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Design rules application in manufacturing industries: a state of the art survey and proposal of a context-aware approach

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Abstract. [Context] In manufacturing industries, the design of a product needs to comply with many design rules. These rules are essentials as they help industrial designers to create high quality designs in an efficient way. [Problem] However, the management of an ever-increasing number of design rules becomes a real problem, especially for novice designers. Even if there exists some knowledge engineering tools for managing design rules, their capabilities are still limited and many companies continue to store their design rules in unstructured documents. Nowadays, the application of design rules remains a difficult task that needs a circular validation process between many experts in a manufacturing company. [Proposition] In this paper, we will analyze the main existing approaches for the application of design rules and we will demonstrate the need of a new approach to improve the current state-of-the-art practices. To minimize rule application impact on the design process, we propose to develop a Context-Aware Design Assistant that will recommend design rules on the fly while using computer-aided design software. Our design assistant relies on the modelling of the design rules and the design context in a single knowledge graph that can fuel a recommendation engine. [Future Work] In future work, we will describe the technical structure of the Context-Aware Design Assistant and develop it. The potential outcome of this research are: a better workflow integration of design rules application, a proactive verification of design solutions, a continuous learning of design rules and the detection and automation of design routines.

Keywords: Design rule, product design, knowledge graph, context awareness, cognitive assistant, lean design and interactive design.

1 Introduction

Designing a product is a knowledge-intensive activity. Thus, to prevent design errors, that is, choices that make certain designs "not allowed" or inappropriate for their intended use, design departments prescribe design rules. A design rule is a prescriptive statement – often an unstructured blend of text and graphical objects (equation, sketch, etc.) – that supports deployed designers for the achievement of a proof design, in compliance with best practices, applicable regulations, and DfX constraints. Design rules are therefore vastly used in the industry. Many recent scientific papers from various industrial domains propose new design rules or review existing ones [1-8]. In every industry, existing design rules are changing and new ones emerge. In fact, factors such as the increasing complexity of design products or the number of norms per industrial domain tend to increase the number of design rules. Many challenges of the industry of the future will be primarily handled by the creation of new design rules [9]. The ever-increasing number of design rules leads to critical issues when industrial companies want to use and manage such "Big Data". In a recent work, Wuni *et* al. [10] explore the many challenges of implementing and maintaining a knowledge base of design rules in the industry.

While a designer is working on a product, he or she often needs to check design rules if he or she wants to provide a design free of errors. An expert designer may have memorized all crucial rules of his domain. However, a non-expert designer does not have in mind all applicable design rules. He/she has no other alternative than to spend a large amount of time finding the subset of design rules that matches his design context by either searching in design manuals or asking expert-colleagues to guide him/her. This task is even more time consuming because design rules often come from different domains and are stored in documents or databases that may not be correctly organized. Unstructured documents are still common in the industry [11]. Many companies still store design rule knowledge in unstructured documents – mainly PDF format – which are over tens or hundreds of pages.

As we will see in the next sections, there already exists many industrial tools and researchers' proposals for managing design rules. For each approach, we selected two types of contributions for our state of the art (Sec.2): Conceptual work to present a definition of the concept or approach, and application work in the domain of industrial design to illustrate pros and cons of the approach. The state of the art is structured in three sub-sections. We will firstly present a design rule definition and classification. Then, we will present the concurrent engineering approach of design that will be our reference through the paper. Finally, we will review the existing tools supporting the application of design rules.

In the final part of the paper (Sec. 3), we will focus on technologies that provide context awareness capabilities and discuss how our Context-Aware Design Assistant will contribute to the current state-of-the-art solutions.

2 State of the Art

2.1 Design rules

For this paper, design rule definition rests on the work of Fu et *al*. [12] as it is the most inclusive definition we found in our literature review. They define Design Principles in four points:

It is stated in the grammatical imperative form.
It includes a prescriptive action for a designer to take
It increases the likelihood of reaching a desirable consequence
It is situated within a particular context and point in time

In this paper, we will reduce the scale of this definition and consider a more technical definition. Calkins et *al*. [13] in the field of Knowledge Based Engineering (KBE) consider that design rules synthesize the knowledge of a company and indicate how it should be used to create a proven design. In our case, we also want to emphasize the way this knowledge is stored in databases or in design books. After reviewing numerous design manuals, we assume that a design rule is a prescriptive statement in natural language, often associated with descriptive graphical objects (equation, table, chart, etc.) guiding the work of the designer in a specific design context to improve design quality.

Both authors previously cited underline the heterogeneous aspect of design rules. Calkins et *al*. [13] consider four different origins for design rules: Heuristic (rules from companies' best practices), Empirical (based on experimental data), Legislated constraints (established by official norms), Physic (based on analytical or numerical physical models). Design rules affect not only the design but also all the phases of a product lifecycle, such as product recyclability [14] or maintainability [15].

We conclude that design rules have various origins and objectives and that each one relates to a specific design context. They are crucial for maintaining the quality level of industrial products and their number is significantly increasing.

2.2 Design rules and methods

Modern design is becoming more complex. Companies introduce new disciplines and specific knowledge in the design process to improve product quality. Multiple design methods exist to comply with this inherent complexity and maximize design performance. These methods belong to the trend of concurrent engineering. Stjepandic et *al*., in the book "Concurrent engineering in the 21st century" [16], analyze concurrent engineering from its creation in the 80's to its evolution in modern days. They describe concurrent engineering as a design approach whose "main aim is to reduce time-to-market, improve quality and reduce costs by taking

into account downstream requirements and constraints already in the design phase". Design rules are one of the easiest way to introduce downstream requirements into the design process. Consequently, their number is ever increasing. However, concurrent engineering faces many challenges.

The first one results from the complexity of managing and applying such large and heterogeneous knowledge. Ballar [17] notices a large number of design iterations are wasted on needless tasks. Design errors (when design output fails due to a known and avoidable cause) are presented as a major cause of these wastes. The author advocate for the adoption of a lean design approach. This approach, reviewed in [18] is a part of the concurrent engineering trend that focuses on the limitation of those unnecessary design operations by adapting lean manufacturing approaches to the design process.

The second issue raised by design rules usage is their cognitive cost for the designer. From the perspective of interactive design, defined by Nadeau et *al*. [19], design rules are a way to simplify the interaction between the designer and the expert's knowledge. This interaction has a cognitive cost for the designer that lowers the design productivity. Design rules allow the designer to access the expert's knowledge directly. However, their usage, especially when stored in unstructured documentation, can generate many unnecessary design iterations that need the designer concentration. The designer needs to find the right design rule in a large PDF document. Then, he or she has to analyze and understand the design rule before applying it onto the design piece. Design rules in unstructured documentation increase the cognitive charge of the designer, thus lowering the overall design productivity and increasing the frequency of design errors.

Interactive design advocate for the development of user-centric tools to support the designer cognitive effort in knowledge management. For example, Fuwen et al. [20] propose an interactive approach to better integrate design rules for additive manufacturing into the design process. This interactive approach consists into proposing interactive aided design tools that simplify interactions between the designer and different factors of the design process like expert's knowledge or client's satisfaction.

2.3 Existing tools for design rules application

A tool for design rule application is an expert system that uses design rules to improve the design quality. This requires the transformation of design rules into a computable format. Different computable formats allow different kinds of automation tasks. Cowan presents this process through multiple examples of knowledge codification for expert systems in various industries [21]. From our literature review, we identify two main trends on design rules application, each one associated with its own modeling strategy of design rules.

Most industrial design rule checkers [22-24] adopt a procedural approach. They have built a set of rules for each possible rule origin. For example, a tool

may have a set of a few dozen rules to check on a part machined using a milling process. Each rule is an algorithm that detects geometrical features in the CAD data that do not respect the rule. Huang et *al*. [25] give a good example of the work realized in this field. Favi *et* al. [26] recently propose a tool on design for welding rules with this approach. Such a rule application strategy results in expert systems that have a pre-defined number of rules focusing on a very specific problem. They are efficient in detecting CAD quality errors and rules directly associated with a design issue like a manufacturing process. However, this approach has some flaws:

- Rules editing requires the work of experts to modify or create algorithms. As explained previously, a design rule evolves with technology or company habits. It is not trivial to maintain or personalize the design rule set with this technology.

- The storage of design rules across multiple domain silos makes multi-domain rules application complicated. Design is a multi-domain process and many design rules do not fit in the pre-defined contexts fixed by those tools.

- Some rules represent unstructured knowledge that cannot be translated into If-Then statements. Traditional rule checking tools cannot process these rules but the designer still need to know and consider them.

To improve the application of design rules, scientists explored declarative approach of design rule application. They use new technologies such as Semantic Networks (SN) to represent the knowledge associated with the product and the design rules. According to Sowa [27]: "*A semantic network or net is a graph structure for representing knowledge in patterns of interconnected nodes and arcs.*" They are primarily used to represent conceptual knowledge as natural language expressions in a structured and unbiased way. This process is not straightforward for design rules but many scientists work to improve design rules representation in SNs like Kang et *al.* [28]. Using a SN could enable us to process all kinds of design rules.
Various research teams implemented SNs for the application of design rules in the manufacturing industry [29-31]. Their strategy is to build a data model that represents the type of product they focus on. In the most frequent case, the data model is specific to a manufacturing process like milling [32], assembly [33] or folded sheet metal [34]. Once this model is built, they implement a translation algorithm to automatically generate a semantic representation from the digital mock-up. Then, they can edit rules that will apply on the knowledge representation of the product. They are able to identify design errors as well as automatically correct some of them. This approach is not limited to the geometry-centered design rules because it formalize the linguistic aspect of a design rule. Some teams even develop their own high-level language to facilitate new design rules editing [30]. Re-

cent researches also explore the possibility of automatically extract design rules from unstructured documentations in order to populate SNs [35-37].

However, this approach is not flawless. Each type of industrial product needs his own semantic representation to perform well. These representations are hard to develop and maintain [31] and are domain specific. An industrial part often goes through multiple manufacturing processes and needs to comply with Design for Excellence (DfX) constraints. Creating the semantic representation of the part and the set of associated rules would be extremely difficult with the previous approach.

2.4 Synthesis

From the point of view of concurrent engineering, we can argue that these tools have a positive impact on the design process. In fact, they reduce drastically the time spent on errors detection. However, even if the validation cycle is shorten, it still exists. In many manufacturing companies CAD data is analyzed during the night and designer begin their next working day by correcting their design errors. Moreover, the deployment of these tools did not end the large usage of unstructured design rules manuals. In fact, it is still a difficult task to develop such tools for a broad set of design rules. Moreover, some design rules contain abstract knowledge that can be general design guidance or design strategies. Abstract knowledge is the most difficult type of knowledge to process for expert systems [20] and most existing tools do not process these type of rules.

These limitations explain why unstructured design rules documents are still used in the manufacturing industries. From the perspective of interactive design, we can say that existing tools are CAD-centric. However, to seamlessly integrate design rules application into the design process, we need to develop a user-centric tool. This is why we propose a new approach for the application of design rules, based on context-awareness and natural language processing.

3 Introducing a Context-Aware Cognitive Design Assistant

3.1 Context-Awareness

In [38], Dey describes the context of a software user as: "*Any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves*." In our case, any information describing the design process, the digital mock-up, or the team members in charge of the design belong to the design context.

Dey gives a definition of a Context-Aware System (CAS): "*A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task*". Engelenburg *et* al. [39] provide an analysis of CAS as well as their uses in practice. Therefore, a context-aware environment for the application of design rules shall recommend design rules based on a definition of the design context in near real time. As context knowledge is multi-domain, such a tool would have a greater ability to process multi-domain design rules. Indeed, CAS are by definition user centered. Each user will have a different context and different information needs at different times. The CAS will adapt itself to each end-user.

This is crucial in industrial context where team members need to coordinate their work on a complex task. For example, context-awareness is used to present manufacturing or maintenance knowledge to workers in the manufacturing industry [40-41]. Design context can be compared to this one as each designer has a specific task and level of expertise, but need to work with his/her team. Context-awareness is often used in information retrieval [42], in order to perform dynamic recommendations while improving accuracy.

3.2 Presentation of the assistant

In this paper, we propose to use context-awareness for facilitating the application of design rules. This tool will process multi-domain and abstract design rules. These rules can be extracted from unstructured documents such as design manuals or from structured databases. It is also possible for domain experts to easily write or modify design rules. Then, the assistant will recommend design rules in near real time based on the design context and queries of the designer. The assistant will then guide the user into the application of design rules (Fig. 1).

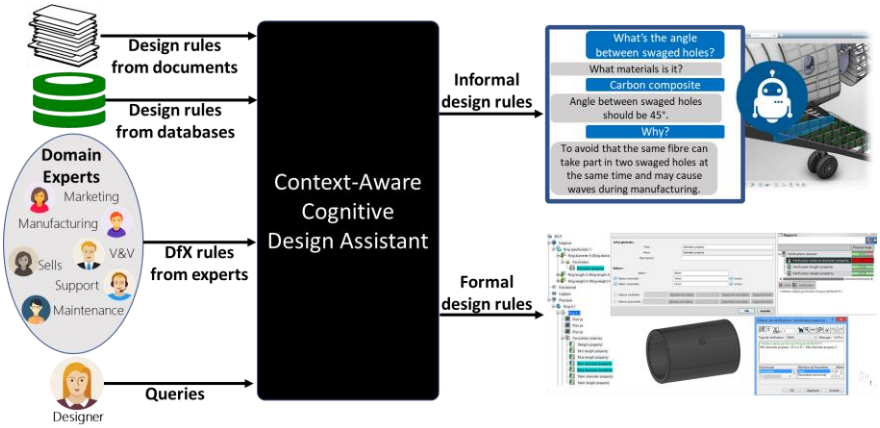

Figure 1 : Context-Aware Cognitive Design Assistant

Consequently, the application of design rules will be seamlessly integrated into the design process to prevent design errors. The amount of time and cognitive effort needed to search a rule in textual documentation will be reduced. This approach limits the needs of validation cycle and the cognitive weight of the user.

The context-aware cognitive design assistant will contribute to interactive design by replacing unstructured design rule documentation and providing a better cognitive interface between the designer and the expert's knowledge. This tool will be a step forward towards lean and interactive design.

On a practical aspect, contextual information is structured in a knowledge graph. The context graph is complex and evolves dynamically. A structured data model is essential to run context aware applications. Aguilar et *al.* propose a general data model for context modeling [43]. A proposal of a graph data model adapted to a context-aware cognitive design assistant is presented in [44-45]. They propose a data model to represent the user's design context and model any kind of design rule. This ability to process any kind of design rules is an advantage toward existing approaches and may be an essential step to replace unstructured documents in the design process.

In future works, we propose to develop a proof of concept of such an assistant to demonstrate the efficiency of context-aware technology for design rule application.

Conclusion and future work

The goal of this paper is to review the state-of-the-art of design rules and design rules application to demonstrate the need for a context-aware design assistant.

First, we discussed about the concept of design rules in the manufacturing industry. We demonstrated that the use of design rules is a crucial issue to improve design efficiency.

Then, we presented concurrent engineering, interactive design and lean engineering theories. Using these design approaches as reference, we argued that design rule storage in unstructured documentation generates inefficiencies in the design process. Lean design and interactive design are used in the article to analyze existing tool for design rule application and demonstrate the need of a context-aware approach.

In a third part, we reviewed existing tools for managing rules. Tools based on a semantic network enable designers to better detect design flaws and ease the edition of rules. Existing tools reduce design iterations relative to the satisfaction of design rules. However, CAD-centric methods do not suppress these validation cycles and fail to process certain kind of design rules. As a result, unstructured documentations are still present in the industry. Therefore, there is the need to propose a new user-centric approach that would be able to replace entirely unstructured documentation usage for design rules.

Finally, we presented CAS and how they could be used to improve the application of design rules and the recommendation of rules according to a design context. We defend that a user-centric approach to the application of design rules can be achieved by a Context-Aware Cognitive Design Assistant. This assistant would minimize the need for validation cycles and speed up the design rules application process.

This is why we propose in a future work to develop a proof of concept of this approach with an industrial dataset.

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