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Applying DMM and DSM to Support the Quantitative Investigation of Process-Oriented Fundamental Elements of Design Thinking

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Abstract: New theories and approaches need to be progressively characterized to achieve maturity and proper handling. The characterization of their fundamental elements is typically approached with qualitative methods. Those procedures may be arduous to perform when the target element to be characterized is numerically expressive. This work is part of a wider project that aims to compare elements of an emerging theory (design thinking) with the elements of a well-established theory (development process). This paper proposes a method for characterizing the fundamental elements of a given process-oriented element category of a theory or approach, mainly when fundamental elements are voluminous. The method proposed in this work is based on content analysis, which was combined with the application of design structure matrices (DSM) and domain-mapping matrices (DMM) in order to process information. The method was tested through experts' analysis attempting to characterize the fundamental tasks of the design thinking approach.

Keywords: DSM, DMM, characterization, method, design thinking

1 Introduction

The design thinking (DT) approach as an organizational resource[1] can be considered a new emerging theory. DT is a trend in human-centered design that "blends an end-user focus with multidisciplinary collaboration and iterative improvement to innovative products, systems, and services" (Meinel and Leifer, 2011), being popularized after Brown's (2008) introductory publication. This approach is relatively new and has been oversimplified in literature due to great focus on practitioners (Dorst, 2011).

In order to perform research about DT theory and handle it properly, it is important to enhance the scientific community knowledge and evolve the DT theory. Characterizing DT by identifying its fundamental elements can provide a better understanding and definition of this theory. This work classifies fundamental as the adjective of a construct or a given theory that forms its base, "from which everything else develops" (Cambridge, 1999). Thus, if an element is fundamental to a theory, it is expected that most propositions of that theory shall contain this element. Investigating the fundamental elements of DT may support the incorporation of this approach into more traditional

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[1] The term "design thinking" (DT) has been used to designate two other research lines that approach different topics of DT as referred in this work. The first one approaches DT as the cognitive process embedded in the design process (Kimbell, 2011). The second one is related to the general theory of design, where the cognition process may lead to the solution of so called "wicked problems" (Kimbell, 2011).

theories, such as product development. This kind of investigation, though, offers some challenges to overcome.

First of all, in order to assure the quality of a qualitative analysis, some requirements must be fulfilled, such as the application of trustful techniques and methods, the credibility of the researcher, and the “philosophical belief” (Patton, 1999). In order to fulfill the first requirement, a proper method for investigating specific elements in literature is essential. Additionally, a way to deal with voluminous data is needed, since those elements may be numerous.

The characterization of new theories is progressively done in literature by means of several methods. Recent approaches, such as agile development, agile manufacturing and DT, have been characterized by means of qualitative analyses derived from literature review (Dybå and Dingsøyr, 2008; Liedtka, 2014; Reimann and Schilke, 2011), single and multiple case studies (Dybå and Dingsøyr, 2008; Thienen et al., 2011; Zhang, 2011), surveys (Dybå and Dingsøyr, 2008; Hinds and Lyon, 2011), among others.

One method that allows researchers to perform a deeper qualitative analysis is known as content analysis. It consists of a set of techniques used to analyze communications, such as written texts and verbal speeches, through systematic procedures in order to decode the content of a message (Bardin, 2013). It requires mathematical operations to be performed in order to quantitatively process the analysis. Those operations depend on the characteristics of the target elements that are being analyzed.

One tool that allows the systematization of large amount of information is the design structure matrix (DSM), “a network modeling tool used to represent a system and their interactions”, relating one domain with itself (Eppinger and Browning, 2012). Although it is usually applied for product architecture representation, Eppinger and Browning (2012) propose the use of this tool for several distinct applications, such as organization architecture, process architecture and even the reorganization of the US senate. Another tool that may be useful for dealing with large amount of data is the domain mapping matrix (DMM), which establishes the relationship of two distinct domains.

Other authors in literature have already combined content analysis and matrix-based methods, i.e. DSM and DMM, for other purposes. Hepperle et al. (2011), for example, combine those methods to increase systems understanding in early planning phases by establishing the interrelation of Design-for-X guidelines based on the product characteristics. However, those methods were not previously combined in literature with the purpose of characterizing a new theory or approach. Additionally, the amounts of elements they deal with are not so numerically expressive.

This work is inserted in the context of a wider research project, which intends to integrate DT in the product development process models. As part of this research project, this particular work aims to combine the content analysis method with the use of DSM and DMMs to structure results of analyses composed by numerous elements in order to identify the fundamental ones.

2 Methodology

The hypothetico-deductive approach was applied in order to develop the proposed characterization method. The first proposal of this method was based in the hypothesis that a theory or approach may be characterized by its elements and that some elements may be complex or too numerous for a simple qualitative analysis. Another assumption is the hypothesis that the content analysis method can support a systematic qualitative analysis and that applying DMMs and DSMs may allow the qualitative analysis to be quantitatively processed for numerically expressive elements.

A first iteration, which resulted in a proposal of fundamental elements, was performed. Several tests were executed in attempts to falsify the results. More than twenty iterations were repeatedly performed, improving the method whenever a failed aspect was identified. The method was developed through continuous improvement based on the findings derived from the iterations, which were performed in a single context.

This method was tested and evolved during attempts to characterize the DT approach. This characterization aims to identify what are the fundamental tasks (process oriented elements) of DT, with the goal of further comparing those fundamental tasks to the development process tasks in order to identify where they superpose and where they diverge (Rosa and Rozenfeld, 2016).

The method proposed in this work evolved until tasks that were identified as fundamental by means of this method effectively represented the main intersection of most DT methodologies, covering the most recurrent tasks. This achievement was analyzed by means of experts with large experience in the DT practice.

3 Content analysis

The content analysis is a set of techniques that are combined to extract the core meaning of a textual composition by means of deep understanding its content, what may include inference of implicit information (Bardin, 2013).

Bardin (2013) proposes that the content analysis is composed by three main stages:

- Pre-analysis: In this stage, the researcher analyzes as many sources of information as possible. This pre-analysis aims to clarify what the goals and hypotheses of the content analysis are. It shall aid the researcher on outlining what is the information to be sought. This is where the corpus of analysis is defined and the rules of cutting, categorization and codification are established.
- Material exploration: This second stage covers the effective textual analysis, where the rules of cutting, categorization and codification are in fact applied. During this stage, the thesaurus may be developed based on the thorough analysis of the material that composes the corpus.
- Statistical operations: This stage covers the statistical operations that are performed based on the textual analysis, which are followed by the results' synthesis, selection and interpretation.

The main frame of the method presented in this work is based on the proposal of Bardin (2013) for content analysis. The procedure, already adapted with the DSM and DMM application, is illustrated and explained in section 4.

4 Procedure

The characterization method procedure proposed in this work is represented in Figure 1.

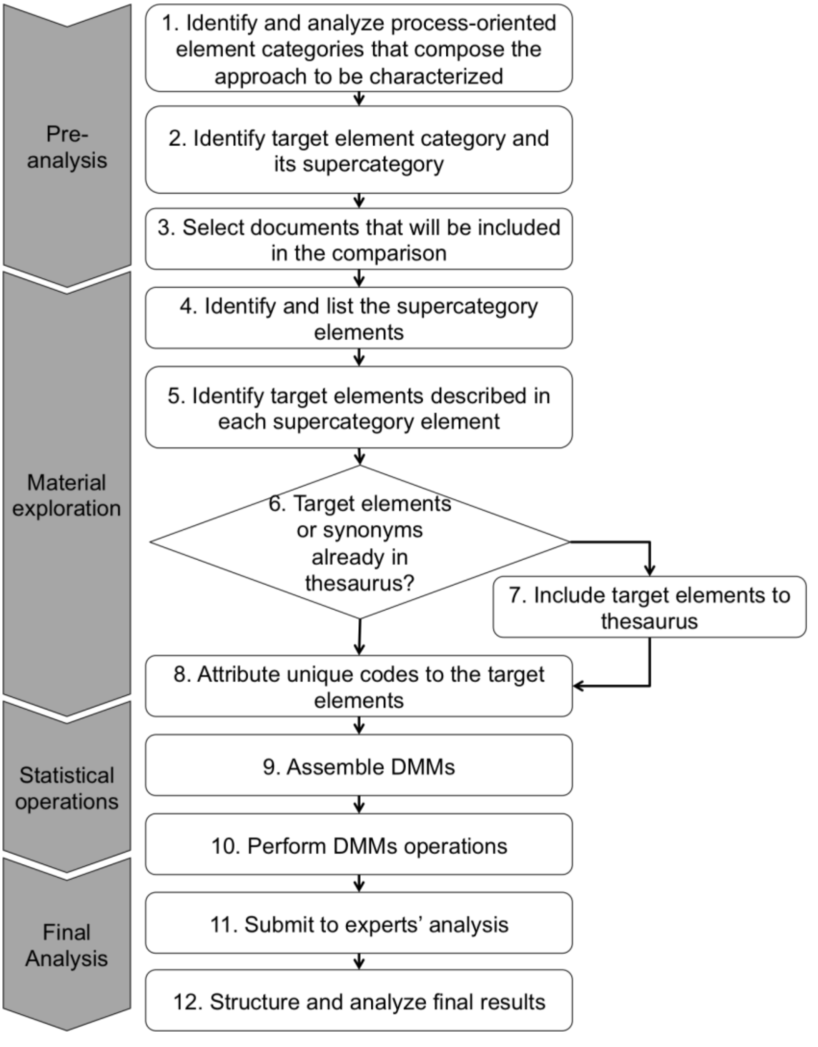

Figure 1. Characterization method procedure

A brief explanation of how each step should be performed is presented in the following topics.

1. Identify and analyze process-oriented element categories that compose the approach to be characterized: Each design approach or theory, such as DT, may be structured by means of element categories, which may be seen as the metadata of that given approach. In this method, it is suggested to structure it in process-oriented element categories. In this step, each element category must be identified, proposing a structure similar to a typology. Those element categories must be structured hierarchically, identifying how they relate to each other. The product development process, for example, could be structured by means of the following element

categories: phase, activities, methods and tools, tasks, good-practices, inputs, deliverables, people and resources (Rosa and Rozenfeld, 2016; Rozenfeld, 2007). DT methodologies, on the other hand, could be structured by means of the following element categories: methodology, stages, methods and tools, guidelines, tasks, resources, people, inputs, deliverables and actions (Rosa and Rozenfeld, 2016).

2. Identify target element category and its supercategory: Depending on the goals of each researcher, one of the element categories must be chosen as a target for comparison. The element category that was chosen as a target is herein after called target element category. The element category that is hierarchically superior to the target element category is hereinafter referred to as supercategory and must also be identified. For example, in this case, it was noticed that DT methodologies are usually presented in the shape of sets of methods, which are described by means of tasks. It was identified that one way to connect DT and the product development process is by means of the tasks (Rosa and Rozenfeld, 2016). In order to characterize what the fundamental tasks of DT are, the element category "task" is to be chosen as target element category, whose supercategory is the element category "method". If the element category is composed by complex elements, it is important to frame the chosen element category properly. For example, a task may be seen as a set of a subject, an event (verb) and an object (deliverable or input). In this particular application, 942 tasks were identified in 184 methods that were presented by 7 methodologies.
3. Select documents that will be included in the comparison: Based on the target element category, prescriptive documents related to the approach to be characterized must be selected. Those documents must contain, at least, the supercategory elements and the target element to be compared. For product, service, or PSS development process, the documents might be process models. For the DT approach, they would be the DT methodologies that are available in literature.
4. Identify and list the supercategory elements: In this step, the analysis is already pre-structured. Then, a thesaurus must be developed in order to guarantee that only unique meanings will be used, avoiding including synonyms that may compromise the analysis. First of all, every supercategory element must be identified in the corpus, extracted and sequenced into a list. For the DT approach case, where "methods" is the supercategory, each method should be listed.
5. Identify target elements described in each supercategory element: Whenever a new supercategory element is identified in the corpus, it is probably accompanied by its description. The proper extracts of the supercategory elements' description must be selected by identifying those that contain elements belonging to the target element category. The elements of those extracts must be identified and selected.
6. Target elements or synonyms already in thesaurus?: This step is part of the analysis explained in the following two steps.
7. Include target elements to thesaurus: If a target element is identified for the first time in the analysis, it must be included in the thesaurus. A similar approach must be performed if a frame of sub-elements composes the target element. In this case, each sub-element that had no synonym identified is included in the thesaurus. This extraction is illustrated in Figure 2.

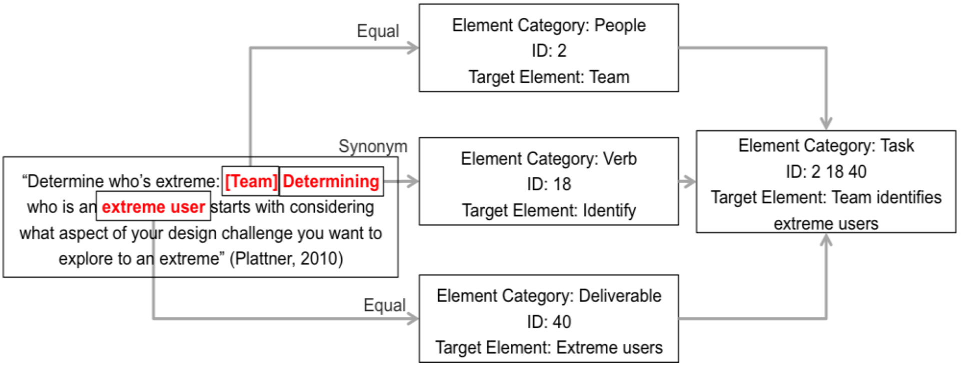

Figure 2. Identification and Codification of the elements of an extract of the method "Extreme Users" proposed by Plattner (2010)

8. Attribute unique codes to the target elements: All target elements that are synonyms in the thesaurus are established under a unique code. If a target element is not composed by a single word, this process is not performed with the target element, but the sub-elements that frame it, i.e., if a target element is composed by given sub-elements, such as a subject, an event and an object, each sub-element is associated to a code in the thesaurus. The final target element is the combination of all sub-element codes. One example of codification is illustrated in Figure 2. This procedure is performed in order to check the recurrence of each target element, avoiding synonyms to be separated. In this particular case, 942 tasks could be allocated in 193 unique identification codes, composing 193 unique tasks.
9. Assemble DMMs: The target elements listed in the thesaurus and the supercategory elements are associated by means of DMMs. For each document in the corpus, a DMM is assembled. Each column of the DMM is associated to a target element code. All target element codes must be included in the DMM and they must appear only in one column. Each row of the DMM is associated to a supercategory element. Only the supercategory elements that appear on the document related to that DMM should be included. For each matrix element (*i*,*j*) of each DMM, it must be identified whether the target element (*j*) and the supercategory element (*i*) are related between themselves, i.e., if that given document cites that target element (*j*) on the supercategory element's (*i*) description. If they are related, the matrix element (*i*,*j*) value is set as 1. If not, it becomes 0. Each DMM would be similar to Figure 3. In our case, the supercategory elements are the methods found in the DT methodologies and the target elements are the tasks that compose those methods. All DMMs must be combined into a complex joint DMM, as shown in Figure 4.

Document X	Target Element 1	Target Element 2	Target Element 3	Target Element 4	Target Element 5	Target Element 6	Target Element 7	...	Target Element N
Supercategory Element 1	1	1	1	0	0	0	0	...	0
Supercategory Element 2	0	0	1	1	1	0	0	...	0
Supercategory Element 3	0	0	0	0	0	1	1	...	0
Supercategory Element 4	0	0	0	0	0	0	0	...	0
Supercategory Element 5	1	0	1	0	0	0	0	...	0
Supercategory Element 6	0	0	0	0	0	0	0	...	0
Supercategory Element 7	0	0	0	0	1	1	1	...	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Supercategory Element M	0	0	0	0	0	0	0	...	0

Figure 3. DMM example

		Target Element 1	Target Element 2	Target Element 3	Target Element 4	Target Element 5	Target Element 6	Target Element 7	Target Element 8	Target Element 9	Target Element 10	Target Element 11	Target Element 12	Target Element 13	...	Target Element M
Document 1	Supercategory Element 1	1	1	1	0	0	0	1	0	0	0	0	0	0	...	0
	Supercategory Element 2	0	0	1	1	1	0	1	1	1	0	0	0	0	...	0
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Supercategory Element N_1	1	0	0	0	0	0	1	1	1	0	0	0	0	...	0
Document 2	Supercategory Element 1	1	1	1	0	0	0	1	1	1	0	0	0	0	...	0
	Supercategory Element 2	0	0	1	1	1	0	1	1	1	0	0	0	0	...	0
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Supercategory Element N_2	1	0	0	0	0	0	1	1	1	0	0	0	0	...	0
.	.	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
.	.	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
.	.	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Document K	Supercategory Element 1	1	1	1	0	0	0	1	1	1	0	0	0	0	...	0
	Supercategory Element 2	0	0	0	0	0	0	0	0	0	0	0	0	0	...	0
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Supercategory Element N_3	0	0	0	0	0	0	1	1	1	0	0	0	0	...	0

Figure 4. Complex joint DMM

10. Perform DMMs operations: To achieve the final results, one mathematical operation must be performed with the complex joint DMM. The DMM must be transposed and multiplied by itself ($[DMM]^T$ x [DMM]). This operation provides a final DSM that

relates each element with the other elements, excluding the supercategory elements of this analysis. The final DSM is similar to Figure 5.

	Target Element 1	Target Element 2	Target Element 3	Target Element 4	Target Element 5	...	Target Element M
Target Element 1	5	3	2	0	1	...	1
Target Element 2	3	7	1	1	1	...	0
Target Element 3	2	1	2	1	0	...	0
Target Element 4	0	1	1	8	4	...	0
Target Element 5	1	1	0	4	5	...	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Target Element M	1	0	0	0	0	...	1

Figure 5. Final DSM illustration

In the main diagonal (green), each element of index (*i*,*i*) represents how many times the target element of code "*i*" appears in all documents that were analyzed, counting each target element just once for each supercategory element. Out of the main diagonal (orange), each matrix element of index (*i*,*j*) illustrates on how many supercategory elements the element of index "*i*" appears related to the target element of index "*j*". In order to identify the fundamental elements, a proper statistical method must be selected based on the characteristics of the performed analysis. For the DT analysis, the fundamental elements were considered those that appear on more than half of the methodologies that were included in the analysis. Techniques such as Bollinger Bands may also be used (Bollinger, 1992). The most recurrent elements according to the statistical analysis are to be considered as the fundamental ones. In this case, the objects to be compared were tasks from different

11. Submit to experts' analysis: It is recommended to submit the final results of this analysis to experts in order to validate the final results. The goal of the experts' analysis is to verify whether target elements that should be considered fundamental were excluded from the analysis or non-fundamental elements were inadvertently included and to validate the content analysis per se, verifying the linguistic validity of the analysis. In this context, people were considered experts when they had a concrete background either on the DT approach, including wide practical application of its techniques, and linguists to assure the linguistic validity of the content analysis. The reasons for why each target element was or was not included must be thoroughly analyzed in order to avoid errors. This analysis shall be done after the researchers analyzed the whole corpora.
12. Structure and analyze final results: Finally, the final results must be structured and analyzed in order to properly communicate the final findings. In the case of this work, 59 fundamental tasks were identified from 193 unique tasks that composed the analysis. One possibility is to structure the results in the shape of a table or to

keep them in the shape of a DSM, what may allow the identification of “chunks” of fundamental elements, i.e. what fundamental elements are usually associated in their supercategory elements. Due to space limitations and since the purpose of this work is to present the method per se, the results of this analysis are not presented in this work.

5 Final discussion

This work showed that matrix-based methods, such as DSM and DMM, are compatible to structuring results of content analyses of corpora composed by numerous elements in order to identify the fundamental ones. This work may be an inspiration on how to perform analyses when large amounts of data need to be handled.

It is important to highlight that the methodology used on the development of this work was the hypothetico-deductive approach, which depends on repetitive attempts to falsify the proposal. Thus, one failed attempt may falsify the method proposed, but hundreds of successful attempts cannot prove its validity for every context. Thus, the experts' analysis was included in the method in order to improve the quality of the results as one qualitative attempt to falsify the proposal on each application. Thus, it restricts this limitation generated by the methodology that was applied.

We believe that the necessity of including experts' analysis to the method may insert a certain bias to the process, since experts may be biased on their perspective about the approach or theory in analysis, which in this case was DT. The authors of this work intend to improve the replicability of this method by better structuring the content analysis with frame analysis and linguistic techniques in order to reduce the need of experts to validate the analysis. This technique shall also be used in the context of analyzing PSS development process models in order to develop it even further.

The method proposed in this work proved to be useful on supporting the characterization of the fundamental tasks of the DT approach based on seven DT methodologies that were previously selected on the corpus definition. However, further tests shall be performed to verify and validate the application of this method in different contexts.

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