factors, social factors, software engineering and artifact design [2]. Analysis the literature shows that requirement research is paid sufficient attention in the field of software engineering and information systems [3, 4]. Although, the importance of requirement management in engineering design has been widely acknowledged in design society [5-9], as pointed by Darlington and Culley [10], engineering design requirement is a relatively poorly researched area in design studies. Searching requirement research in prestigious design journals, such as *Design Studies (6), Research in Engineering Design (3), Journal of Engineering Design (10), Artificial Intelligence for Engineering Design Analysis and Manufacturing(3), Computer-Aided Design(5), Journal of Mechanical design (0), Journal of Computing and Information*

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Science Engineering(4), Concurrent Engineering: Practice and Application (13) , and *Advanced Engineering Informatics* (4), verified that only 48 papers have been published since the year of 2000 (Note that the date for searching is March, 2014, and the search engine is *ISI Web of Knowledge*). The research area of design requirements in the aforementioned design journals has developed some approaches and tools for requirement elicitation, requirement analysis, requirement management and for understanding the characteristics of requirement. However, from the requirement lifecycle and requirement management lifecycle view of points, to our knowledge, there still a lack of a closed-loop based approaches or tools for requirement management in relation to engineering design. This paper devotes effort to develop a closed-loop based framework for a better design requirement management.

1. Literature review

Due to its significance, considerable studies have been carried out on requirement management in engineering design community (e.g., [5, 7-9]). Due to limited space, only several typical related research works are briefly reviewed as follows. More complete reviews on requirement in the area of engineering design or product design can be found in the review papers presented by Darlington and Culley [10], and by Jiao and Chen [2].

Brace and Cheutet [11] defined a framework to develop a systematic approach. Based on the approach, they presented a model driven approach for deriving requirement. Zenun and Geilson [12] proposed a framework for completeness in requirement engineering and applied the framework in aircraft maintenance scenario. Robertson and Robertson [13] gave a plenty of advice on techniques for eliciting requirement. Wang and Zeng [14] proposed a generic process for eliciting product requirement by asking questions based on linguistic analysis. A software prototype is also developed to support the proposed process. Cascini et al. [15] explored how to situate needs and requirements in Gero's FBS [16, 17] framework. Xu et al. [18] developed an analytical Kano model to quantitative analyze and classify customer needs. Darlington and Culley [19] used an empirical study to investigate and model the influencing factors to design requirement. Liu et al. [20] proposed a scenario-based approach for the management of design requirement. Baxter et al. [21] developed a framework for the integration of design knowledge reuse and requirements management. This framework enables the application of requirements management as a dynamic process. Gershenson and Stauffer [22] developed a taxonomy for the classification of corporate requirements. Corporate requirements come from internal sources such as marketing, finance, manufacturing, and service that reflect the internal needs of corporate on product development. Rounds and Cooper [23] presented and applied taxonomies of environmental issues to the development of product design requirement.

By integration of the requirement classification works by Ullman [9] and Salonen et al. [24], requirement can be classified into: 1) functional performance requirement; 2) human factor requirement; 3) physical requirement; 4) reliability and feasibility related requirement; 5) lifecycle concern requirement; 6) resource concern requirement; 7) manufacturing and assembly requirement; 8) installation and use related requirement; 9) service related requirement; and 10) economical and technical related requirement.

In fact, the above ten classes of requirements can be reclassified into three categories based on a product lifecycle view: 1) BOL (Begin of Life, including planning, design, and production) related requirement; 2) MOL (Middle of Life, including use, service and maintenance) related requirement; and 3) EOL (End of Life, including reuse, material reclamation and disposal) related requirement. In an analogy with the lifecycle of a product or a piece of knowledge, a piece of requirement also has its lifecycle. Therefore, it needs a lifecycle oriented framework the understanding and management of design requirement.

2. Understanding design requirement

A better understanding of design requirement is a precondition for the development of a feasible requirement management framework. From a research perspective, the focus of the most current design requirement research is on the design object related requirement. However, in the existing works in this field, there is still a lack of design requirement research with considering both design object and design process aspects. Moreover, there also rarely exists a requirement lifecycle oriented management framework. In order to contribute to the research in design requirement management, it is of first important to explore what design is, what design requirement is and the connection of design requirement with design and design knowledge themselves.

2.1. Understanding design

What is design? Many prestigious scholars in design community have discussed its definition (e.g. [6-7, 16]). As pointed by pioneer studies, "*to design is to pull together something new or to arrange existing things in a new way to satisfy a recognized need of society"* [7]. Hence, the word design can be either a noun or a verb. The verb form of design is *designing* (i.e., design process), which refers "to conceive or to form a plan for". The purpose of designing is to transform design requirement into a solution for production, BOL and EOL. The noun definition of design is also *design* itself (i.e., design object), which often refers to "the form, parts, or details of something according to a plan". Both design and designing can be ontologically illustrated by Figure 1, as that presented by Gero et al. [17] and Ullman [9].

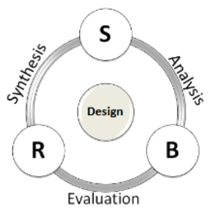

Figure 1. Design and design process

As shown in Figure 1, design object is about what the requirement (R), solution or structure (S), and behavior (B) should be; design process is about how designers fulfill the design activities of synthesis, analysis and evaluation for the transformation of requirement into a desired solution. Design process can be viewed as a series of decision nodes (see Figure 2). The decisions made on each node are based on its existing design knowledge and the gained new design knowledge; the design knowledge is classified into design object knowledge and design process knowledge by Hubka and Eder [25]. Design requirement is also a kind of design knowledge. In this regard, design requirement should also consist two parts, i.e., design object related requirement and design process related requirement.

Figure 2. Elements of a decision node

Today's engineering design especially the design of complex long service life product (e.g., air crafts, continuous casting machines, ships etc.), should both take the design stage and the after design stage into account, see Figure 3. In this circumstance, the design does arrange existing things or pull together something new in a new way to satisfy a recognized need of society and the whole product lifecycle, which requires more information flow or knowledge flow between different user groups and projects [26]. Therefore, today's design requirement management is more complex than that have been explored in existing works.

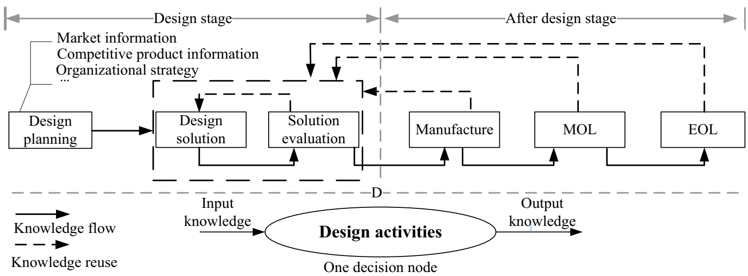

Figure 3. Product lifecycle and closing the information loop

2.2. Understanding design requirements

In the engineering design field, the characteristics of design requirement are highly related to the nature of design or design knowledge itself. Based on the above understanding of design, it should be confirmed that design requirements can classified into (see Figure 4): 1) design object related requirement, and 2) design process related requirement. The classification of design requirement is similar to that of design knowledge by Hubka and Eder [25]. Figure 5 is an ontological framework for the representation of both design object and design process and also the design knowledge required for each design activity.

- Design object related requirement

It has been widely recognized that customer value, product quality, cost and etc., are all factors that can be improved by effective requirement management. In fact, these factors are all design object related requirement. In the front end of product development, it needs effort to better understand customer requirements. It is the start point of a business successful product, which named as "do the right thing", see the right part of Figure 5. Detailed description of object related requirement can be found in engineering design texts (e.g., [5, 7, 8]). As mentioned by Dieter and Schmidt [7], in much of new product design, 40 percent are existing parts reused without modification, about 40 percent are existing parts used with minor modification, and only 20 percent of the parts are new. It can be concluded that most of information and knowledge are reused from previous design. For example, up to 70% of information is reused from previous solution in the case of variant design [27]. Therefore, in order to support the reuse of design knowledge in an efficient and effective manner, design object related requirements should be presented as a component of design object knowledge. It is another guarantee of a successful product, which improved the probability of "do the thing right", see the left part of Figure 5.

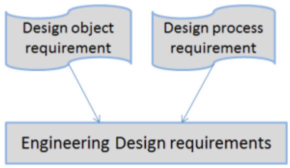

Figure 4. Design requirements

- Design process related requirement

As shown in Figure 2, designer is the key element of a decision node. Designers fulfill design activities to complete design tasks. A design activity can be characterized as a goal-oriented, constrained, decision-making, exploration, and learning activity that operates within a context that depends on the designer's perception of the context [16]. As shown in Figure 2, in order to complete a design activity, a designer has the process related requirement for input information, know-how knowledge and also context knowledge. Effective process requirement management can improve the efficient and effective of design work. Therefore, the management of process related requirement should be paid sufficient attention.

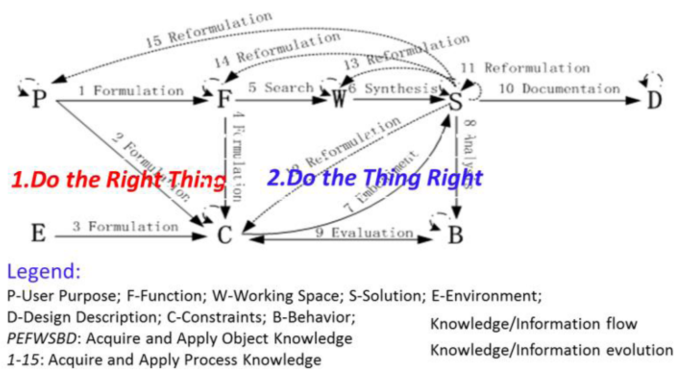

Figure 5. Design requirement (after Zhang et al. 2013)

There may be too much characteristics of design requirements; the focus of this paper is on the following two natures of design requirements.

- Incomplete nature of design requirements

Design knowledge is incomplete [7, 28]. In analog with the nature of design knowledge, design requirement is also incomplete. The requirement development process is also an evolution process of requirement knowledge, i.e., the state of requirement knowledge will be changed from an initial high degree of incompleteness into a final considerably complete state. It should be note that, there will be no absolutely complete requirement knowledge. It is similar to that as a satisfied solution stated by Herbert Simon.

As shown in Figure 5, each concept (i.e. P, E, F, and C) in the figure can be viewed as a requirement knowledge set for product planning. At initial design stage, the set of requirement knowledge is incomplete and new requirement knowledge should be acquired to improve its degree of completeness. For example, a complete requirement knowledge set about a customer need and environment can be represented as $P= (P_G, P_A, P_O)$ and $E= (E_S, E_N, E_L, E_O)$, respectively. P_G stands for the goal, P_A is used for describing the actions sequentially taken by a customer to achieve his goal, and P_O explains the desired artifact described by a customer. E_S represents the constraints from a social aspect (e.g. laws, regulations and culture). E_N describes the constraints from a nature aspect (e.g. humidity and temperature). E_L refers to the constraints from product lifecycle operations (e.g. transportation and maintenance). E_O is used for describing the environmental entity, which is indispensable for an artifact to work properly (e.g. gasoline is necessary for the operating of gasoline engines, charging pipes are necessary for e-cars). For example, in the beginning of a design, designers only have the requirements set of $P'= (P_G, ?, ?)$, $E'=(?,?,?,?)$ to achieve his complete requirements knowledge sets P and E, the designers have to acquire the needed new requirement knowledge sets $P^*= (?, P_A, P_O)$ and $E^*= (E_S, E_N, E_L, E_O)$ to construct a complete requirement knowledge set.

- Dynamics nature of design requirements

According to the incomplete nature of design requirement knowledge, we know that the state of requirement knowledge is dynamic. The dynamics of requirement knowledge refers to the right requirement at the right time for the right participant. The dynamics nature means 1) the evolution of design requirement knowledge from an incomplete state into a complete one, 2) changing the form of design requirement knowledge from one into another (i.e. from informal to formal, from tacit into explicit), and 3) transferring design requirement knowledge from one decision node to another.

The dynamic nature of design requirement knowledge describes the state of requirement knowledge within a specific scenario. As have been explored by Dieter and Schmidt [7], a good design should consider 1) achievement of performance requirement, 2) life-cycle issues, and 3) social and regulatory issues. All the three considerations may be a scenario which drives the evolution of design requirement knowledge from an initial incomplete state to a desired state. The environment refers to the inner or outer factors which influence a design. It should be remember that requirement knowledge is a dynamic resource, which is constantly changing. Therefore, a novel requirement management framework is necessary for guiding designers to understand the change of requirement knowledge and reuse design knowledge the design process.

3. Framework development

The proposed framework aiming at managing design requirement (includes both design object and design process requirements) taken the nature of design requirement into consideration. Due to the social, technical and cognitive characteristic of design, the attentions to social and cognitive issues are also of prominent important to requirement management, but it is out of the scope of this paper. The focus of RM is on the technical characteristics of design, i.e., the development of technical framework of RM

3.1. The closed-loop requirement management concept

According to the affordance-based relational design theory [29], customer, actor and product should provide affordable requirement information between each other. Therefore, a closed-loop [30] requirement management will allow the actors (i.e. designer, manager, production, service, maintenance, recycler engineers, etc.) who play roles during the lifecycle of a product development to elicit, analysis, transfer, manage and utilize requirement information at any stage of its lifecycle (i.e., design, production, MOL and EOL) without limitation to time and place. Figure 6 shows the closed-loop requirement management (RM) concept. The concept requires a RM system to support closing the information loop in product lifecycle and in the actor networks (customer, product, designer).

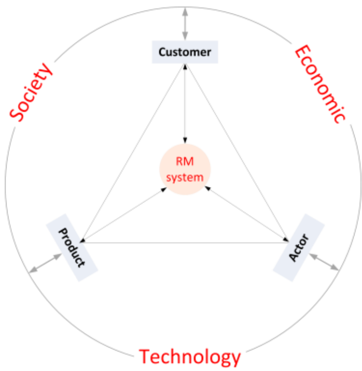

Figure 6. The closed-loop requirement management concept

As shown in Figure 6, the main elements of the closed-loop RM concept are:

- RM system to support the capture, modeling, retrieval, reuse and update of requirement information
- Knowledge flows (includes data and information) to support decision making of each actors (includes customers)
- Scenarios for the understanding of requirement to different actors.

According to the above concept of closed-loop RM, the main functions of the concept are:

- Closing the information loop in product lifecycle, aiming at gaining a better performance of transfer, sharing, application and reusing of requirements

- Closing the requirement lifecycle, aiming at improve the degree of completeness of requirement knowledge and the performance of RM.

3.2. Closed-loop requirement management framework

Figure 7 illustrates a diagram of the RM framework. The basic units of this framework are the requirement elicitation (RE), requirement analysis (RA), and requirement transfer (RT), requirement application (AAP) and requirement management system (RMS). The extended FBS framework (see Figure 1 and 5) can be employed to discuss the above units.

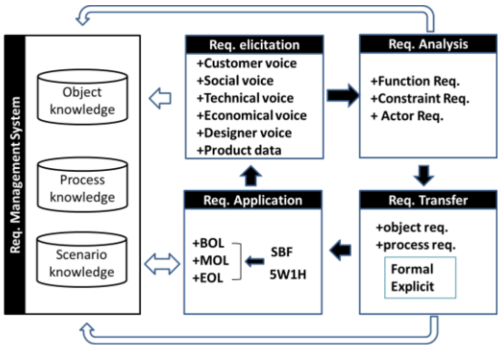

Figure 7. The closed-loop RM framework

- Requirement elicitation

The process of RE can be represented in a clearly defined structure as:

[Data Source]→[R Capture Methods]→[R Data]

The function of RE is to capture raw data from several data sources, e.g., customer voice, social voice, technical voice, economical voice, designer voice and product data, etc. these data sources can be categorized into: customer, society, corporate and product, and supporting facilities related requirement data.

The methods and tools (e.g., interview, observation, brainstorm, questionnaire, benchmarking etc.) for the capture of requirement data have been given sufficient attention in literature. It will not be discussed here. The focus of RE is on the management the output of RE process and construct scenario for the shared understanding of requirement data.

- Requirement analysis

The process of RA can be represented in a clearly defined structure as:

[R Data]→[R Methods]→[R Information]

Kano model [18] and QFD method [31] are widely used for the translation of requirement data into requirement information. The outputs of RA are function requirement, constraint requirement and actors' knowledge requirements.

- Requirement transfer

The process of RA can be represented in a clearly defined structure as:

[R Information]→[R Transfer Methods]→[Formal or Structure R]

The function of RT is to provide actors with an easier way to retrieval and understand the content of requirements. A scenario-based approach [20] can be employed to represent requirement in a formal way and thus to assist RT.

- Requirement application

The process of RAP can be represented in a clearly defined structure as:

[R Information]→[R Interpret Methods]→[R Knowledge]

The function of RAP is to provide actors with requirement knowledge to drive effective decision makings. The SBF and 5W1H (i.e., who at where and when, why and how to do what) framework can be employ to assist requirement management for application.

- Requirement management system

A RM system will provide affordable functions to manage the elicitation, analysis, transfer and application processes and the information or knowledge created in these processes. All the requirement related activities in a corporate should be record in the RM system.

4. Conclusions and future work

The objectives of this study are to highlight the importance of requirement lifecycle management and closing the requirement information loop in a product lifecycle. We address the requirement management in engineering design field with focusing on the dynamics nature and incomplete nature of requirements. The two natures explores that there is a need of a lifecycle oriented approach for requirement management, i.e., requirement and requirement management lifecycle, and embedded requirement into product lifecycle. In analogy with design knowledge, two types of requirement (design object related requirement, and design process related requirement) are recognized. The concept of closed-loop requirement management is then proposed with emphasizing consumer, product, actor and context as key elements. Furthermore, a closed-loop based framework was proposed to provide affordable functions for actors to manage requirement lifecycle information.

Further work needs to be done for a better understanding of design requirement, and the requirement information loops should also be identified in industry using deep case studies. The benefit and weakness of the proposed framework should be assessed and improved.

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References

[1] A. Mckay, A. de Pennington and J. Baxter, Requirement management: A representation scheme for product. *Computer-Aided-Design*, **33**(7) (2001), 511-520.

[2] J. Jiao, and C.H. Chen. Customer requirement management in product development: A review of research issues. *Concurrent Engineering Research and Application*, **14**(3) (2006),173-185.

[3] V. Sinha, B. Sengupta and S. Chandra, Enabling Collaboration in Distributed Requirements Management. *IEEE Software*, **10**(2006), 52-61.

[4] M. Lang, and J. Duggan. A Tool to Support Collaborative Software Requirements Management. *Requirements Engineering*, **6**(2001),161–172.

[5] G. Pahl, and W. Beitz, *Engineering design. A systematic approach (3rd ed)*. Wallace, K. and Blessing, L., translation and edition. Berlin: Springer, 2007.

[6] N.P. Suh, *Axiomatic design: Advances and application*. New York: Oxford University Press, 2001

[7] G.E. Dieter, and L.C. Schmidt, *Engineering design (5th ed).* New York: McGraw-Hill, 2012.

[8] K.T. Ulrich, and S.D. Eppinger, *Product design and development (5th ed).* New York: McGraw-Hill, 2011.

[9] D.G. Ullman, *The mechanical design process(4th ed)* . New York: McGraw-Hill, 2009.

[10] M.J. Darlington, and S.J. Culley. Current research in the engineering design requirement. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, **216**(2002), 375-388.

[11] W. Brace, V. Cheutet, A framework to support requirements analysis in engineering design. *Journal of Engineering Design*, **23**(12) 2012, 873-901.

[12] M.M.N. Zenun, and L. Geilson. A framework for completeness in requirements engineering: An application in aircraft maintenance scenario. In: Bil, Cees (Editor); Mo, John (Editor); Stjepandic, Josip (Editor). *20th ISPE International Conference on Concurrent Engineering: Proceedings*. Amsterdam, Netherlands: IOS Press, 2013, 569-578.

[13] S. Robertson, and J. Robertson. *Mastering the requirements process: Getting requirements right* (3rd Ed) Addison-Wesley Professional, 2012.

[14] M.Wang and Y. Zeng, Asking the right questions to elicit product requirements*, International Journal of Computer Integrated Manufacturing*, **22**(4)(2009), 283-298

[15] G.Cascini, G. Fantoni, and F. Montagna. Situating needs and requirements in the FBS framework. *Design Studies*, **34**(5)(2013), 636-662.

[16] J.S. Gero, Design prototypes: A knowledge representation schema for design. *AI Magazine*, **11**(4)(1990), 26-36.

[17] J.S. Gero, and U. Kannengiesser. A function–behavior–structure ontology of processes. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **21**(4)(2007), 379-391.

[18] Q.L. Xu, J. Jiao, X. Yang and M. Helander. An analytical Kano model for customer need analysis. *Design Studies*, **30**(1)(2009) ,87-110.

[19] M.J. Darlington, and S.J. Culley. A model of factors influencing the design requirement. *Design Studies*, **25**(2004), 329-350.

[20] Z.L. Liu, Z.N. Zhang, Y. Chen, A Scenario-based approach for requirements management in engineering design. *Concurrent Engineering: Research and Applications*, **20**(2) (2012), 99-109.

[21] D. Baxter, J. Gao, K. Case et al., A framework to integrate design knowledge reuse and requirements management in engineering design. *Robotics and Computer-Integrated Manufacturing*, **24**(2008), 585-593.

[22] J.K. Gershenson, and L.A. Stauffer, A Taxonomy for Design Requirements from Corporate Customers. *Research in Engineering Design,* **11** (1999),103–115.

[23] K.S. Rounds, and J.S. Cooper, Development of product design requirements using taxonomies of environmental issues. *Research in Engineering Design*, **13** (2002), 94–108

[24] M. Salonen, C.T. Hansen, and M. Perttula. Evolution of property predictability during conceptual design. *International Conference on Engineering Design (ICED 05)*, Melbourne, August 15-18, 2005

[25] V. Hubka, and W.E. Eder. *Design science: introduction to needs, scope and organization of engineering design knowledge*. Springer Verlag, 1996.

[26] G. Vianello, S. Ahmed. Transfer of knowledge from the service phase: a case study from the oil industry. *Research in Engineering Design*, **23**(2)(2012), 125-139.

[27] D.V. Khadilkar, and L.A. Stauffer, An experimental evaluation of design information reuse during conceptual design. *Journal of Engineering Design*, **7**(4)(1996), 331-339.

[28] Z.N. Zhang, Z.L, Liu, Y. Chen, Y.B. Xie, Knowledge flow in engineering design: An ontological framework. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, **227**(4)(2013), 222 - 232.

[29] K. Dimitris, Closed-loop PLM for intelligent products in the era of the internet of things. *Computer-Aided Design*, **43**(2001): 479-501.

[30] J.R.A. Maier, and G.M. Fadel. Affordance based design: a relational theory for design. *Research in Engineering Design*, **20**(1) (2009), 13-27.

[31] Y. Akao, *Quality function deployment: integrating customer requirements into product design* (st ed). Cambridge: Productivity Press, 2004.