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Causal design knowledge: Alternative representation method for product development knowledge management

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ABSTRACT

This paper presents a mathematical comparison of procedural knowledge and causal knowledge, and discusses the potential roles and feasibility of causal knowledge across product development knowledge management. Since reuse of knowledge is so important in product development, various knowledge management approaches have been introduced. Most of the product design knowledge is represented by procedural knowledge, which unfortunately requires cumbersome processes to define, and is typically inadequate for representing the kind of knowledge generated during the product development process. A causal knowledge representation, however, can help us to overcome this limitation and is an alternative formalism for representing product design knowledge. In this paper we compare the procedural and causal knowledge representations. We present the mathematical definitions of two knowledge paradigms, then mathematically describe the relationship between the two. Both knowledge paradigms are then compared based on the perspective of knowledge expression, decision alternative representation, reasoning capability, and knowledge cultivation. This paper concludes that causal knowledge representation is superior to procedural knowledge representation based on the four perspectives. Finally, the knowledge systems are modeled using Systems Modeling Language (SysML), and we present a case study that demonstrates the causal knowledge features using a realistic example from industry.

1. Introduction

The issue of reusing product design knowledge has been a significant barrier to realizing a robust product development knowledge management system [1–4]. Ettlie and Kubarek [4] found that levels of reuse in manufacturing companies is significantly low: an average of 42% reuse for services and 28% for manufacturing applications. In product design, Busby [2] notes three issues as follows: design reuse was desirable but it was not practiced, unexpected additional efforts to reuse the design are required, and knowledge loss, inappropriate replication, and error were all common problems for reapplying knowledge to a new design. These issues are still current in product development knowledge management [5]. Furthermore, problems in various product development processes may arise when the expertise is no longer available or the knowledge is forgotten—resulting in long delays in recognizing potential failures in product design. When a potential failure is not promptly identified in the early stage of product development processes, it greatly increases various costs, such as warranty and maintenance.

To overcome these challenges, product design knowledge should be properly codified within an organization. However, the tools and techniques currently available are inadequate for industry product development knowledge management and reuse. Previous research on product development knowledge management has focused on search by matching keyword and file name, or search by specific indices (e.g., part number, relationship among parts, etc.). However, these methods indicate various drawbacks based on Iyer et al. [6]: first, product design knowledge is often incomplete or is not adequately defined at a detailed level for current information search methods. Second, the proper initial information (e.g., project name or part name) is often unknown, partially contributing to the third drawback, the search space and time requirements are often cumbersome and hence impractical, generating search results that are either too detailed or too broad.

Owing to its simplicity and efficiency, most product design knowledge in current industry is represented by procedural knowledge (such as knowledge templates) that includes declarative and contextual knowledge [7]. Global, competitive markets, time pressure, shorter time-to-market, and 'brain drains' make the

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procedural knowledge approach more attractive [8–10,7]. However, industries also realize that since the knowledge build process of procedural knowledge is not clearly defined [11] and hence is very time-consuming, procedural knowledge is sometimes more complex and critical when insufficient information exists [12]. It is also task-dependent, and cannot be used for general knowledge practices within the industries [13]. The knowledge is among three different knowledge modes: declarative, procedural, and contextual knowledge. However, capturing procedural knowledge (PK) individually is a cumbersome process and is often insufficient for representing product design knowledge. To overcome these limitations, an alternative formalism to represent product design knowledge is essential. Therefore, this paper proposes causal knowledge (CK), which represents the relationship between cause and effect and is accepted as a natural way to understand causality. While some research has addressed the use of causality, environmental uncertainties, and a framework for information transfer in new product development [14–17], our research addresses causal knowledge representation for product development knowledge management and compares procedural knowledge and causal knowledge. We also show how to use a transformation method to generate causal knowledge from procedural knowledge. To the best of our knowledge, no literature has discussed the effectiveness of CK for representing product design knowledge, nor discussed the relationship between procedural knowledge and CK.

In this paper, we examine the feasibility of causal knowledge representation for product development knowledge management. We focus on comparing CK and PK with the knowledge perspectives generated for the product development knowledge management, and discuss CK's effectiveness in realizing an integrated representation of the product design knowledge with comparison results. In Section 3, we present the mathematical definitions of PK and CK by set theory. We also mathematically define and compare the relationship between PK and CK. After understanding the relationship between them, the knowledge transformation method is briefly introduced in Section 3. In Section 4, we mathematically compare the effectiveness of causal and procedural knowledge in four perspectives: knowledge expression, decision alternative representation, reasoning, and knowledge cultivation. In Section 5, we implement knowledge modeling with SysML, a general-purpose modeling language for systems engineering applications. In Section 6, we present the demonstration of the causal product development knowledge management system, as well as the features of CK with the illustration of a realistic industry case study (i.e., a fuel nozzle on an aerospace engine). Finally, in conclusions, limitations and future study are discussed.

2. Background

2.1. Different views of knowledge

Knowledge may be viewed from several perspectives: (1) a state of mind, (2) an object, (3) a process, (4) a condition of having access to information, or (5) a capability [18]. Knowledge has been described as a state or fact of knowing, with knowing being a condition of understanding gained through experience or study; the sum or range of what has been perceived, discovered, or learned [19]. The perspective on knowledge as a state of mind focuses on enabling individuals to expand their personal knowledge and to apply it to the organization's needs. The second view defines knowledge as an object [20–22]. This perspective posits that knowledge can be viewed as a thing to be stored and manipulated. Alternatively, knowledge can be viewed as a process of simultaneously knowing and acting [20–22]. The process perspective focuses on the application of expertise [22]. The fourth view of knowledge is that of a condition of access to information [20]. According to this view, product design knowledge must be organized to facilitate access to, and retrieval of, content. This view may be thought of as an extension of the view of product design knowledge as an object, with a special emphasis on the accessibility of the knowledge objects. Finally, the view of knowledge as a capability suggests a knowledge management perspective that is centered on building core competencies, understanding the strategic advantage of know-how, and creating intellectual capital. The major implication of these various conceptions of knowledge is that each perspective suggests a different strategy for managing the knowledge and a different perspective of the role of systems in support of knowledge management. Based on different perspectives of the role of knowledge management, this paper focuses on knowledge representation, and discusses causal knowledge representation and reuse issues. To compare the proposed causal knowledge representation, procedural knowledge representation is selected, because it is commonly used in current product development practices.

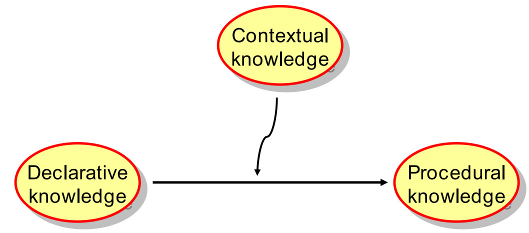

Fig. 1. Three different knowledge notions.

Product design knowledge shows three different knowledge modes as mentioned earlier: declarative (DK), procedural (PK), and contextual knowledge (CoK). For example, if we use an assembly method of certain parts, then this method and the parts themselves form DK. When we start to consider how the parts are assembled, the DK of the assembly method becomes PK. If we consider the context of CoK (i.e., how the parts can be assembled under which conditions (when and why) as well as how the resultant outputs would be), then CoK embeds PK. Therefore, PK can represent an assembly, which has objects, methods, conditions, and outputs (see Fig. 1).

2.2. Design knowledge reuse

Baxter and Gao's research addresses design knowledge reuse issues and the next step of design reuse research [23]. They noted that approximately 20% of the designer's time is spent searching for and absorbing information. Furthermore, approximately 40% of all design information requirements are met by personal information storage, despite the fact that more appropriate information may be available from other sources. Even if knowledge stored in computer-based systems is accessed, if it is to be reused, several additional factors must be met: reusability, availability, and relevance. Efficient exploitation of past designs has been prohibited by the lack of a complete or consistent methodology to structure past designs and information [1,3]. With a well-structured library of past designs and a method to make new design reusable, the issue of design reuse would be greatly simplified. Busby provided a detailed study into problems with design reuse [5]. Most reuse issues that Busby presented were cases of reuse being desirable but not practiced. The next most common problem was an unexpected amount of effort required to reuse. Other problems were knowledge loss through inappropriate replication and error where existing designs were reapplied to new purposes.