APPLYING ENGINEERING DESIGN ONTOLOGY FOR CONTENT ANALYSIS OF TEAM CONCEPTUAL DESIGN ACTIVITY

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ABSTRACT

Studies of design activity have been dominantly reporting on different aspects of the design process, rather than the content of designing. The aim of the presented research has been the development and application of an approach for a fine-grain analysis of the design content communicated between designers during the team conceptual design activities. The proposed approach builds on an engineering design ontology as a foundation for the content categorisation. Two teams have been studied using the protocol analysis method. The coded protocols offered fine-grain descriptions of the content communicated at different points in the design session and enabled comparison of teams' approaches and deriving some generalisable findings. For example, it has been shown that both teams focused primarily on the use of the developed product and the operands within the technical process, in order to generate new technical solutions and initial component design. Moreover, teams exhibit progress from abstract to concrete solutions as the sessions proceeded and focused on the functional requirements towards the end of the sessions.

Keywords: Content analysis, Teamwork, Ontologies, Protocol analysis, Conceptual design

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1 INTRODUCTION

The conceptual design activities are characterised by qualitative and ad hoc decision-making situations (Ziv-Av and Reich, 2005) that significantly impact the subsequent product development phases. Considering that the typical design activities such as idea-generation and design reviews are typically performed as team activities (Sonalkar *et al*., 2013; Toh and Miller, 2015), major design research efforts have been directed at understanding how teams conduct conceptual designing. Due to the primarily verbal nature of team communication in conceptual design (Frankenberger and Auer, 1997; Andreasen *et al*., 2015), investigations of team designing have most often been conducted in the form of concurrent verbal protocol analysis (Kan and Gero, 2017). Three types of subjects can be discerned in existing studies of team communication: topics of team discussions, different aspects of communication as a process and type of communication media used (Kleinsmann, 2006). The protocol coding schemes have primarily been focused on the design process (Wasiak *et al*., 2010), although sharing of design information and knowledge via design communication implies primarily the discussion about the design content (Valkenburg, 2000; Chiu, 2002; as cited in Kleinsmann, 2006). Except for FBS-based studies (see, e.g. Kan and Gero, 2017), concurrent protocol studies have dominantly been reporting on different aspects of the design process (process-oriented), rather than the content of designing.

Dorst and Dijkhuis (1995) argue that in order to obtain a deeper understanding of the designing, at least some aspect of "what is going on in the design activity" should be addressed. Studies have shown that although homogeneous teams are likely to exhibit similar process steps, they can differ significantly in terms of content they manipulate throughout the design activities, e.g. cost-oriented versus market-and-production-oriented teams in the study of Ensici and Badke-Schaub (2011) and focus on technical feasibility presented in teams during concept selection as presented by Toh and Miller (2015).

Cash and Štorga (2015) propose to tackle the multifaceted nature of design by linking the designers' actions (process steps) to the context within which they appear and thus provide a more embracive description of design work. Thus, rather than focusing solely on the design process and investigating the design content in its documented form, additional research efforts need to be directed at concurrent analyses of how the communicated design content changes throughout team design activities. Such efforts would bridge the gap in understanding the role of design content as the context within which new ideas emerge, and decisions are made. Therefore, the focus of the presented research is on the development and application of an approach for a fine-grain analysis of design content communicated between designers during the team conceptual design activities. Here, the fine-grain analysis considers the investigation of micro-level fragments of communication conducted by members of design teams.

As shown later in the paper, the existing content-oriented studies have generally focused on topic analysis and been closely tied to the particularities of the problem that design teams had to solve. The ad-hoc and problem-dependent coding schemes, the diversity in categorising design content and the use of different units and means of analysis hinders direct comparison and generalisation of the previous studies results. To assure the comparability, but also to encompass a wide range of design-related topics, it is proposed to develop a content-analysis approach that builds on an engineering design ontology as a foundation for the content categorisation. Two main research questions have been explored:

- Can a content-focused engineering design ontology be utilised to produce comparable and generalisable fine-grain models of design content communication during team conceptual design activities?
- What kind of insights regarding the design team's approach to generating conceptual solutions for the given design problem can be attained by adopting the content analysis approach based on the utilised engineering design ontology?

2 BACKGROUND: CONTENT-BASED DESIGN RESEARCH

Studies of design teamwork have mainly utilised the protocol coding as a means of empirical investigation of the content handled and communicated by the designers. A brief review of content analysis studies focused primarily on the categorisation of the content into design-related topics and information behaviour is presented within this section.

Huet *et al*. (2007) have studied design review meetings and analysed the emergence and development of various topics, with the goal of understanding information and knowledge loss due to the use of different methods for capturing information transactions. One of the content analysis methodologies that Huet *et al*. (2007) have considered introduces a protocol coding scheme for segmenting and coding of meeting

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transcripts based on topic, information type and artefact type. They conclude that, while time-consuming and inconvenient for practical meeting capture applications, the proposed content analysis method provides a thorough and comprehensive research strategy towards understanding information transactions in the design session. Ensici and Badke-Schaub (2011) analysed multidisciplinary design teams' conversations and concluded that while the communicated design content is problem dependent, teams are likely to exhibit different information behaviour. They have shown this by measuring frequencies of information behaviour categorised into different aspects of design content, such as function, material, production, cost, stakeholders, etc. Dorst and Dijkhuis (1995) analysed the topics that designers dealt with by means of a comprehensive coding scheme consisting of 60 task-specific topic codes. Their conclusions suggest that content analysis can provide insights into the general nature of design processes, primarily in the form of topic-related patterns in information-seeking and embodiment design activities, where more routine-like behaviour is expected.In contrast, hardly any patterns in conceptual design activity have been identified. Moreover, Dorst and Dijkhuis (1995) emphasise that while the protocols based on comprehensive coding schemes are valuable in comparing design processes, they are hard to segment and code due to the varying degrees of interpretation required. Goldschmidt (2014) uses the Linkography methodology to capture the design process and the design content in the form of design moves and links between the moves. The moves represent the process (coded protocol segments), and the links are determined based on the contents of the moves. The resulting linkographs have been particularly valuable in identifying the features of divergent and convergent thinking in design, and shifts between these two modes of thinking (Goldschmidt, 2016).

In addition to studying individual design sessions, there also exist efforts at longitudinal research of design content, where different types of data (intermediary objects) collected throughout design projects are examined. Examples of longitudinal research include the analyses of records of design ideas and rationale (Li and Ramani, 2007), work sampling datasets containing contextual information of individual and team activities in product realisation (Škec *et al*., 2017; Martinec *et al*., 2017) and email messages appearing throughout the design projects (Wasiak *et al*., 2010).

Due to the use of context-dependent coding schemes, most of the reviewed content analysis studies lack generalisation and inter-comparability of results. A similar problem in process-focused research has been tackled by employing an abstract categorisation of notions used to describe designers' actions. It is here argued that the same approach can be applied when analysing design content. For example, Ensici and Badke-Schaub (2011) made a distinction between design content and design issues by explaining that specific (problem-dependent) design issues could be categorised into one or many aspects of the design content. Hence, it is here proposed to separate the design content from the particularities of the given design problem and to develop an approach in which the design content is portrayed independently of the research study context (e.g. design brief, activity type, team size, etc.). Typically, the required categorisation is achieved by employing ontologies, whether the focus is set on the design process (e.g. Sim and Duffy, 2003), on the design content (e.g. Ahmed and Štorga, 2009), or both (e.g. Kan and Gero, 2017). For example, many state-of-the-art protocol studies are based on the function-behaviour-structure (FBS) ontology of design (see, e.g. Kan and Gero, 2017). The FBS ontology, as part of the FBS framework, primarily describes the design as an artefact (concerning requirements, functions, behaviours, structures), while the design process is derived from transitions between the artefact elements. It allows researchers to explore the structuredness, the differences and similarities in design processes across different experimental studies. Nevertheless, Danielescu *et al.* (2012) explain that the FBS framework leads to high-level descriptions of design and that more expressive and flexible descriptions require elements which go beyond these function, behaviour and structure.

Hence, the MOED ontology (Ahmed and Štorga, 2009) has been selected as the foundation for design content categorisation. MOED was developed as a template ontology and can be tailored for a specific application, whereas the concepts within the ontology include design as an artefact and its attributes and the different phases in the product's lifecycle. As such, this taxonomically based design ontology enables comprehensive design content classification and fine-grain segmentation of the team's verbal outputs.

3 EMPIRICAL STUDY

Typically, the content of design activity is investigated based on retrospective protocol analysis (Kan and Gero, 2017, p. 8), since it implies reflective verbalisation of content-related thoughts and the access to the final outputs generated during the experimental activities. Nonetheless, the empirical part of the

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presented research has been designed in the form of concurrent (think-aloud) verbal protocol analysis due to several advantages. Namely, when it comes to design teams, concurrent protocol analysis is a more direct and efficient method, considering that the verbalised communication represents an authentic output of designers' real-time thinking (Goldschmidt, 2014). In addition, the concurrent analysis outperforms retrospective analysis in capturing comprehensive insights into the decision-making process (Kuusela and Paul, 2000).

3.1 Participants and design task

Two teams consisting of three members have been selected for the empirical study. Participants were chosen among third- and fourth-year students of mechanical engineering, who have experience in project-based courses which included planning, conceptual and detail design, and prototype assembly and testing. Additionally, the students have been enrolled in courses such as Product Development, Design Methods and Advanced Computer-Aided Design (CAD) and Global Product Realisation. Such background provided students experience in both working in teams and developing conceptual solutions. The two teams are regarded homogeneous due to the students' background, whereas no cultural or gender issues have been taken into consideration when composing the teams.

The experiment was designed in the form of a 60-minute conceptual design session during which teams had to propose concepts for the given design problem. The design brief introduced the problem and listed several design requirements and constraints. In short, the task was to come up with a concept of a portable key-organising solution to help users deal with everyday key usage. Since keys are artefacts used on a daily basis, the participants should be able to understand the problem without the support of any external information gathering methods or tools (computer with internet connection, experts, books, etc.). Nevertheless, the problem can be characterised as ill-defined, as it stimulated the teams to explore the problem space and develop new requirements and constraints. The concepts should have been in the supported with sketches, including the approximate dimensions, materials selection and usage scenarios. Participants were encouraged to work on the development of multiple concepts but to indicate the solution which they selected to be further developed.

Both teams were left alone in a room equipped with the recording equipment: two cameras recording video, one voice recorder for audio, and one digital notebook for the recording of sketching. Design brief was given on a wall-mounted screen and could thus be consulted at any time. The screen also included a timer, so they would not have to keep track of time. Teams did not receive any information on the design task until they were left in the room and until the brief appeared on the screen.

3.2 Coding scheme

The coding scheme for design content analysis was developed based on the MOED ontology by Ahmed and Štorga (2009). Initially, during the process of familiarisation with the recorded dataset, the overall MOED ontology was considered. Eventually, some of the ontology items and levels have been rejected due to their irrelevance within the context of the experiment sessions (e.g. the item Technical Document or the elaborated types of Technical Functions). On the other hand, the Engineering Component item has been divided into two categories: one related to the engineering component as part of the product (technical system) being designed, and the other related to the components whose state-changes due to the effects provided by the products (see e.g. Hubka and Eder, 1992). Moreover, the item Technical Solution was added to include the abstracted representations of objects which could not be adequately captured using the MOED ontology. These changes provided a balance between scope and reliability which is needed to ensure the practicability of the coding scheme and the validity of the results (Wasiak *et al*., 2010). Further and more detailed categorisation has been omitted due to the ontology scope and to maintain the generalisation of the content-codes. The complete coding scheme and the definitions of individual content codes are presented in Table 1.

3.3 Protocol coding

Before the adapted coding scheme could be applied, the recorded experiment sessions had to be transcribed. The transcripts provided information on who was speaking and what was said. Protocol coding then included parsing of the protocols into small segments of speech (determining the start and the end of protocol segments) and assigning each segment a single content code presented in Table 1. An example of a segmented and coded transcript can be seen in Table 2. Coding was performed by a

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novice primary coder and was then proofed by a secondary coder, who has experience in utilising the MOED ontology. Prior to the protocol coding, the primary coder was familiarised with the data set and trained in applying the MOED ontology.

Table 1. Coding scheme used to capture the design content discussed during team conceptual design activity.

Content codes: 1st level	2nd level	Definitions adopted from Ahmed and Štorga (2009)	Code label
Object	Material	A tangible substance that goes into the makeup of a technical product	O1
	Engineering Component - Product	Individual part with specific task in realization of a technical function, and of which an engineering assembly (product) is made up	O2
	Engineering Component - Operand	Individual part whose state changes due to the effects provided by the developed product	O3
	Engineering Assembly	A group of engineering components that fit together to form a self-contained structural and functional unit of the product	O4
	Form Feature	An individual part of and engineering component's form	O5
	Technical Solution	A solution description on the highest level of abstraction that partially satisfies the functional requirements	O6
	Technical Product Family	A collection of different variants of the same kind of technical product	O7
	Human Agent	Someone that could take the role of an operand or operator in the different product life cycle phases of the product life cycle process	O8
Process	Planning	An intentional process of drawing up the design issues and plans for development of a technical product	P1
	Designing	An intentional process of working out the technical product characteristics based on the required technical function, and by solving design issues resulting with the full description of a technical product in technical documentations	P2
	Manufacturing	An intentional process of making engineering components from raw material and assembling them together into engineering assemblies of technical product	P3
	Distributing	An intentional process of transporting, selling and installing technical product from a producer to a customer	P4
	Using	An intentional process of putting technical product into service and make it work for a particular purpose of fulfilling its technical function	P5
	Disposing	An intentional process of processing used technical product for use in creating new technical product	P6
Attribute	Technical Function	A what technical product is manufactured and used for	A1
	Form	The spatial characteristic of technical product defined by its surface area	A2
	Dimension	The magnitude of a technical product in a particular direction	A3
	Tolerance	A permissible difference of a nominal dimension of a technical product	A4
	Manufacturing Method	A particular method applied in fabricating and assembling engineering component or engineering assembly	A5
	Surface Texture	Totality of the micro-geometrical incorrectness of an engineering component's surface	A6
	Structural Characteristic	A manner of product designing of technical product and the arrangement of its parts	A7
	Spatial Characteristic	A characteristic resulting from the arrangement of technical product's parts in relation to each other and to the whole	A8
	Functional Requirement	Required behaviour of technical product under specified conditions	A9
	Life Cycle Systems Requirement	Attribute of technical product required by different life cycle systems	A10
	Environmental Requirement	Attribute of technical product required by totality of surrounding conditions of its physical environment during product life cycle process	A11
Other	-	Verbal acts that cannot be categorised using any of the above codes	X

The boundaries of the segments highly depend on the content being discussed by the team members. Hence, both the segments and the content codes are based on the coder's critical judgment. All segments without verbal acts were not coded and represent periods without verbal team communication. When compared to some of the standard approaches to parsing protocols, such as time-based, sentence-based or turn taking-based segmentation, the application of the proposed coding scheme increases the protocol granularity. In most cases, a longer sentence was fragmented into several segments, which were assigned to different codes. Segments related to part of the sentences that do not correspond to the ontology codes (e.g. conjunctions) have been coded as other (X). As shown in Table 2, the segments often lasted less than a second. Because of this, the resulting protocols exhibit a level of detail which is higher even when compared to the use of design moves in linkographs, which usually last for a few seconds and are the most common unit of analysis used in design thinking research (Goldschmidt, 2014, p.30).

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Table 2. An excerpt of segmenting and coding the experiment transcripts.

Time	Participant	Transcript	Code
38:01.3 – 38:02.2	P2	Take into account that	Other (X)
38:02.6 – 38:03.4		this	Engineering Assembly (O4)
38:03.4 – 38:04.0		is connected to	Functional Requirement (A9)
38:04.0 – 38:04.8		this thing beneath which	Engineering Assembly (O4)
38:04.8 – 38:05.5		holds	Functional Requirement (A9)
38:05.5 – 38:05.9		the key	Engineering Component - Operand (O3)
38:05.9 – 38:06.6		because you have to	Other (X)
38:06.6 – 38:06.9		connect	Functional Requirement (A10)
38:06.9 – 38:07.3		this	Engineering Component - Product (O2)
38:07.3 – 38:08.0		to the key.	Engineering Component - Operand (O3)
38:08.0 – 38:10.5	P3	Definitely yes. So, we can say that	Other (X)
38:10.5 – 38:11.0		all of this…	Engineering Assembly (O4)
38:11.0 – 38:11.6		That our	Other (X)
38:11.6 – 38:12.1		whole key	Engineering Component - Operand (O3)
38:12.1 – 38:12.3		is within	Other (X)
38:12.3 – 38:13.4		some kind of case.	Engineering Component - Product (O2)

4 RESULTS AND DISCUSSION

4.1 Overall distribution of design content codes

In total 2624 segments have been identified for Team 1 and 3286 for Team 2. The high number of segments indicates that utilising the MOED-based coding scheme exhibits a considerably higher granularity representation of the design process than, for example, the use of the FBS coding scheme (e.g. 400-1500 segments for a 60-minute session according to Gero and Song, 2017). The higher number of segments is primarily the result of a variety of codes in the coding scheme and due to the fact that team members often referred to multiple aspects of design content during a single verbalisation. Nevertheless, the majority of these segments have been assigned with the "Other" content code, meaning that the concerned fractions of sentences could not have been categorised using any of the content-related codes.

As for the first level of the MOED ontology codes, the most have been assigned with the "Object" codes (680 segments for Team 1 and 1034 segments for Team 2), followed by the "Attribute" codes (475 for Team 1 and 622 for Team 2) and the "Process" codes (154 segments for Team 1 and 233 segments for Team 2). Since each segment has a certain duration, the distribution of codes can also be analysed based on their total timeshares. Hence, most time for both teams was spent on "Other" codes (59.6% for Team 1 and 57.5% for Team 2). As for the MOED content codes, the most time was spent on "Object" codes (18.19% for Team 1 and 19.8% for Team 2), followed by "Attribute" codes (16.0% for Team 1 and 15.3% for Team 2) and "Process" codes (5.4% for Team 1 and 6.7% for Team 2). The time and frequency distributions for all coded categories are presented in Table 3.

When discussing objects, both teams focused primarily on engineering components (both product and operand) and technical solutions. As for the process, teams have addressed mainly the product use phase. When compared to a study of design activities lasting six hours by Stempfle and Badke-Schaub (2002), the presented one-hour design task exhibits a significantly lower amount of process planning segments. Finally, most of the attribute-related communication was related to functional requirements, followed by dimensions and structural and spatial characteristics. Such content distribution reveals a direct effect of the given design task to the teams' focus on particular aspects of design.

Namely, teams directed a substantial amount of content-related communication to discuss the engineering components as operands within the technical process (Hubka and Eder, 1992). Since the design task was the development of a key organising solution, it was inevitable for both teams to discuss keys in many shapes and forms. The conceptual nature of the given design task is also reflected in teams' focus on individual engineering components rather than assemblies or product families. Similarly, regarding the process-related codes, both teams concentrated primarily on using the product, with little considerations for the other product lifecycle phases. The focus on using the product can also be deduced within the study by Ensici and Badke-Schaub (2011). Moreover, conceptual design assumes reciprocating decomposition of design problems and the exploration of possible solutions before a final concept is proposed (Liikkanen and Perttula, 2009). Such approach is particularly the case with ill-defined problems, as designers progressively and iteratively discover, structure and address the newly

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emerged requirements (Cross, 2001; Wynn and Eckert, 2017), which is here reflected in the high proportion of functional requirements-related discussion.

Table 3. Distribution of coded segments based on their duration and frequency.

Content codes:		**Time distribution:**		**Frequency distribution:**	
1st level	**2nd level**	**Team 1**	**Team 2**	**Team 1**	**Team 2**
Object	Material	0.9 %	0.3 %	1.2 %	0.3 %
	Engineering Component - Product	7.4 %	7.6 %	10.6 %	11.1 %
	Engineering Component - Operand	4.2 %	4.7 %	7.3 %	8.9 %
	Engineering Assembly	0.8 %	2.3 %	1.0 %	5.0 %
	Form Feature	1.1 %	1.7 %	1.5 %	2.3 %
	Technical Solution	3.2 %	3.1 %	3.5 %	3.7 %
	Technical Product Family	0.4 %	0.0 %	0.5 %	0.0 %
	Human Agent	0.2 %	0.1 %	0.3 %	0.2 %
	Total Object	**18.2 %**	**19.8 %**	**25.9 %**	**31.5 %**
Process	Planning	0.6 %	0.1 %	0.2 %	0.1 %
	Designing	0.1 %	0.1 %	0.2 %	0.1 %
	Manufacturing	0.1 %	0.0 %	0.2 %	0.1 %
	Distributing	0.2 %	0.0 %	0.2 %	0.0 %
	Using	4.4 %	6.5 %	5.1 %	6.8 %
	Disposing	0.0 %	0.0 %	0.0 %	0.0 %
	Total Process:	**5.4 %**	**6.7 %**	**5.9 %**	**7.1 %**
Attribute	Technical Function	0.1 %	0.0 %	0.1 %	0.1 %
	Form	0.7 %	0.9 %	0.8 %	1.3 %
	Dimension	5.4 %	1.3 %	4.5 %	1.7 %
	Tolerance	0.0 %	0.0 %	0.0 %	0.0 %
	Manufacturing Method	0.1 %	0.6 %	0.2 %	0.8 %
	Surface Texture	0.1 %	0.2 %	0.2 %	0.3 %
	Structural Characteristic	2.2 %	1.8 %	2.6 %	2.2 %
	Spatial Characteristic	2.1 %	0.9 %	3.7 %	1.5 %
	Functional Requirement	4.8 %	8.8 %	5.0 %	9.7 %
	Life Cycle Systems Requirement	1.2 %	1.5 %	0.8 %	1.3 %
	Environmental Requirement	0.1 %	0.0 %	0.2 %	0.0 %
	Total Attribute:	**16.8 %**	**16.0 %**	**18.1 %**	**18.9 %**
Other		59.6 %	57.5 %	50.1 %	42.5 %

4.2 Distribution of design content codes throughout the activity

Since the captured protocols are structured as time series data, it is possible to analyse also the change in focus on different aspects of design content over the course of the design activity. For this purpose, a moving average (windowing) approach has been applied on coded protocols (see, e.g. Pourmohamadi and Gero, 2011), as it provides a qualitative overview of the change in proportions of highly granular data. The width of the sample window covers a fixed number of session protocol segments, which was set here at 10% of the total number of segments. Hence, for each protocol segment, the average proportions of content codes have been calculated by taking into consideration 10% of segments appearing before the analysed protocol segment. The window is moved from the start to the end of the session, one segment at a time. The moving average graphs have been generated for three content categories: object, process and attributes (Figure 1). These visualisations provide insight into design content of interest at different points of the experiment sessions.

No apparent patterns are evident within the graphs, which is aligned with the findings of Dorst and Dijkhuis (1995) for the conceptual design activities. However, several interesting insights on the change of design content distribution have been derived. First, the technical solutions (solution description on the highest level of abstraction) were most intensively discussed at the beginning of the sessions, while the product's engineering components and assemblies were mostly addressed towards the end of the sessions. It can be argued that teams utilise high levels of abstraction early in the activity to cope with the initial functional requirements (see, e.g. Yang, 2009; Andreasen *et al*., 2015 p. 109), thus advancing from abstract ideas to a concrete solution. Accordingly, the peaks in the engineering component- and assembly-related content codes are followed by intensive communication of dimension and form content. Such sequences can be explained as shifting from abstract concepts to concrete product definition (Andreasen *et al*., 2015 p. 109). Second, functional requirements have continuously been discussed throughout both sessions. The focus on requirements is particularly evident towards the end of

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the session when convergent actions are more likely to appear (Goldschmidt, 2016), resulting in evaluation of solutions against the given and the emerged functional requirements.

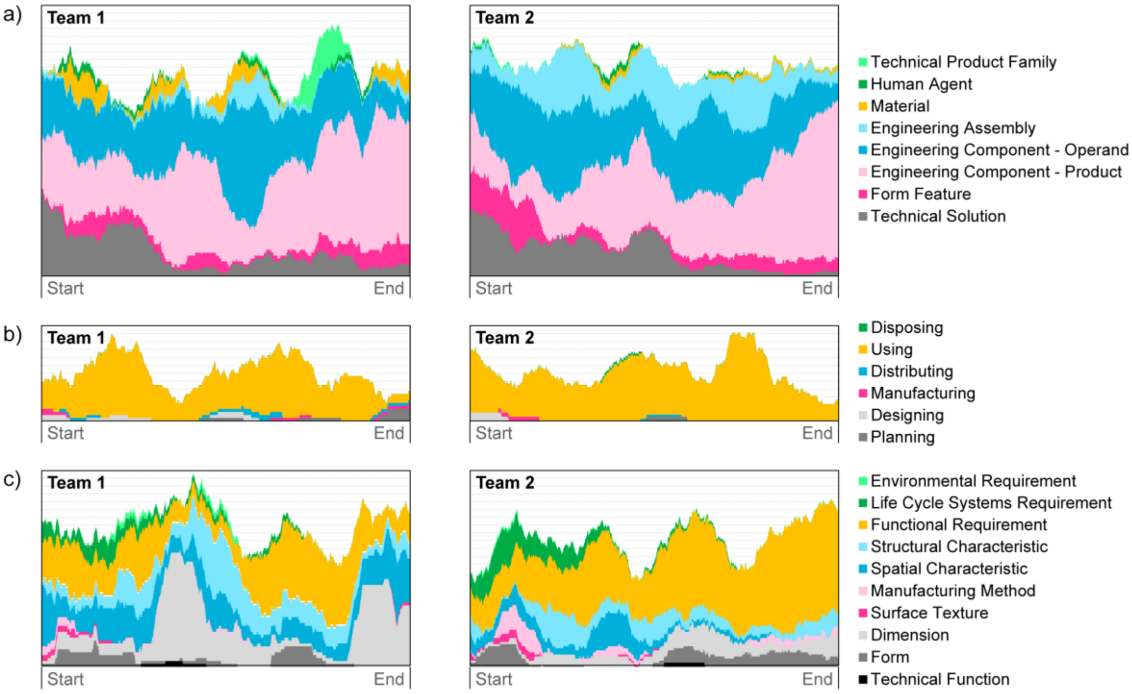

Figure 1. Moving average distribution of (a) Object, (b) Process and (c) Attribute related codes during the experiment sessions of the two teams.

Third insight concerns the dynamics of the discussion on the operands in the technical process (primarily the keys). According to Figure 1, the discussion about the Engineering Component - Operand is present throughout the complete duration of the sessions, peaking at about 30% of discussion for both teams. These peaks can be assigned to the episodes where teams directly explore different types (shapes and sizes) of keys. Team 1 focuses intensively on the operands in the middle of the session, while Team 2 does that at the beginning of the session. Interestingly, the peak in discussing the dimensions in Team 1 is followed by a spike in discussing the operands, which is again followed by a spike in discussing functional requirements. The approach of Team 2, which included early introduction of keys as operands in the process, resulted in a higher overall distribution of codes related to functional requirements, structural and spatial characteristics and manufacturing methods, and less focus on dimensions.

4.3 Limitations and future work

There are several limitations to the proposed approach. Firstly, the coding process is extremely resource-intensive, mainly because of an extensive coding scheme (26 different low-level codes, see, e.g. Dorst and Dijkhuis (1995) for a similar experience) and the fine granularity of the protocol segments (single sentences have often been fragmented into several segments). In the future, the coding scheme can be tailored to involve only the design content of interest within a particular team activity, hence reducing the overall number of codes. Secondly, since the order of the coded segments is language-dependent, there is no substantial benefit of performing sequence analysis. It is expected that the results would significantly change for different speakers and different languages. Therefore, only the distribution-based analysis of content codes has been performed. Future work could be directed at defining rules of sequencing different content codes for the cases when sentences are fragmented into several segments, thus avoiding the dependency on language or one's way of vocal expression. Thirdly, the fine-granularity and the use of a comprehensive design ontology hinders direct comparison with other studies within the design research and the complete validation of the findings. Mapping of higher-level coding schemes should facilitate the comparison and completion of the results. For example, the preliminary inter-study comparison by mapping of the FBS (Kan and Gero, 2017) and P-maps (Danielescu et al., 2012) coding schemes suggest similarity in teams' foci on structure (FBS) and artefact (P-maps). Finally, the design ontology-based protocol coding scheme could be utilised as support in examining the effects of different types of methods and tools used in team conceptual design activities. For example, the

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protocols could be used to explore teams' foci on different design ontology categories throughout design activities and identify the desirable patterns of team behaviour.

5 CONCLUSION

Based on the presented analysis of empirical data and discussion of the results, both research questions can be addressed. It can be argued that a templated engineering design ontology can be tailored and used to analyse different aspects of design content communicated during team conceptual design activities. Moreover, the presented study shows that the protocol analysis using an ontology-based coding scheme provides fine-grain descriptions of the content of designing, which can be employed to make a comparison of teams' approaches and to derive some generalisable findings. For example, the protocol analysis shows that both teams focused primarily on the use of the developed product and the operands within the technical process, in order to generate new technical solutions and initial component design. The described foci are aligned with what are assumed to be the main aspects of design content communicated in the conceptual design phase. Although mentioned, the issues such as tolerances, manufacturing and assembly and are all expected to be adequately addressed during the embodiment and detail design phases. The dynamic distribution of design content codes reveals additional insights regarding the design process, such as the change from abstract to concrete solutions as the sessions proceed and focus on the functional requirements towards the end of the sessions. It can be concluded that insights on the team processes regarding any of the content codes can be attained using temporal analysis (e.g. the moving-window as shown in Pourmohamadi and Gero, 2011) of the proposed protocol coding approach. Particularly, the concurrent change in several content codes can be investigated in order to gain richer insights on how the focus on different ontological categories varies throughout the session, thus revealing the various strategies employed by the teams.

The presented approach can provide new insights into the understanding of design, especially the team conceptual design activities. The need for the increase in understanding of conceptual design is reflected in lack of adequate computer-aided support within the conceptual design phase and human-computer interfaces which do not consider the nature of the designing (Vuletic et al., 2018). Proper models of the actual design processes have thus become essential for understanding designers and developing tools that could assist them in designing (Goldschmidt, 2014), specifically, design teams in formulating design problems and providing solutions to these problems throughout the conceptual design phase.

Additionally, the study can also be considered as a first step in testing the appropriateness of a design ontology as a means for automatic protocol coding of engineering design activity. For example, automatised coding could be performed by parsing transcripts based on the predefined ontology codes and the related vocabularies.

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