THE POTENTIAL OF DESIGN-BY-ANALOGY METHODS TO SUPPORT PRODUCT, SERVICE AND PRODUCT SERVICE SYSTEMS IDEA GENERATION

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Abstract

Design-by-Analogy (DbA) is the process of developing solutions for design problems through the mapping of attributes, relations and purposes that a source problem or situation may share (or at least partially share) with an existing target solution or situation. There is a range of available DbA methods that have been developed to assist designers during the ideation stage to identify potentially useful analogies to solve design problems. However, generally these methods have been developed and applied in the product domain rather than in the service and product service systems domains. The purpose of this article is to identify the characteristics and nature of products, services and product service systems; to provide an overview of existing DbA methods and their drivers to evaluate the potential transferability of DbA across domains.

Keywords: Design methods, Design by Analogy, Creativity

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1 INTRODUCTION

Humans are continuously solving design challenges in their quest to improve their surroundings, to improve society and the human condition, or the ways they interact with their environment and with other humans. Developing solutions for such design challenges requires effort and in most cases creativity. Markman and Wood (2009) discuss three possible sources for new ideas: serendipity (by coincidence), research and development or discovery (systematic exploration of a well-defined problem), and analogical reasoning (cognitive processes when solving problems). From these sources, reasoning (specifically analogical processes) is an area that has been explored to support designers when developing innovative solutions and overcome fixation as part of an existing paradigm or an existing solution. Some well-known designs that have been developed using analogies are: DaVinci's bat-like wings for his flying machines, or natural cooling systems for buildings taken from termite mount designs.

To enhance designer's analogical capabilities and support the development of solutions in a continuous and consistent manner several Design-by-Analogy (DbA) methods have been developed. Some have been derived from the synthesis of cognitive findings related to analogical reasoning, others have been based on functional analysis and problem framing.

Most of the existing DbA applications have been in product domains such as engineering and architecture (Dahl & Moreau, 2002; Linsey, 2007; Linsey, Wood, & Markman, 2008; Linsey, Markman, & Wood, 2012; Segers & De Vries, 2003) (Segers, De Vries, & Achten, 2005) This poses a question about the transferability of existing DbA methods to solve design problems in the service and product service systems (PSS) domains. In particular, because design processes for products and services are considered to be the same in the early stages, which includes the ideation stage, and then diverge in the detailed design phase (Cagan & Vogel, 2013).

To provide perspective and an answer to this question, this article will examine product, service and PSS characteristics and review existing DbA methods to identify opportunities in the methods that may enable them to be successfully implemented across domains.

2 PRODUCTS, SERVICES AND PRODUCT SERVICE SYSTEMS (PSS)

Various definitions for products, services and PSS can be found. Products have been defined as tangible objects that exists in both time and space, while services have been defined as acts that only exist in time (Shostack, 1982). Vermeulen (2001) extracted a set of characteristics that differentiate services from products: intangibility, simultaneity of production and consumption, heterogeneity and perishability. In earlier work, we added two additional characteristics: research and data nature (qualitative, quantitative) and statistical distribution (parametric on non-parametric) (Moreno, et al., 2014). The collated set of characteristics can be found in Table 1.

Table 1. Characteristics of products and services

CHAR.	PRODUCT	SERVICE
Tangibility	Tangible	Intangible
Production	Separation of production and consumption: customers do not normally participate in production	Simultaneous production and consumption: customers participate in production
Uniformity	Homogenous	Heterogenous
Storability	Can be kept in stock	Perishable: cannot be kept in stock
Statistical distribution concerning performance	Typically parametric statistics (normal distributions)	Typically non-parametric statistics
Data Nature concerning performance	Typically expressed with quantitative data	Typically expressed through qualitative data

There has been some debate about the degree of differentiation between products and services. However, it has become more accepted that services and products are interconnected in varying degrees. The design solutions that combine products and services have been termed product service systems (PSS) (Goedkoop, Halen, Riele, & Rommens, 1999; Morelli, 2002), or functional products (Reed, et al.,

2010; Lindström, Löfstrand, Karlberg, & Karlsson, 2012). Baines, in his review of PSS research, defined PSS as "an integrated product and service offering that delivers value in use. A PSS offers the opportunity to decouple economic success from material consumption and hence reduce the environmental impact of economic activity." (Baines, et al., 2007). This definition highlights the inclusion of environmental and social gains in the value added.
Interest in PSS from research and practice has seen a strong increase. From a business point of view, the delivery of PSS requires a different business model involving a more intensive and continuing relationship with the customer, and a shift from income based on selling a product to income based on selling a (continuous) functionality (hence the use of the term functional product).

3 DESIGN-BY-ANALOGY

Analogy is the association of a situation from one domain (source) that is usually poorly understood, to another domain (target) that is well-understood. The association is possible due to relations or representations (Gentner & Markman, 1997; Kurtz, Miao, & Gentner, 2001).
Design by analogy (DbA) requires accessing and then transferring elements from an existing solution for a design problem to the solution for another design problem. Such elements may be components, relations between them, or configurations of components and relations (Goel, 1997). Gentner and Markman (1997) defined analogy as a two dimensional design space defined by 'relations shared' and 'attributes shared'. Hey et al. (2007) added a third dimension, 'purpose', to expand the understanding of analogy within the design context.
DbA is based on the premise that the solution to a given design problem may already -or partially- exist, either in an analogous domain or in an analogous solution, and that it can be extracted or mapped once the analogy connections between source and target are made (Moreno, Yang, Blessing, & Wood, 2014)
We reviewed 100 papers related to design and analogy. The subset of papers selected for this article are the ones that explicitly discuss and propose DbA methods. In some cases the selected subset concerns the same methods or slight variations of these. Considering the source of inspiration for the analogies, two main categories of methods are distinguished in this section: those inspired by nature and those that do not use nature as source of inspiration. The former use terms such as bio-inspired, bio-mimetics and bionics. We aggregated these under the term BioX analogies. This section contains a short description of the selected methods. A comparison can be found in Section 4.

3.1 BioX analogies

This category comprises all methods that use nature, its principles, structures, functions or behaviours as possible sources of analogy for mapping a given design problem characteristics/elements. There are a number of formal and informal BioX design approaches currently available; however, below we are describing those found by Fu et. al. (2014) to have structured formal methods and tools.

3.1.1 Biomimicry and AskNature

Biomimicry comprises: a method, a taxonomy and a web-based tool, AskNature, developed by Benyus and colleagues (Deldin & Schuknecht, 2014). The drivers behind the analogical process of this approach are functions and physical principles.
The method requires a designer to define the context of the problem and identify functions. The designer then uses AskNature, the taxonomy, or both to find analogies. AskNature searches its database for examples of how nature fulfils the function identified by the designer. The taxonomy, which contains biological information in terms of functions and physical principles, can be used by a designer to find related or alternative functions, which can trigger ideas for solutions directly, or be used as alternative inputs into AskNature. The collection of examples in the repository of AskNature is dynamic and enriched through social networking and sharing of biological knowledge.

3.1.2 IDEA-INSPIRE

IDEA-INSPIRE is a computational tool developed by Chakrabarti et al. (2005), which allows a systematic search that enables analogical reasoning using inspirations from natural as well as artificial systems (Chakrabarti, Sarkar, Leelavathamma, & Nataraju, 2005). The approach is function-driven: the tool requires that the design problem be expressed as a triplet, verb–noun–adjective/adverb (VNA), to

find natural or artificial systems that fulfil the same function. It may be necessary to divide the problem into sub-problems to focus the solution finding process.

3.1.3 Biomimetic Design Through Natural Language Analysis

The approach proposed by Cheong et al. (Cheong, Shu, Stone, & McAdams, 2008) extends the Functional Basis terms (Stone & Wood, 2000) with biological keywords that can then be used to search and explore available biological knowledge. The approach involves identification of functions (key action verbs) and flows (nouns), then a semantic expansion of key action verbs by means of Princeton's WordNet® and the categorization of biologically relevant nouns that may correspond to the expanded set of verbs.

3.1.4 Engineering-to-Biology Thesaurus and Function-Based Biologically Inspired Design

Nagel et al. stated that to abstract problems in engineering design it is common to use functions (actions) instead of specific forms (components), where this approach enabled connections to biological systems which can be described in a similar way by means of their functionalities (Nagel J. , Nagel, Stone, & McAdams, 2010). Their approach uses an engineering-to-biology thesaurus (Nagel, Stone, & McAdams, 2010), which is a tool that facilitates the association of terms from the biological domain to the design problem domain. This approach differs from other BioX design approaches in the fact that it starts from a biological system to extract analogical elements (Nagel, Stone, & McAdams, 2013; Nagel, Nagel, & Stone, 2011). This approach is driven by functional basis terms (Stone & Wood, 2000).

3.1.5 Design by Analogy to Nature Engine (DANE) (Computational Tool)

DANE provides access to a repository of biological and engineering systems, supports analogical mapping between biological and engineering systems by means of representations of the structure–behavior– function (SBF) type, and delivers a model with additional inspirational multimedia content such as schemas, texts, photographs, diagrams, graphs, etc (Vattam, Wiltgen, Helms, Goel, & Yen, 2010).

3.2 Non-BioX analogies

3.2.1 WordTree Method

This method begins with the identification of "key problem descriptors (KPDs)" which can be functional requirements, customer needs, or clarifying descriptions of the design problem. KPDs are then located in a diagram known as a WordTree, which is constructed by populating the branches through selected hyperonymys and troponyms extracted from Princeton's WordNet or VisualThesaurus™. From the WordTree diagram, potential analogies can be researched and analogous domains explored to discover solutions (Linsey, Markman, & Wood, 2012; Linsey, Wood, & Markman, 2008).

3.2.2 SCAMPER Method

This method provides designers with seven sets of questions to steer the finding of analogies to solve a design problem. The seven sets are called operator categories (Eberle, 1996). These are (S) Substitute, (C) Combine, (A) Adapt, (M) Modify/Magnify/Minimize, (P) Put to other uses, (E) Eliminate, and (R) Reverse/Rearrange. Each operator category comprises a set of questions that allows to redirect the analogical search to solve a problem.

3.2.3 Synectics

Synectics is related to SCAMPER and represents a group problem-solving approach to expand creative thinking capabilities (Gordon, 1961) by guiding problem analysis and supporting analogical and metaphorical reasoning to develop possible solutions. There are a number of variations of the method, one of such has been formalized by Rettig and Canady (2013). They propose the following steps: (1) problem definition and identification of keywords, (2) direct analogies creation of previous step words, (3) personal analogy creation, where participants select and become a direct analogy of the previous step, (4) conflict identification in the list of personal analogies generated of previous step, (5) generate new direct analogies for the conflicting personal analogies, (6) original problem re-examination to produce solutions that make use of the ideas previously generated, (7) results usefulness evaluation.

3.2.4 TRIZ-Based Methods

TRIZ is the Russian acronym of Theory of Inventive Problem Solving, which was developed by Altshuller in 1946 after analyzing an extensive patent database. He found that almost all design problems could be modelled as contradictions of 39 technical characteristics (39x39 matrix named "Contradiction Matrix") and that those contradictions could be solved by applying a set of 40 principles (Altshuller, 1999). The process is supported by analogy or meta-analogy starting from a specific problem then defining the contradiction problem that already approaches or characterizes for developing a specific solution. TRIZ has been applied in product development and Bioinspired design through the representation of the design problem in terms of functions and formulated as contradictions (Vincent & Mann, 2002).

3.2.5 Visual-Based Methods

This approach proposes the use of visual analogies to enhance problem solving. Studies of the design process have found that visual prompts may be a potential source of analogies for designers, who can establish mappings through structural or surface relations (Goldschmidt, 1994; Goldschmidt, 1995; Casakin & Goldschmidt, 1999; Casakin & Goldschmidt, 2000). The available empirical studies indicate that the use of visual analogy improves the quality of design solutions (Casakin & Goldschmidt, 1999; Casakin, 2004).

3.2.6 Search engines and Algorithm-Based Methods

There are a number of computational approaches based on cognitive science to support designers with forming and identifying analogical connections between terms. An example is the Structure Mapping Theory (SMT) (Gentner, 1983), which is implemented in the Structure Mapping Engine (SME) (Falkenhainer, Forbus, & Gentner, 1989). SMT describes a set of implicit constraints that enable interpretation of analogy and similarity. Falkenhainer, et al. (1989) argued that the best search engine results could be achieved when problems were decomposed with a psychological motivation, i.e. were based on a computational model of how people form analogies. SME uses such a model to produce analogical mappings between the source and target representations.
Computational approaches to analogy focus on either attributional similarity (appearance), relational similarity (analogy), or a combination of both (literal similarity) (Medin, Goldstone, & Gentner, 1990). Latent Semantic Analysis (LSA) measures the degree of attributional similarity between words (Landauer & Dumais, 1997) based on a mathematical and statistical technique for extracting, representing and identifying relations of words within a semantic context (Landauer, Foltz, & Laham, 1998). Latent Relational Analysis (LRA) measures relation similarity and determines analogies. It starts from a query and produces a similarity-ranked list of documents (high to low) (Turney, 2005). The Latent Relation Mapping Engine (LRME) combines SME and Latent Relational Analysis (LRA) and seeks the mapping that maximizes the sum of the relational similarities.
These computational approaches have been employed to assist designers to overcome design fixation, to support novice designers, to identify new and unexpected analogies and analogous domains. These algorithms have been enriched by other authors adding Bayesian approaches and including refined searches in patent databases to discover relationships and extract near and far field analogies, resulting in clusters of source analogies, connected by their relative similarity (Fu, Cagan, Kotovsky, & Wood, 2011; Fu, et al., 2012; Fu, et al., 2013; Fu, et al., 2014).

4 QUALITATIVE LITERATURE ANALYSIS

DbA methods can be analyzed using different dimensions. For the purpose of understanding and predicting the transferability and suitability of analogy approaches across products, services and PSS, we have elaborated two separate qualitative analyses. The first analysis concerns the current application domains of the DbA methods in order to identify potentially dominant method drivers across the spectrum from Product to Service. The second analysis contrasts the findings of the first analysis against the characteristics of Product, Service and PSS, to identify potential gaps that may be impairing or limiting the application of DbA methods across the spectrum of Product to Service domains.

4.1 DbA methods, application domain and drivers

We first mapped the methods across the Product to Service continuum according to the type of design problem used which provides information about the application domain. From Figure 1 it can be seen that BioX methods have been mostly applied in the product domain, and that half of the non-BioX methods have applications in the service domain.

The resulting mapping of DbA methods will allow the evaluation of the transferability of the methods across domains. The transferability evaluation will be enabled through the analysis of the characteristics of product, service and PSS, along with the DbA method's drivers. The hypothesis is that the product design methods may have some difficulties to be transferred to service design domain due to the specific service characteristics and the drivers of each method.

With respect to the drivers, it is found that BioX methods 3.1.1 to 3.1.5 and TRIZ (3.2.4) have been applied in the product domain and the driver of their analogical processes are functional terms. TRIZ has also been implemented in service domains.

Visual-based methods are mainly used in the product domain and their drivers are structural or surface relations, which in some cases may match functionalities. The search engines and algorithms have the capability to find analogies for any type of word or text. Search engines tend to focus on discovering analogies in databases of documents such as patents by means of functionalities (verbs) and surface attributes (nouns).

WordTree and SCAMPER have been applied in product and service domains. They include functional as well as relational and attributional components. For WordTree, the drivers are key problem descriptors, i.e. functional requirements, customer needs and problem descriptors. SCAMPER drivers are linked to the problem description.

Synectics has also been applied in product and service domains, however, the method has been used in the form of brainstorm sessions and their full capabilities have been limited. Synectics drivers are key words from problem descriptors.

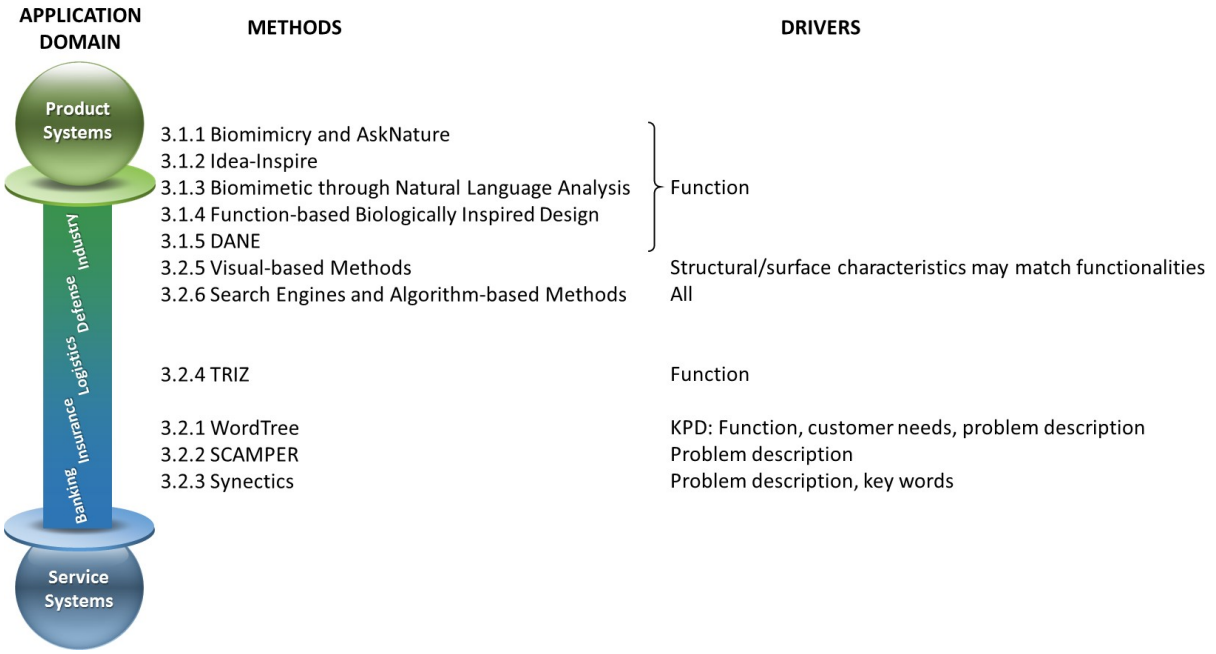

Figure 1. DbA Methods application and drivers

The driver identification is important, considering that the outcomes for each method are closely related to their inputs and each method therefore may provide near of far field analogies, i.e. within or outside the domain of application. From the literature review and the synthesis presented in this section (see graphical summary in Figure 1), it appears that the DbA methods have different capabilities to support ideation and design across product to service continuum. It appears that as we move from product to service domains, the drivers shift from a functional (verb) type of driver, towards structural attributes (nouns) or additional semantical search categories. This behavior is important, because a method when

applied in a different domain, may provide analogies that are far for the domain of application and be perceived as non-useful.

4.2 DbA and Product, Service and PSS characteristics

To perform an analysis that contrasts the characteristics of Product, Service and PSS to the mapping of application and drivers of the DbA methods, a review of relevant components of Section 2 was made.
The characteristics summarized in Table 1 correspond to different stages of products and services life cycles, for example, "statistical distribution" and "data nature" relate to performance, i.e. when the product or service has already been developed and used. Therefore, for the design stage, specifically, during ideation (earlier design stage) some of the listed attributes are not applicable.
It appears that the relevant characteristics for Product and Service at the design stage are: Tangibility and Production. For the Tangibility characteristic, Wordtree, SCAMPER, Synectics and TRIZ appear to have overcome the intangible nature of service design solutions, perhaps because service problems are usually expressed verbally, textually or as a semantic construct, rather than through physical models. As presented in previous section, the drivers of these methods enables metaphorical or analogical reasoning at the attributional and relational levels.
To analyze "production" it is important to first understand the logical sequence of product and service development, i.e. being designed, produced, delivered and used (see Figure 2). From this sequence, it can be seen that in the case of products, customers are usually not involved in production process, but they may be in the design process. The inclusion of the customer during the design stage for services may provide flexibility and customization.
Products and services can be described more broadly as processes. Processes have the purpose of fulfilling functions, are carried by people or products and those may require products (people require products, then PSS) or services. When the process is exclusively carried by people a pure service occurs, and if it is carried exclusively by an artifact (tangible object) a pure product occurs. If the processes require additional products or services, a PSS emerges. For example, when products have functions that require human services (beyond ignition or pressing a button); or when services require the support of products to be developed.

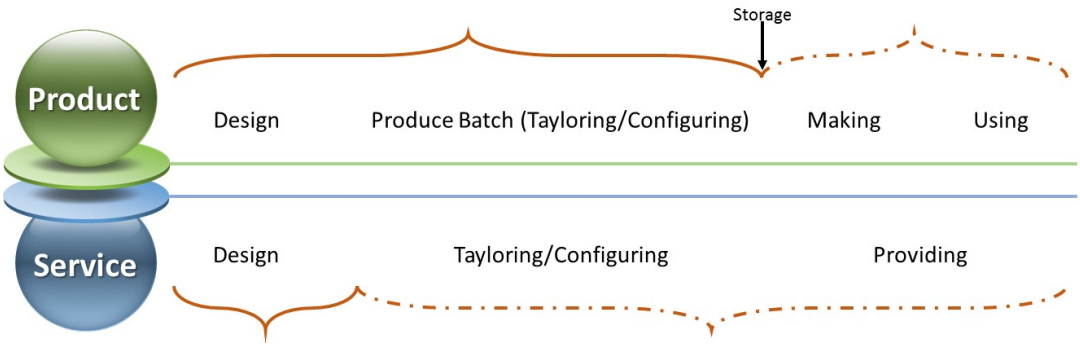

Figure 2. Product and Service development logic

Contrasting the findings of the first analysis against the characteristics of Products and Services as presented processes that have an intangible or tangible nature and that may require customer interaction; enable the identification of potential gaps that may be impairing or limiting the application of DbA methods across the spectrum of Product to Service domains and by extension, its use for PSS.

The potential link to find meaningful analogies could perhaps be done through processes instead of functions. Surface of the products may hardly help to find analogies, whereas with the use of structural attributes (nouns) or additional semantical search categories some analogies may be derived. With this consideration, there might be methods that may easily be transferred and others will require further adjustments.

5 DISCUSSION

The support of designers' creativity during the ideation stage is crucial to assure a continuous and reliable generation of innovative and successful solutions for design problems.
Despite the different characteristics of products, services and PSS, the ideation processes in these domains are considered to be the same. This means that the use of design by analogy, which currently is more typical for the ideation of product, could be a promising approach across domains.
Most DbA methods are currently applied in the product domain and some may have difficulties to be applied in the service area, especially considering that the main service characteristic appears to be its intangibility. An additional difficulty appears to be the drivers of the DbA methods, because they determine in part the type of retrieved analogy, i.e. a functional driven DbA method may preferable have as inputs functions represented in the form of verbs, and its results may also be of the type of analogous verbs that may enable accomplish the required function. This type of representation is not as straightforward in the case of services, as it was found, the drivers of the DbA methods applied in the service domain include structural attributes (nouns) or additional semantical search categories; which may require that the analogical reasoning of other DbA methods be adapted to process driven instead of exclusively functional driven.
There is also the case of combinations, i.e. PSS and many systems nowadays are of this type, I think there is a lot of potential and particularly xxx methods and refer to the drivers. Link drivers to the differences and be able to say that functionality should work but the methods that ate more in the product characteristics may be much further away, structural are in the middle.
Function driven DbA may be transfer from the current product domain to PSS or service domains, however, the applicability of the functionally driven methods in their current state is limited due to their product-focused supporting material (product repositories, technical language and representations). For example, TRIZ has been applied to develop solutions for both product and service design problems, even though the 39 technical characteristics and 40 principles of TRIZ were abstracted from patent data bases, i.e. products. Although several TRIZ principles are general enough to be applied in services and PSS when they are viewed as processes or when the problem is formulated as contradictions between processes; other principles require translation, interpretation or abstraction of their technical terminology.
Services and PSS can be supported through semantic approaches, therefore search engines and algorithm-based methods offer tremendous potential to support ideation across domains. Dynamic repositories or search tools, where designers can include solutions, functional and other related representations, would also enhance DbA capabilities to support ideation across domains.
Approaches that make use of search repositories such as Ask Nature, Idea-Inspire, DANE, WordTree, search engines and algorithm-based methods, should be expanded or redirected to include diverse entry forms, not only patents, certain codified biological phenomena or product databases that correspond to solutions in the form of a product or artefact, but solutions in a broader sense as well as functions, activities, processes, human interactions and principles.
Semantic approaches such as WordTree and SCAMPER could also embed broader semantic explorations to include not only functions (action verbs) but function modifiers (adverbs), attributes (adjectives), gerunds, and entities (nouns), which may enhance analogical retrieval for design problem solving across domains.
These findings are preliminary and will require further studies to understand creative cognition with DbA in the area of service and PSS innovation, building upon the work carried out in cognitive science, in engineering and architectural design, to develop more holistic DbA approaches that enables the transferability of DbA methods and benefits innovation across domains.

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