Introduction of a standardized Notation of Design Heuristics for Knowledge Formalization

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Abstract

A wide range of tools simplify product development, e. g. Knowledge-Based Engineering Systems (KBES). Many KBES draw on knowledge derived from DfX methods. The knowledge of these methods is often available in varying degrees of detail, arising from the explicit knowledge of experts and scientists. When passing on knowledge, product developers often do so in the form of easy-to-understand rules of thumb, so-called design heuristics (DH). However, published DH do not offer sufficient clarity and usability to be integrated in daily engineering practice. This paper describes the development of a standardized notation form to make DH describable as a first step towards automated integration into KBES and towards integrating implicit knowledge of designers in future MBSE models.

Keywords

Design Heuristics, Knowledge-Based Engineering, implicit knowledge, knowledge formalisation

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1. Introduction

Product development is characterized by a high level of complexity due to high expectations regarding function (e.g. in smart products) and impact (e.g. design for sustainability). At the same time, product developers have access to a wide range of tools that simplify the development of products. Knowledge-Based Engineering Systems (KBES) help product developers with design tasks. For example, many CAD programs check developed designs for manufacturability for additive manufacturing technologies [1] or support product developers already during the development of designs, such as in variant management [1]. KBES often draw on knowledge derived from DfX methods. DfX methods usually refer to well-established, often empirically-verified advice in form of guidelines, checklists, metrics, and models. Less verified but nevertheless valuable practical design knowledge is often passed on in the form of rules of thumb, named “design heuristics” in literature. The knowledge of DfX methods and design heuristics alike is available in varying degrees of detail and arises from the explicit knowledge of experts and scientists. They come along in diverse forms of presentation, thus facing the shared challenges of low findability and lacking machine readability, hampering automatized integration. In the DFG-funded research project “design heuristics” we are developing a standardized notation in order to tackle these challenges to lay the foundation for a) integrating individual practical knowledge into KBES, supplementing DfX methods as a source, b) increase findability of DfX methods and design heuristics, and c) enable fast noting-down and sharing knowledge in order to increase knowledge transfer between practice and science. The notation development drew on extensive literature review, and 26 in-depth guided interviews with design experts from industry and higher education.

In this paper, we first summon up the state of research on design heuristics and their connection to DfX, deducting our research question and research aim. In the next step, our research design is explained and the outcome discussed. After that we introduce the deducted standardized notation in theoretical detail and showcase a walk-through of how to use it.

2. State of Research

When product developers pass on knowledge to other product developers, they often do so in the form of easy-to-understand rules of thumb, so-called design heuristics (DH). Heuristics are defined as "context-dependent directives, based on intuition, tacit knowledge, or experiential understanding, which provide design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution" [2]. An integration of DH and DfX methods in the product development process is shown in Figure 1.

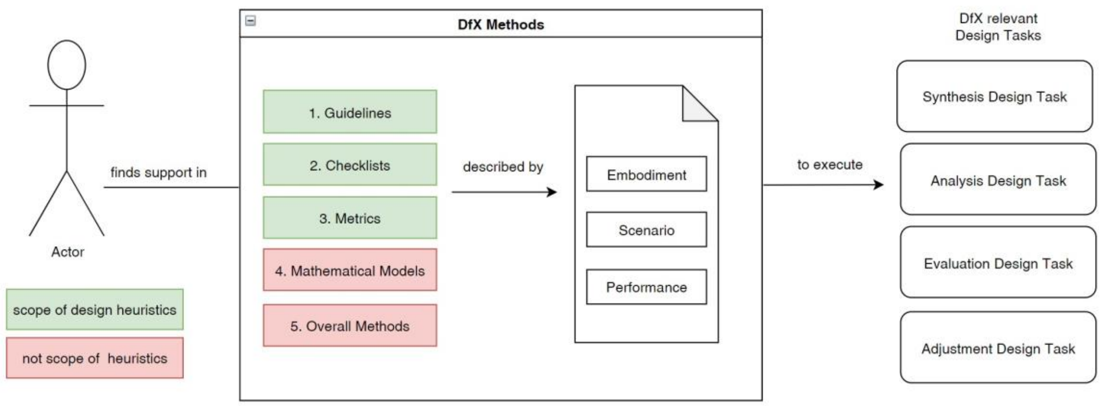

Figure 1: Own depiction of the scope of design heuristics based on a classification of DfX Methods by [3]

As the goal of using DH is defined as information support to guide engineers to reach an acceptable solution [4], a DH should contain some specifications, restrictions and suggestions. It can be delivered in a written form and/ or as a visualized representation [5]. Hence, each DH should include a description, applicative examples or case studies with images which include a specific instruction to show the engineer explicitly or implicitly how to implement it to their own case. Moreover, some instructions to solve equations or calculate some numbers should be provided within the DH, if it is necessary for the case. Also, useful web links as an extra source could be beneficial for the application of the suggested strategy [6].

The written form of a DH should have a defined characteristic to help design engineers with quick comprehension and be assistive with the case. Firstly, the content should be summarized as short and instructive statements and secondly, the language should avoid technical/ scientific jargon and an academic language [7]. Lastly, statements should be formulated as an imperative phrase to be concrete.

However, some research indicates that visual DHs are more preferred by design engineers compared to text formats [7] [8]. A visual format of a DH should include maximum use of graphics and images for instructions respectively and videos if possible.

2.1. Research Question and Aim

A problem of the acquisition, transfer and use of DH is that there is no standardized way describing them. Published DH sets are generally weakly structured, difficult to navigate in, partly competing and overlapping, and offer differing levels of detail. As a result, they do not offer sufficient clarity and usability to be integrated in daily engineering practice. Only with the help of a standardized notation DH become controllable and usable for both knowledge-based assistance systems, such as KBES and product developers. In the context of our research, a standardized notation format should be developed, so that DH are made describable as a first step towards automated integration into KBES, which are highly dependent on individual knowledge of designers as described in [9]. More than that, formalisation offers the opportunity to integrate implicit knowledge of designers in future MBSE models [10].

Thus, our research question was: Can there be a standardized notation for DH in acquisition, usage and transfer for both users and KBES and what artifacts would it need to it consist of?

3. Research

The aim of our research was to harmonize previous findings on design heuristics from literature with the needs for knowledge representation and knowledge content required by professionals.

3.1. Methods and Approach

A comprehensive literature review was conducted in order to collect and analyse the forms of DH descriptions displayed in there. Subsequently, 26 expert interviews were conducted with experts from the fields of product development from industry and higher education for product development, asking about the role of DH in their discipline and its potential.

The interview with was divided into four question areas. First, demographic questions were asked, then the interviewees were asked about their general knowledge of design heuristics. After that, the interviewees were given the scientific definition of a design heuristic which was further explained using examples from design for recyclability. The interviewees were then asked about the product development process as applied or taught respectively, as well as about the integration of experiential knowledge in this process. After that, the requirements for a description standard of design heuristics were collected.

3.2. Interview Partners

As part of the industry survey, 15 experienced product designers and development engineers who are actively working in product development were interviewed. The interviewees came from different industries, such as the development of household appliances, solar modules and semiconductors, motor scooters, cars, medical products, robotics or additive manufacturing. The work experience of the interviewees ranged from 6 months to 20 years with a median of 9 years. We spoke with both freelancers and employees of companies ranging in size from 3 to 300,000 employees.

For the survey on design heuristics in teaching, eleven university teachers were interviewed. To increase the diversity of the recorded practices, interview partners were acquired with a focus on differing cultural backgrounds. Thus, the answers reflect teaching experiences from Brazil, China, England, Germany, Italy, the Netherlands, Russia, the USA, and Vietnam. Four interviewees held the position of full professors, two were associate professors, one assistant professor and three lecturers. Their fields of expertise were mostly mechanical, industrial and product engineering. Two interview partners were teaching manufacturing engineering and one software engineering. Except for two interviewees who had started teaching in 2015 and 2021 respectively, all had more than 10 years of teaching experience and taught 30 to 300 students a year.

3.3. Results

It was particularly striking in the interviews that 21 of 26 respondents did not know the term “design heuristic”, whereas at least the teaching staff was familiar with “design principles” as a term. Only after a definition and the naming of an example of a design heuristic could the survey be continued in most cases. Due to the differences in the professional settings, the results from interviewing industrial and educational professionals are discussed separately below.

With regard to the interview partners from industry 7 out of 15 respondents use a form of knowledge management for experiential knowledge. This takes a variety of forms, ranging from written down company-wide guidelines to digital wikis with a forum function. The captured knowledge was not recorded in a fixed syntactic or semantic form for any respondent. 13 out of 15 respondents indicated that the reason for using guidelines was to better achieve the goals of set requirements. 14 of 15 respondents provided information on the desired form of heuristics. Of the 14, 7 emphasized that it was important to them that design heuristics be described particularly briefly. 7 of the 14 felt it was important that the description includes a listing of the type of product categories for which the use of the heuristics is appropriate. 10 of the 14 also mentioned the importance of visual representation of the design heuristics in the form of best practices and negative examples. 3 specifically mentioned that it is important to them to know the effect relationship of a heuristic with other design aspects that are not specifically addressed by the heuristic (trade-offs). Furthermore, 5 emphasized that easy discoverability of design heuristics is particularly important to them, while 2 stated that they would like to have a mechanism to identify good design heuristics.

Although most educational professionals (8 out of 11) did not know the term “design heuristics”, all of them concluded that they use them in their teaching, usually within project-based learning settings, 2 even making their students define own heuristics, either as part of their reflection task or as project goal. Heuristics are presented in heterogeneous ways by all teachers, depending on the students’ experience and the project goal. While 2 have developed own sets of teaching materials and 1 is using existing materials covering diverse design heuristics, 8 formulate design heuristics themselves spontaneously as the need arises, often as a method to convey their own design knowledge. 3 teachers expressed the worry that especially with less experienced students, design heuristics are seen as lists of sufficient criteria for a good design so that those students concentrate on following the heuristics strictly instead of putting them into context and using them for orientation rather than as predefined rules. Except for 1 interviewee who is striving for “right and reasonable” designs from his students, all teachers rejected the idea of making the use of some design heuristics mandatory for their students during their project work, expressing the opinion, that students need to learn critical thinking and should think about and justify their design choices rather than following a catalogue of rules. Design heuristics formats that are easily applied by students are heuristics embedded in checklists or templates. The more in-depth knowledge is required to put heuristics into context, the more difficult the application. The most common motivation for integrating design heuristics in teaching is to help students achieve better results during their practical design tasks (5 out of 11) but also for decision making, keeping one’s focus on the target and learning to work with limiting factors (2 out of 11 each). What the interviewees considered important with regard to displaying design heuristics in a tool varied greatly. The strongest congruency was the need for credibility information such as the source of each heuristic (4 out of 11), followed by the need for contextual information, especially putting the different heuristics into relation (3 out of 11). Only 2 put emphasize on good visualization, just as 2 demanded the display to be simple and easy- to-use and another 2 expected some kind of scoring system to judge the validity of a heuristic.

3.4. Discussion

Obviously, there are some differences in industrial designers’ and design teachers’ expectations regarding the presentation of design heuristics. Whereas the teachers, being true to their scientific setting, emphasize transparency of sources and context information enabling integrated networked thinking, engineers from industry wish for straight-forward easy-to-apply solutions. However, the criteria of both groups are not contradictory but complementary and some, e. g. good visualization, overlap.

Of particular importance to many users when using design heuristics in practice was that the heuristics described were also suitable for their use case. Distinguishing characteristics that were frequently mentioned were the targeted industrial sector and the targeted type of manufacturing process. In addition, a classification of the application areas of design heuristics on system levels seemed useful since many heuristics manifested as guidelines address specific system levels. The example of guidelines for sustainable product design makes this particularly clear when a heuristic e. g. refers to the system level ("Design systems that enable sharing.") or to the product level ("Design the product so that it can be easily disassembled.") or to the component level ("Place high-quality components in easily accessible locations.") or to the part level ("Use materials that are recyclable."). In addition to a brief instructive formulation of the heuristic, the description standard should also provide the opportunity to include more detailed information/explanations about the heuristic. From the desire for better findability, the requirement to enter keywords into the standardized notation could be derived. From the multiple demand for a graphical support to explain the heuristic the requirement was derived that in a standardized notation the possibility should be given to explain the heuristic by a positive and/or negative and/or neutral graph. From the desire for credibility of the heuristic, the need to include a source citation for the heuristic was deducted. From the observation that the vast majority of respondents, use design heuristics to better achieve set objectives, the decision was made that users who enter their own heuristic can select which established DfX objectives it targets.

In addition to implications for the standardization of a design heuristics notation, it was also possible to derive the insight that it would be better to use the term “design guideline” instead of “design heuristic” when communicating the standardized notation to industry partners and “design principles” or “rules of thumb” when talking with teaching staff.

4. Standardized Notation of Design Heuristics

By means of this, requirements for a standardized description of DH were deducted and starting from there, a description was developed. To do so, the scope of the standardized description of DH was narrowed down beforehand. Then, the results from the requirements analysis were condensed into our final requirements set.

In this chapter we introduce the developed standardized notation format for design heuristics. First, the chosen form of DH formalization is discussed. Then, the individual elements of the notation are presented. Subsequently, examples for the collection of the heuristics are given for better understanding. The goal of the standardized notation is to enable industrial practitioners as well as researchers and design teachers to incorporate design heuristics. For this reason, we speak of “users” who can note down design heuristics with the help of a UML class.

4.1. Structure of the Design Heuristic UML Class Diagram

First, it was decided in which form of knowledge manifestation design heuristics should be included. Design heuristics refer to the empirical knowledge of product developers. One of the goals of a standardized notation should be that the individual experiential knowledge of product developers is quickly and easily assimilated by them. For this reason, the decision was made that design heuristics should be formalized as a UML class, since this is suitable for the structured recording of user knowledge and a format engineers are already familiar with.

The developed UML class diagram for design heuristics can be found in Figure 2.

The developed class is named DesignHeuristic. The core of the class is formed by the artifacts listed above for clarity. These are the *orderArtifact*, the *embodimentArtifact*, the *embodimentAttribute*, the *orderAttribute*, the artifact *positiveInfluence* and the artifact *source*. The attributes to the associated artifacts can be described with the data type string, whereas the artifact *positiveInfluence* can only be an attribute of the enumeration *DesignforX*.

The developed description thereby combines different research results and requirements, which were derived from the interviews. Basis of the description was the formal system for the description of design heuristics developed by [11], which consist of the artifacts

- Heuristic = Instruction Causality Consequence
- Instruction = Property Artifact
- Causality = („positively | negatively “) „Influences“
- Consequence

An example for a design heuristic, which is described in that sense could be described as “Sortability of materials positively influences product recyclability”.

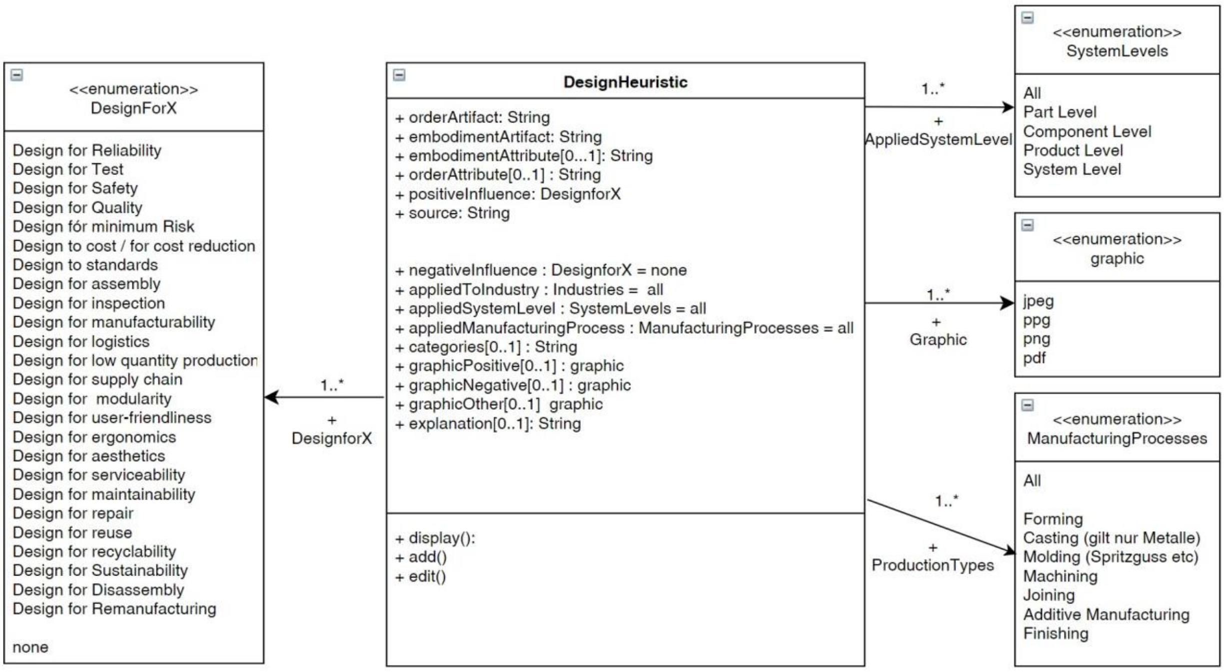

Figure 2: UML Class Diagram of the Standardized Design Heuristic Notation

Other researchers, however, describe design heuristics primarily as "context dependent directives", which are described as "orders" [2]. Also, the professionals wish for an intuitively understandable form for the formulation of the design heuristics, which seems to be fulfilled by a simple order. In addition, users of the design heuristics want the heuristics to be easy to sort and search. If one describes the heuristics following the English syntax by an order verb, the addressed object, which can then be specified more closely by an attribute and an order adverb, these requirements can be considered. At the same time, such a description allows for better machine readability and sortability. It also takes into account the definition of [3], according to which DfX methods are always described by a design embodiment and an associated scenario. In addition to this, the authors of design heuristics can specify one or more positive influences with respect to DfX objectives. This has the advantage of accounting for the fact that a design heuristic may serve multiple objectives. For example, a guideline for better disassembly may have a positive impact on Design for Recyclability and Design for Sustainability. In addition, the core of the design heuristic description also includes the source from which the heuristic originates, so that users can evaluate the credibility of the heuristic.

This leads to the structure of the hereby developed design heuristic. The core of the heuristic consists of mandatory and voluntary information. A heuristic always contains an *orderArtifact*, an *embodimentArtifact*, the DfX goal which is described by *positiveInfluence* and the *source*. Voluntarily, users who formulate a design heuristic can also specify an *orderattribute* and an *embodimentattribute*, which describe the *orderArtifact* and the *embodimentArtifact* in more detail.

In addition, the design heuristics are enriched with further information according to the requirements. For example, users can specify additional negative effects on defined DfX targets with the artifact *negativeInfluence*. The specification is voluntary. The default value of the class is *none*. In addition, users can specify whether a design heuristic is only designed for certain industries. If a user does not specify this in the *appliedIndustries* artifact, the default value is *all*. In addition, a user can use the *appliedSystemLevel* artifact to specify the system level to which a heuristic applies. The user can select from the levels *system*, *product*, *component* and *part*. If the user does not specify a level, the default value is also *all*. The same applies to the artifact *appliedManufacturingProcess*. The user can choose between the values *forming*, *casting*, *molding*, *joining*, *additive manufacturing* and *finishing*. If the user does not specify any information, the artifact is instantiated by the default value *all*. Furthermore, users can categorize the design heuristics using keywords. It is also possible to enrich the design heuristic with images (png, jpg and pdf were chosen as data formats) using the artifacts *graphicPositive*, *graphicNegative* and *graphicOther*. In addition, the artifact *explanation* can be used to include further explanations or write down best practices. add(), edit() and display() functions were selected as methods.

4.2. Exemplary Walkthroughs to collect Design Heuristics

The following are examples of the collection of two design heuristics in different forms of expression. Heuristic 1 is from [12] and was originally formulated as „Provide drains for operating liquids and gases to take out the operating liquids and prevent them from polluting the material streams or the air", heuristic 2 is from [13] and was formulated as "Avoid packaging". Both heuristics address Design for Sustainability goals. Both heuristics are translated into and instantiated by the previously defined UML class in Table 1.

Table 1: Examples of Design Heuristics collected by the Standardized Notation

UML Artifact	**Heuristic 1**	**Heuristic 2**
orderArtifact	provide	avoid
embodimentArtifact	components	packaging
embodimentAttribute	with operating liquids	
orderAttribute	with drains	
positiveInfluence	disassemblability, recyclability, sustainability, safety	sustainability
Source	[12]	[13]
negativeInfluence	none	none
appliedToIndustry	all	all
appliedSystemLevel	component	product
appliedManufacturingProcess	all	all
categories	liquids, pollution	material consumption
graphicPositive	none	

graphicNegative	none	
graphicOther	none	none
Explanation	To provide drains is considered important for the recycling process since drains make it possible to take out operating liquids and gasses and prevent them from polluting the material streams or the air. Therefore, it is also important to consider the removal of these components in the design, and make sure they are easy to remove.	Example 1: Celaflor has substituted its former blister packaging of gardening products for a new container that has the refills fitted into an internal cavity, thus effectively avoiding multiple packaging Example 2: Lancôme has partly removed its cream packaging, reducing the package weight by 40%. Example 3: Tertiary packaging and pallet stabilisation methods can be designed in a way that avoids using the internal layers that are normally employed for granulating.

It can be seen in the table that both design heuristics could be translated into the standardized notation. At the same time, it becomes clear that many of the voluntary artifacts do not have to be populated in order to formulate a design heuristic in an understandable way. At the same time, more complex design heuristics, such as Heuristic 1, can be described without problems if the *orderArtifact* and the *embodimentArtifact* are additionally enriched with associated attributes.

4.3. Discussion

The notation presented here is well suited for recording individual experience knowledge of designers. At the same time, scientifically published guidelines can be recorded well with the help of the standardized notation. The standardized notation is suitable for the structured inclusion of design heuristics, which simplifies the sortability of and the search for design heuristics, thus positively influencing the usability for future users. Thus, the inclusion of knowledge in a standardized notation is a first step towards a machine-readable form of individual knowledge.

At the same time, the notation presented here currently does not allow design heuristics to be connected to each other. But here, too, a first step has been taken through the structured division of design heuristics into predefined artifacts.

5. Outlook

Future research needs to further investigate the usability and completeness of the described notation format. In addition, as stated in the previous section, the extent to which the notation allows the relationship of design heuristics to each other to be adequately represented needs to be verified.

The research presented here was undertaken as part of a DFG project (project number 426205459). Further content of the project and thus also of the further research is to use the presented notation to develop an application with which scientists as well as industrial practitioners can collect their own design heuristics. A further part of the research will be the examination of how such an application and the use of design heuristics offers advantages for industrial practice as well as for university teaching.

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