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Navigating complexity: visualising sustainable product development knowledge through dynamic heatmaps

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Abstract

The paper presents a novel approach to visualize the impacts of design heuristics in sustainable product development. Focusing on the integration of ecological sustainability, our research introduces a multivariate visual approach, combining Sunburst Charts and Radial Heat Maps. The methodology, based on a description standard for design heuristics, enhances knowledge sharing and provides an intuitive tool for designers. A dynamic three-series radial heatmap facilitates comparisons across different product properties, fostering informed decision-making in product development.

Keywords: product development, visualisation, design heuristics, knowledge-based engineering (KBE), sustainable design

1. Introduction

In 2015 the United Nations published the 17 Sustainable Development Goals (SDGs), aiming to secure a sustainable future for humanity on the planet (Gigliotti et al. 2019). To reach these goals, product developers play a direct role in achieving two critical objectives: building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation and ensuring sustainable consumption and production patterns. A current focus of product developers lies in the implementation of circular economy measures (Garcia-Saravia Ortiz-de-Montellano et al. 2023). However, the pure willingness to reach the goals is not enough; designers need to be provided with the right knowledge during the product development process. Navigating the expansive and complex landscape of engineering knowledge, especially in the domain of sustainable product development, the volume of available knowledge poses challenges for designers (Yuan Fu et al. 2006). It becomes increasingly challenging to maintain a complete overview of relevant knowledge and to understand the consequences of using that knowledge in the product development process (Yuan Fu et al. 2006). The impact of implementing knowledge from guidelines and other knowledge representations can have both positive effects and trade-offs, necessitating a nuanced understanding.

A research project led by the Department for Industrial Information Technologies at TU Berlin has addressed this challenge by developing a description standard for design heuristics (Kremer et al. 2022). Design heuristics are intuitive rules of thumb that guide designers toward satisfactory results, though not necessarily optimal solutions (Fu et al. 2015). The appeal of heuristics lies in their simplicity, ease of understanding, and the fact that they do not overly constrain designers' creativity. The description standard links heuristics to their effects, providing a valuable resource for designers seeking guidance during the product development process.

In this paper, we propose a method to visualise the effects of heuristics with a specific focus on sustainable product development. The visualisation aims to offer insights into the outcomes of employing heuristics, especially in the context of sustainability. We will describe the methodology behind the development of this visualisation and highlight the key requirements considered in visualising heuristic knowledge effectively. Moreover, we commit to making the code of the interactive visualisation publicly accessible, fostering transparency and collaboration in advancing sustainable product development practices.

2. State of research

2.1. Visualisations in the product development process

Visualisations have emerged as an essential tool for humans to comprehend and interpret information, particularly when dealing with large and complex datasets (Michalos et al. 2012). By transforming abstract data into visually appealing representations, visualisations enable us to understand complex knowledge, make sense of large amounts of data, and identify patterns and relationships (Al-Kodmany 2001). that would otherwise remain hidden. This ability to translate intricate information into easily digestible formats has made visualisations indispensable in various fields, including research, education, and product development (Card 2008).

In the realm of product development, visualisations play an important role in enhancing the user experience (Nicolas Gebhardt und Dieter Krause 2016). By providing clear and concise representations of product features, functionalities, and interactions, visualisations facilitate effective communication between designers, developers, and stakeholders (Danfulani et al. 2010). This visual dialogue ensures that the product's design aligns with user needs and expectations, ultimately leading to a more intuitive and user-friendly experience (Shneiderman et al. 2009).

Visualisations serve several crucial purposes in product development, each contributing to the overall success of the product. They:

- Enhance Understanding: Visualisations translate complex data into easily understandable formats, enabling users to quickly grasp key information and identify patterns or trends (Al-Kodmany 2001).
- Improve Communication: Visualisations facilitate clear and concise communication of product ideas, features, and functionalities among designers, developers, and stakeholders (Tufte 2001).
- Support Decision-Making: Visualisations provide insights into user behaviour and product performance, guiding informed decision-making throughout the product development cycle (Card 2008).
- Promote Discovery: Visualisations encourage exploration and discovery, enabling users to uncover hidden patterns and make unexpected connections within the data (Tufte 2001).
- Enhance Accessibility: Visualisations can make information more accessible to users with diverse learning styles and abilities, promoting inclusivity and engagement (Bobek und Tversky 2016).
- Inspire Innovation: Visualisations can spark creativity and inspire innovative ideas, leading to new product features and functionalities (Heer et al. 2012).

As design heuristics in product development often operate in sets and highly influence each other (Hwang und Park 2018), the choice of an appropriate visualisation method becomes crucial. Therefore, the research will compare various visualisation methods for large datasets, with the goal to develope a concept that enhances understandability of the complex and wide landscape of design heuristics.

Recognizing the transformative power of visualisations in translating intricate information into comprehensible insights (Comai 2014), the focus is on creating an intuitive and user-friendly visualisation that facilitates the representation and exploration of design heuristics and their interdependencies.

2.2. Property driven product development regarding sustainability

In product development, ecological sustainability has emerged as a goal of great importance alongside traditional considerations of quality and costs (Laszlo 2011). The aim of ecological sustainability introduces a multifaceted objective that encompasses various dimensions that require a deep understanding and overview of the topic (Sohnius et al. 2023). To effectively address this complexity, a key strategy is to analyse the product's effects throughout its entire life cycle, startingfrom raw material acquisition to the product's end of life (Quernheim et al. 2023).

Within the domain of product development, designers work with the concept of product characteristics, which they can define, select, model, and choose (Suh 1990). The decisions that are made influence the properties of the product including sustainability related properties (Weber et al. 2003). Product characteristics reach from the geometry and materials of individual parts to broader systemic considerations at the product or system level, such as chosen tolerances, business models, or associated services (Buchert et al. 2016). This paradigm of characteristics and properties can be used across all phases of the product development process, ranging from product planning and conceptual design to series design (VDI 2221 Blatt 2).

In the context of sustainability, the properties of a product can be categorised into technical properties, those related to specific life cycle phases, and those pertaining to the complete life cycle (Buchert et al. 2016). Technical properties might encompass factors like the weight or complexity of a product. Life cycle phase properties consist of properties like assemblability, maintainability, or recyclability. Life cycle properties, on the other hand, include metrics such as energy usage, material consumption, and emissions (to air, water or land) generated throughout the product's life (Buchert et al. 2016). It is crucial to consider all these properties, with particular emphasis on life cycle phase and life cycle properties, when evaluating the ecological sustainability of a product. This holistic approach ensures that sustainability considerations are embedded at every stage of the product's begin, mid and end of life , fostering environmentally responsible practices in the field of product design. Nonetheless depending on the product and the effects that are analysed other than sustainability other classifications of properties e.g. functional and shape properties as proposed by (Mattmann et al. 2016) are used.

2.3. Linguistic knowledge formalisation in product development

In the domain of product development, knowledge can be displayed to product developers at various levels of detail and formalisation. When considering linguistically modelled knowledge - expressed in natural language - with the aim of guiding product development towards specific predefined goals, a distinction is commonly made between principles, guidelines, rules, and heuristics (Fu et al. 2015).

- Principles: These encompass fundamental considerations for development and exist within a broader context. An example could be principles for user-centred product design. Due to their broad scope, principles are not typically subjected to scientific evaluation (Fu et al. 2015).
- Guidelines: More formalised than principles, guidelines are often issued by institutions, such as company standards or ISO guidelines. They provide comprehensive assistance for product development and are often evaluated.
- Rules: Offering clear cause-and-effect relationships, rules are also scientifically evaluated and provide explicit guidance in product development (Yates und Murphy 2019).
- Heuristics: In product design, heuristics play an important role. They are often less formalised and exist subconsciously in the minds of designers (Yilmaz et al. 2015). Heuristics draw from the empirical knowledge of product developers. When explicitly articulated, heuristics are usually expressed as easy-to-understand rules of thumb. They guide product developers toward satisfactory outcomes but do not necessarily guarantee optimal solutions (Fu et al. 2015).

As part of a research project, a description standard was developed to facilitate the articulation and integration of design heuristics into databases (Kremer et al. 2022). This standard allows product developers to describe heuristics, making their implicit knowledge more explicit. Furthermore, a platform was created to enable product developers to share their knowledge with others by incorporating it into the standardised format (Kremer et al. 2023). Initial evaluations indicate that the use of the description standard and platform facilitates the transfer of knowledge and renders the recorded knowledge more accessible and understandable than when such standards are not employed (Kremer et al. 2023b).

3. Need of research and research methodology

The integration of heuristics into the product development process has revealed a multitude of potential effects, influencing various properties related to life cycle phases, the overall life cycle, and technical properties of a product. Given the abundance of potential heuristics for specific product characteristics, the development of a corresponding visualisation holds significant promise in aiding product developers in selecting the most appropriate knowledge to design products that align with pre-defined requirements.

As part of the research, the requirements for a visualisation for complex knowledge assets which multiple possible effects and trade-offs were systematically derived. Subsequently, diverse visualisation concepts were analysed to assess their adherence to these requirements. Building upon these findings, a prototype implementation of a dynamic visualisation was developed. The goal is to provide product developers with a practical tool that enhances their ability to navigate the complexity of heuristics and their impacts on product characteristics, facilitating informed decision-making throughout the product development process.

4. Development of the visualisation and logic of data processing

4.1. Comparison of visualisation techniques

In product development, clear communication is key, and that is why traceability is of great importance. The essence of traceability lies in seamlessly connecting the dots between requirements, design elements, and specific product features. To navigate this intricate web of connections, various visualisation techniques come into play, adapting to different artefact types and structures to ensure comprehensive coverage.

In the pursuit of effective traceability visualization, numerous visualization techniques were evaluated to best represent intricate relationships, dependencies, and hierarchies within large and complex datasets. The objective was to select methods that align closely with the unique criteria essential for traceability analysis, ensuring clarity, comprehensibility, and accuracy in conveying complex relationships.

Among the array of visualization options explored, Heatmaps, Dendrograms, and Sunburst Charts emerged as standout choices for several reasons:

Heatmaps present an efficient overview of associations between various elements by employing colors to represent the strength or frequency of connections. This technique excels in displaying large volumes of data, making it suitable for identifying patterns and trends within the traceability matrix. Dendrograms, with their tree-like structures, stood out due to their exceptional portrayal of hierarchical relationships, aiding in illustrating nested dependencies and categorizations within systems. Sunburst Charts, with their compact radial design, offer an intuitive means to display hierarchical data, enabling users to navigate through different levels effortlessly and interactively explore complex relationships and allows for the representation of multi-level relationships within a confined space, making them particularly advantageous when dealing with limited screen space or when trying to display a large amount of hierarchical information concisely.

While these selections offer significant advantages, other visualization techniques were considered but didn't make the final cut for traceability visualization. Sankey Diagrams, known for illustrating flow and relationships, were overlooked due to limitations in handling hierarchical data representations. Network Graphs, although adept at showcasing interconnected relationships, have been excluded due to potential complexity and clutter for larger datasets. Tree Maps, while useful for hierarchical data, have been sidelined due to their limitations in effectively managing the complexities inherent in large and interconnected datasets.

In the subsequent table, the top three techniques will be compared based on the essential traceability criteria and interaction design elements, providing a structured evaluation of their suitability for the task at hand. Other visualization techniques were analysed in the research. These include tables, pie-, bar-, radar bar-, donut-, line-, sankey and column charts, tree maps, histograms, box- and scatter plots, dependency- and network diagrams, concept maps.

Table 1. Analysis of visualization techniques regarding set requirements

Traceability Visualisation Criteria	Sunburst chart	Heatmap	Dendrogram
Visually depict hierarchical relationships	Yes	No	No
Visually depict artefact internal relationships	No	Yes	Yes
Visually depict artefact-crossing relationships	Yes	No	Yes
Allow for a flexible number and type of artefact	No	Yes	Yes
Hierarchical structure of individual artefacts must be representable	Yes	Yes	No
Consider hierarchical transitivity of the artefacts	Yes	No	No
Allow selection and reduction of displayed data	Yes	Yes	Yes
Keep elements in hierarchical context	Yes	Yes	No
Provide interaction possibilities	Yes	Yes	Yes
Sorting	Yes	Yes	Yes
Comparison	Yes	Yes	Yes
Filtering	Yes	Yes	Yes
Searchability	Yes	Yes	Yes

A comparative analysis of Sunburst Charts, Heatmaps, and Dendrograms reveals their specific strengths. Sunburst Charts excel in displaying hierarchical relationships, Heatmaps in representing impacts, and Dendrograms in showcasing hierarchical structures. To strike a balance and address the diverse criteria, a multivariate visualisation approach is considered.

Multivariate visualisation involves combining techniques, and after careful evaluation, the Sunburst Chart with Radial Heat Map emerges as the preferred choice. This combination efficiently utilises space, provides a hierarchical overview, allows interactive exploration, and offers effective colour representation. Balancing complexity and user comprehension, this multivariate approach maximises the visualisation's potential for conveying complex information while maintaining visual appeal.

Visual Communication Science principles were followed. That means paying attention to colour contrast, typography, and visual consistency for readability and appeal.

On the technical side, JavaScript and React framework was used, with Amcharts as the main library and MongoDB as the database.

4.2. Logic of semantically connecting linguistic elements of design heuristics

The structure of the heuristics in the database is outlined in Figure 1, designed to facilitate comparative visualisation.

The developed description standard consists of five linguistic elements based on the language commonly used for formulating heuristics as rules of thumb or concise instructive statements. These elements are:

Order Verb: Represents the action the product developer must take, such as Locate, Design, Plan, Calculate, etc.

Artefact: Refers to the reference point of the heuristic within the product, which can be a physical part (e.g., parts, fasteners) or non-physical components (e.g., services, business models).

Artefact Attribute: Provides a more detailed description of the artefact. For instance, the heuristic may apply to specific forms of an artefact, such as wheels on motorcycles, ferromagnetic parts, or drains for toxic chemicals. This element is optional.
Order Attribute: Allows the product developer to give precise instructions on what to do with the artefact to achieve a specific effect. It works in conjunction with the Order Verb.
Effect: Specifies the potential positive or negative effects achieved by the heuristic on a property.

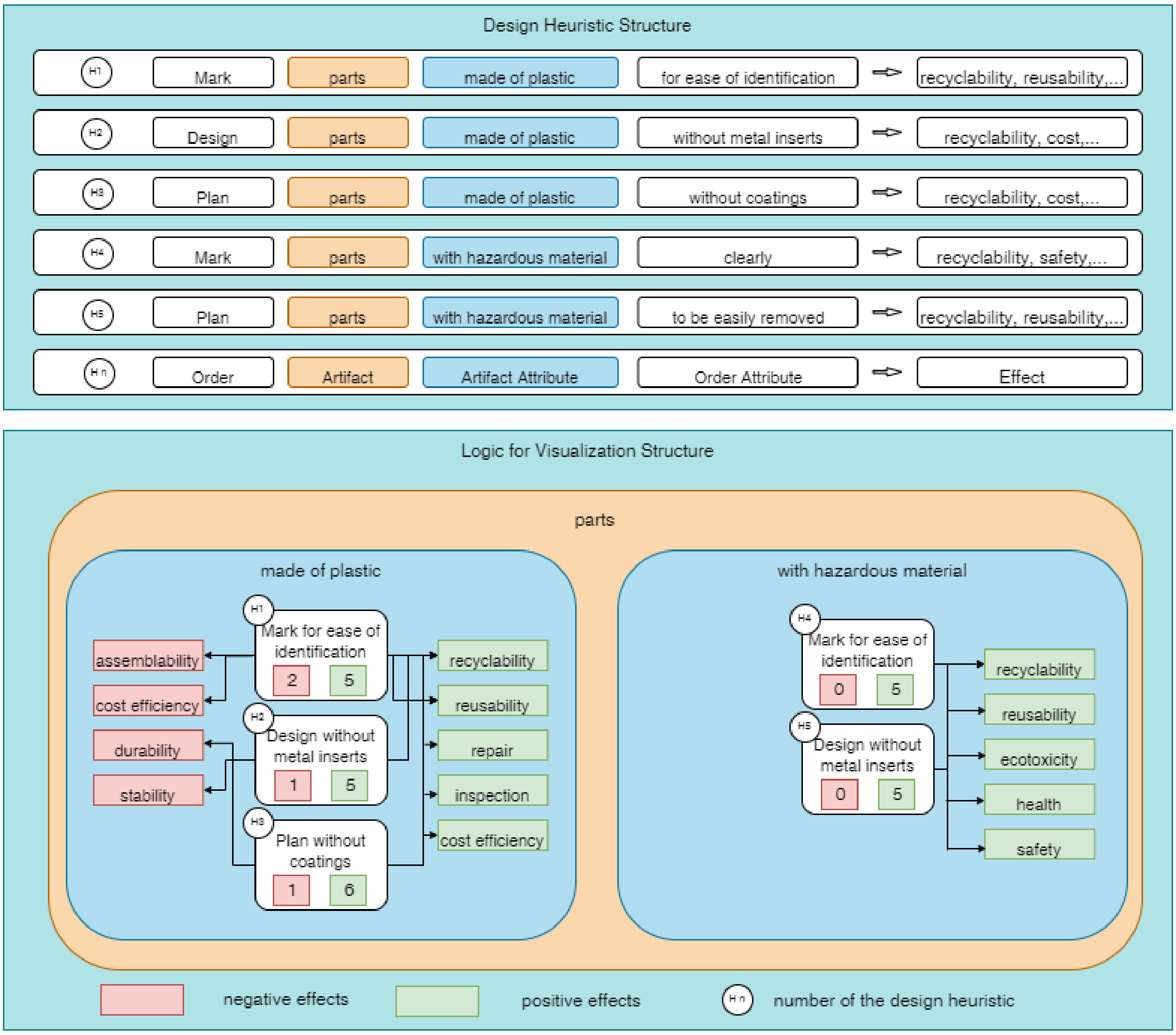


Figure 1. Design heuristics structure and logic for visualisation structure

The original description standard was based on common Design for X (DfX) objectives for effects as e.g. (Telenko et al. 2016) proposes regarding design knowledge for sustainability. However, for the purpose of giving a more holistic overview of sustainability knowledge for product development, the effects were expanded. While DFX (e.g. recyclability, reusability) objectives address Life Cycle Phase properties, neither technical properties nor properties regarding the complete life Cycle are focussed on in DFX objectives. This is why properties often examined in Life Cycle Assessments (LCAs) were incorporated as life cycle properties, and technical properties were introduced as an effect property. For Life Cycle Properties impact categories for LCAs proposed by (Mikosch et al. 2022) were implemented. As technical properties the current basis for the visualisation are the analysed technical properties in the design-dependency-model developed by (Bonvoisin et al. 2018) An excerpt of potential properties can be found in Fig. 2.

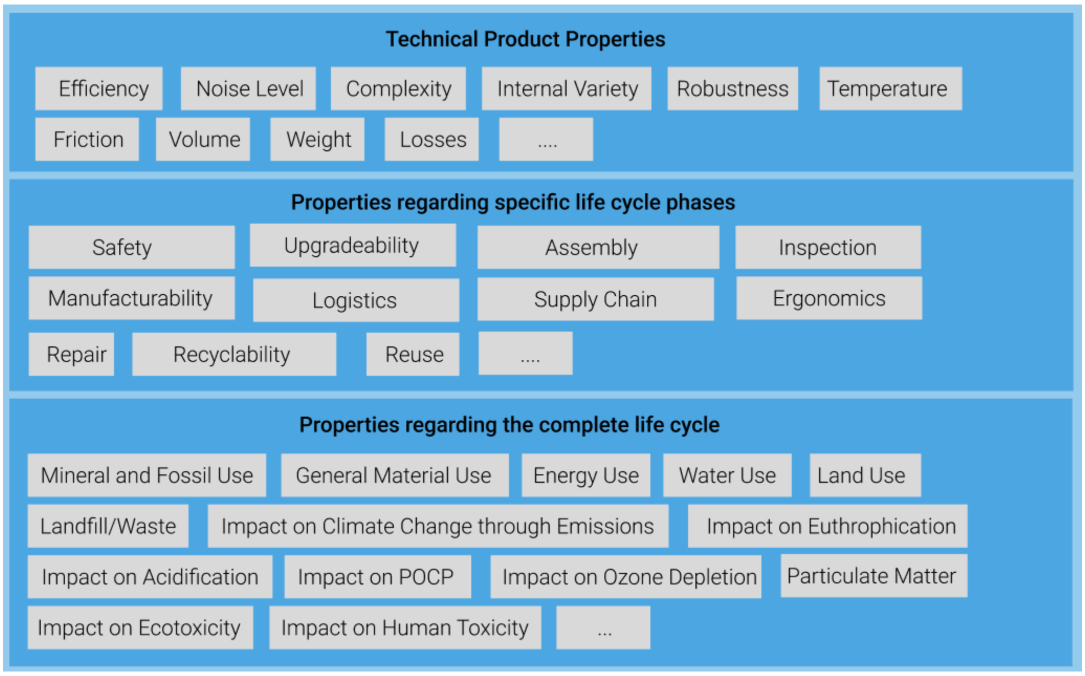


Figure 2. Excerpt of potential product properties/effects of heuristics

4.3. Technical implementation

A JSON file serves as the bridge, connecting the heuristic components with the user interface. Through this connection, users can navigate the heuristic details, understand the effects, and glean insights from the information embedded in the database.

In the json file, all design heuristics are represented with the following details: design heuristic title, order, artefact, artefactAttribute, orderAttribute and positive and negative effects.

The positive and negative effects are displayed in an array with an effect Category and effect Category Specification.

In this exploration of the final implementation, the focus lies on the intricacies of integrating and customising the amCharts4 library to bring forth a tailored radial heatmap.

Firstly, the design phase shapes the radial heatmap, aligning it with the required style and aesthetics. This involves setting the inner radius, adjusting font size, and determining start and end angles to create the desired circular representation that offers enough of a gap for the design heuristics to be readable and clear.

Accurate representation follows in the setup of x and y axes, utilising CategoryAxis to display positive and negative effects across three different categories. However, the challenge arises in data manipulation, converting categorical data into a heatmap. A creative approach assigns numerical values to categorical information, effectively portraying relationships, and patterns.

Two Filtering/Searchability options are added: Users can filter through the different embodiment attributes of the selected embodiment artefact. In addition to that, users can also filter through the three effect Categories. Once filtered, the different titles of the relevant design heuristics will appear alongside all the positive and negative impacts (effectCategorySpecification). The implementation introduces a series change function for interactive control, allowing users to dynamically visualise data based on their property of interest. Visual aspects are fine-tuned for clarity, and hover tooltips provide additional details during exploration.

Handling large datasets becomes easier with the incorporation of a vertical scrollbar, offering users smooth navigation through extensive data. A dynamic dropdown filter enhances chart functionality, empowering users to explore various embodiment attributes.

For versatility, a scrollbar facilitates a transition between radial and rectangular heatmap views. Despite a technical limitation in label display during the transition, this feature caters to diverse preferences.

The interactive nature and filtering functionality empower users to derive valuable insights from the data, enhancing the clarity and impact of the research findings. The code of the visualisation can be found under https://github.com/berkayb6/DesignHeuristics.git

5. Description of the developed visualisation

The developed prototype is a dynamic three-series radial heat map visualisation designed for comparing different heuristics in the context of specific product artefacts. The visualisation assesses heuristics across three dimensions: technical properties, life cycle phase properties, and life cycle properties.

Key features of the prototype include:

Integration of Database Properties: All properties from the database, along with their corresponding classifications, are incorporated into the visualisation. Each property is represented with its classification. If a heuristic indicates a positive effect on a property, it is visualised in green; if a trade-off or negative impact is specified, it is marked in red. Unspecified properties are left unfilled.

Dynamic Comparison: The user can dynamically select which dimension to compare on the right-hand side of the visualisation. The three dimensions—technical properties, life cycle phase properties, and life cycle properties—are available for user selection.

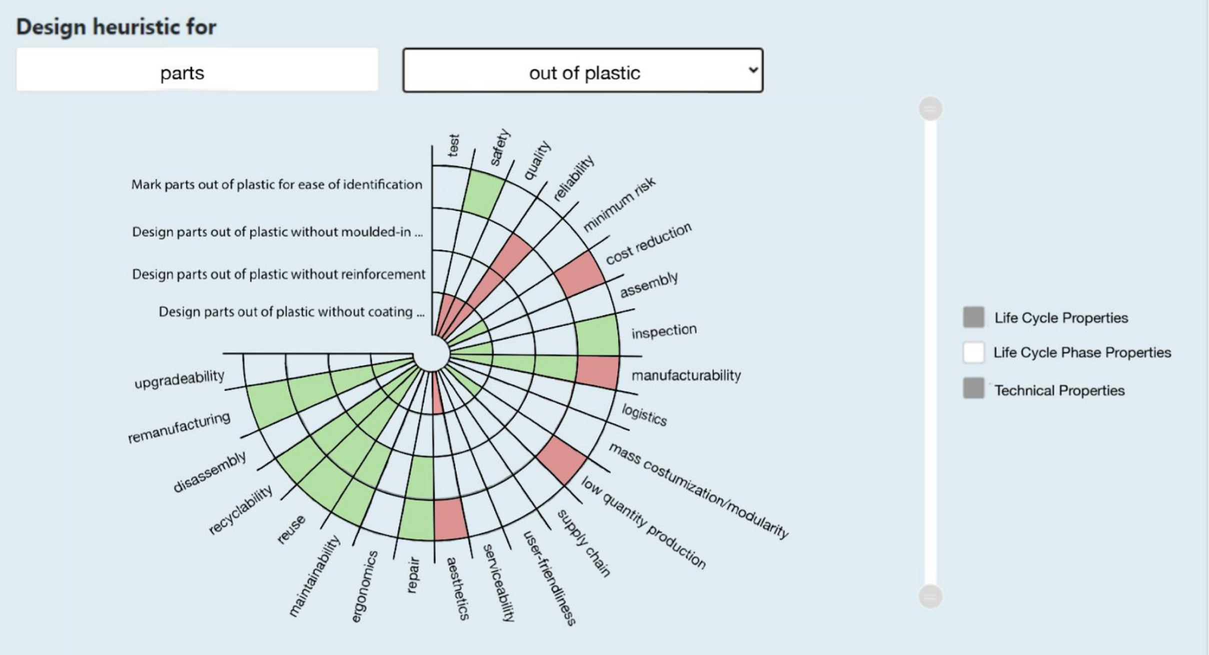
Artefact Specification: The user has the option to choose a product's artefact for comparison. Two drop-down menus facilitate this selection. The left-hand menu allows users to choose the overarching artefact term (e.g., systems, parts, engines), while the right-hand menu enables the selection of a more detailed artefact specification (e.g., systems reliant on water consumption). The radial heat map then displays all heuristics related to the specific artefact characteristic chosen.

5.1. Exemplary heuristics visualisation

A screenshot of the visualisation can be found in Figure 2.

The figure illustrates examples of four design heuristics from the database (Kremer, 2022) that pertain to the same artefact category (parts) with a specific specification (made out of plastic). These heuristics are as follows:

"Mark parts out of plastic for ease of identification"
"Design parts out of plastic with moulded-in metal inserts"
"Design parts out of plastic without reinforcements"
"Plan parts out of plastic without coatings"



Design heuristic for

parts

out of plastic

Figure 3. Screenshot of the developed visualisation

Design heuristics are individually formulated by designers and can exhibit varying levels of detail. They may complement, specify, or even contradict one another based on different design objectives. In evaluating these heuristics, a designer can independently assess whether they are mutually exclusive or if multiple heuristics can be selected concurrently. Alternatively, the designer might need to focus on a single heuristic, especially if it aligns most closely with their primary goal and involves minimal trade-offs.

For instance, considering the level of life cycle properties, a designer could recognize that employing the heuristic "Design parts out of plastic without moulded-in metal inserts" yields positive effects in terms of recyclability, repair, or remanufacturing. However, the designer would need to acknowledge the associated negative effects or trade-offs, such as a potential compromise in structural robustness. This insight empowers designers to make informed decisions based on the specific goals and trade-offs associated with each design heuristic in the context of the artefact being considered.

6. Conclusion and outlook

The implementation stands as a valuable tool for visualizing complex knowledge bases, ensuring an effective and interactive user understanding. The visualisation tool offers a dynamic and intuitive platform for users to explore and compare heuristics, facilitating a deeper comprehension of their impacts on various dimensions of product development. Users have the flexibility to customise their comparisons based on specific product characteristics, enriching the functionality of the visualisation for informed decision-making in product development.

It is important to recognize that the effectiveness of the visualisation is dependent on the quality of the data input into the system. If product developers input incomplete or inaccurate knowledge into the database, the visualisation may convey inaccurate information. Therefore, the accuracy and reliability of the knowledge in the visualisation depends on the integrity of the data. A special focus hereby needs to be put on the data input of the linguistic elements of design heuristics which is needed for the appropriate filtering and display of heuristics.

In order to understand and make the best possible use of visualization, it is ideal to have a basic understanding of sustainable product development. Nevertheless, the clear color coding and clear presentation of effects are intended to make the tool intuitive to use and to make the advantages and disadvantages of using specific heuristics easy to understand.

To further validate the application's utility, a comprehensive evaluation in a real working environment is essential. Once its suitability is confirmed, potential expansions of the visualisation tool into other domains and applications become conceivable. This could extend to incorporating various heuristics beyond product design or adapting the visualisation for scenarios involving trade-offs in diverse fields, broadening its applicability and impact.

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