Identifying Indicators for the Use of Virtual Prototypes in Distributed Design Activities

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Abstract. This paper presents an approach to identify and validate indicators for the use of virtual prototypes (VPs) during distributed design activities. Identification of indicators is based on various data collection methods (interview, observational methods, literature review), whereas their validation and usage are based on the protocol analysis method. Using the approach, four indicators are proposed for a design review activity context. These indicators describe both the individual and collaborative use of the VP. To further delineate collaborative use, indicators distinguish personal and shared viewpoints, providing insights into synchronous collaboration. The implementation of the proposed approach and the four identified indicators were demonstrated on a design review session. The preliminary results show that, in a distributed design review activity, team members spend a small fraction of the time viewing the VP. On a team level, about half of that time was spent viewing the VP individually, while another half of time was spent working simultaneously (either synchronously or asynchronously) in pairs, triplets or four-members. However, this distribution varies among team members. Furthermore, team members utilised both personal and shared viewpoints, again varying among team members. Finally, instances of using the VP were usually brief but occurred throughout the whole session. Based on the conducted study, it can be argued that the design review involves continuous use of the VP throughout the session, either individually or with others (sharing the view or not). The proposed approach, indicators and preliminary results provide new insights for practitioners who develop tools for VP use, design teams that want to improve their efficiency in using VPs, and scholars that study the collaboration within distributed design activities.

Keywords: Distributed Team, Distributed Design Activities, Collaboration indicators, Virtual Prototype (VP), Collaborative CAD
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1 INTRODUCTION

Design teams use prototypes – artifacts that approximate a feature of a product, service, or system [24] – to communicate with stakeholders, identify design issues, learn from failures, make decisions, etc. [22]. In order to reduce the time and costs needed for building and testing physical prototypes, development organisations make use of virtual models called virtual prototypes (VPs) for testing and evaluating specific characteristics of products and processes within a computational environment [7]. Virtual prototyping can be found across different domains, from new product development where it assists different activities, including conceptual and detail design [6,21,31], production planning [15,34] and user interaction [11], to the medical field where it supports surgical training and planning by means of virtual organs [7,29].

While researchers have identified many different contexts of using the VPs [8], they can be categorised into activities where VP use is focused on building and editing the VP and activities focused on viewing the VP. The most common examples of the first type of activities would be the creation and refinement of computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE) models used for describing and analysing products and processes throughout the development phases. On the other hand, the use of VPs is manifested mainly as viewing it in order to make decisions and plan the subsequent development activities. For example, this is when CAD or CAE models are reviewed and evaluated by different stakeholders to decide on the next steps.

The benefits of using VPs are even more emphasised in distributed teams – a common team setting in today’s development organisations [28] – since all the members have access to an up-to-date version of the prototype. Due to the central role of virtual prototyping in the design process, distributed design teams must strive towards efficient and purposeful use of VPs throughout the collaborative design activities. This is true for both the personal and shared views of VPs in distributed design meetings. Hence, in order to better support collaborative and distributed designing, it is important to better understand how VPs are utilised by different team members (TMs) when they meet in virtual environments. Thus far, researchers have been more focused on supporting the individual aspects of virtual prototyping and providing designers with methods or tools for the creation and modification of VPs, rather than understanding of whether and how they can facilitate communication (boundary object). Nevertheless, studies of collaborative design activities (see, e.g. [5,30]) have shown that the discussion, interpretation and shared understanding of design entities (which also includes VPs) constitute a large portion of design meetings and should be given appropriate attention. While some computer-aided design (CAD) tools already support the transition between personal and shared views of VPs (e.g., synchronous collaborative CAD tool such as Onshape [23]), none of the researchers has focused on the prototype’s use dynamics throughout design sessions, whereas the frequency of these transitions and the dynamics of their occurrence remains unclear.

One particular type of collaborative activity that makes large use of prototype viewing are the design reviews [18] - inspection periods in which the team has to understand the design intent, validate requirements and resolve design issues [14]. During these periods, design teams use various prototypes to explain ideas and receive feedback from other TMs to iterate and improve the design [18]. Through these iteration cycles, design teams quickly develop new versions of the product and gain knowledge on the solutions that work. Hence, prototypes are a crucial component of design reviews as they provide the ability to have similar mental models of a design within the review team [18]. While both physical and virtual prototypes can be used during these reviews, the latter is far more flexible in supporting more rapid testing at a lower cost [4]. As such, VPs represent the main boundary objects of design review meetings [19].

The limited understanding of VP use in distributed design activities might delay the implementation of new methodologies and tools since not all aspects of “use” have been considered. This study aims to prompt virtual prototyping researchers to take into account all relevant indicators of VP use in distributed design activities and align their methods and tools accordingly. Such a goal is grounded on the assumption that if relevant indicators of VP use are considered, more inclusive methods and tools can be developed to support designers in creating products with a lower number of design failures in a more rapid manner. The study thus introduces an approach for the identification and validation of indicators relevant to the use of VPs in distributed design activities.

The following two research questions have been addressed:

- How should indicators relevant for the use of virtual prototypes in distributed design activities be identified and validated?
- How can these indicators be applied to study the use of VPs in distributed design activities?

The utilisation of the proposed approach is demonstrated in a case of distributed design review activity, in which members of a design team review VPs by means of personal and shared views. Although the case study has been contextualised by focusing on the reviewing aspects of designing, the approach is conceptualised as applicable for any type of distributed activity involving VPs. Hence, the goal of the case study results is not generalisation, but rather the validation of the approach.

The remaining of the paper is structured as follows. Section 2 gives an overview of the related work. Section 3 presents the approach to identify the indicators for analysing the VP use. Section 4 utilises the proposed approach and identifies four indicators in a design review session. Section 5 presents the strengths and weaknesses of the both the proposed approach and the identified indicators. Finally, Section 6 concludes the paper.

2 RELATED WORK

In product development, a common virtual prototyping technique involves the use of CAD tools. These tools enable quick creation and editing of VPs and support stakeholders throughout the product development process. The recent proliferation of collaborative CAD tools has a great potential to support distributed design teams with an up-to-date version of VP and enable parallel use for more than one team member. Hence, the first part of the related work includes a review of collaborative CAD (Section 2.1). Furthermore, given the focus of this paper on developing indicators for viewing the VP in a design review context, an overview of the previous work also includes studies related to this particular type of VP use. However, as previous work of using VPs in this context is scarce, this subsection also reflects on studies related to physical prototypes (Section 2.2).

2.1 Collaborative CAD: VP Use Indicators

Designers have collaborated in CAD since its inception, primarily by employing the top-down modelling approach and dividing complex models into sub-assemblies and components that multiple individuals could handle themselves [26]. Whereas such an approach has proven to be efficient when it comes to CAD modelling, the asynchronous tools used in such an approach do not allow real-time collaboration for distant TMs, which makes the overall design process fragmented [10]. In addition, the asynchronous tools support individuals to create or modify CAD models (VPs) that have been clearly assigned to them but fail to support collaborative activities such as the design review, which also requires a shared view of the model (VP).

The need to solve these drawbacks, coupled with the maturity of cloud-based technology, has shifted focus towards the development and implementation of synchronous CAD systems that allow real-time collaboration. With a number of new cloud-based CAD tools introduced into the market, it is now feasible for design teams to simultaneously manipulate and modify VPs from their own workstations [10].

The increasing acceptance of collaborative (multi-user) CAD tools and synchronous CAD platforms has been followed with preliminary studies of its efficacy compared to traditional, single-user CAD systems. For example, one of these studies [10] found that multi-user CAD increases TM communication and awareness of TMs' activities. Another study [25], which contrasted single CAD users and pairs of designers working in CAD collaboratively, noted that pairs expressed more positive emotions, which might reflect higher user satisfaction. Nevertheless, the same preliminary analysis [25] suggests that collaborative pairs were slower than single CAD users, which may be attributed to the model-tree scanning used to seek awareness of TMs' work.

Multi-user CAD raises the question of how many TMs should work together on the same VPs. A study addressed this question by investigating teams of different sizes and found out that while larger teams needed more time to model simple parts, they also exhibited a higher quality of the final models [33] - hence the optimal number of users probably depends on the VP complexity. They also add that due to the nature of multi-user CAD modelling, TMs can learn from each other's modelling techniques [33]. An analysis of TMs' emotions in collaborative CAD has highlighted that a chat section in such systems can be highly emotion-evoking compared to single user environment in which antecedent events of emotions were related to the graphics area [35]. This finding highlights the important role that other communication channels, other than the shared view itself, can have on satisfaction, creativity, and performance. The importance of communication during designing in collaborative CAD has also been emphasised by other studies, e.g. [32], concluding that shared mental models coupled with effective communication can significantly increase performance in producing CAD assemblies.

A wide range of indicators and measures of VP usage is used in the aforementioned studies, including the exhibited emotions and their frequencies, cursor positions, menu access and use of different regions within the collaborative CAD environment, number of changes and spatial manipulation of VPs [25,35], frustration caused by either communication, software or TMs, awareness of other TMs activities [10], number of features created in a particular time frame [33], points awarded per minute [32], and other. Nevertheless, additional studies are needed to explore different use cases other than 3D modelling in collaborative CAD, and how they affect shared understanding in distributed teams (design reviews in particular).

2.2 Use of Prototypes for Viewing: A Design Review Context

During design reviews, teams benefit from both personal and shared views of the prototype [2,9]. Personal viewing of a prototype provides an opportunity for team members to personalise the viewpoint and hence supports their understanding of the prototype [1]. Indeed, Groen et al. [13] showed that, in a co-located educational environment, all the reviewers interact with the physical prototype to understand and evaluate the design. However, the prototypes' sturdiness and functionality affected this individual interaction and thus the review process, as more developed prototypes facilitated more constructive feedback and decreased power relations between the designer and the reviewer [13]. Hence, individual interactions with prototypes facilitate team members' contribution to team activities [2].

On the other hand, shared views help TMs in developing shared understanding [9], generating alternatives [2], and problem-solving [9]. While focusing on the prototype during reviews supports the team agreement on the issues discovered by individuals [9], the reviewers also make use of other types of documents (e.g., analysis reports, requirements lists, etc.) that might help them during the review. Namely, the simultaneous use of a VP with additional documents supports engagement and knowledge exchange among reviewers [9]. Hence, in distributed design reviews, TMs change their views between the personal view of VPs, team (shared) view of VPs, and other documents (e.g., list of requirements).

3 APPROACH TO IDENTIFY INDICATORS FOR ANALYSING THE USE OF VIRTUAL PROTOTYPES

This section describes the approach for identifying the indicators of VP use during distributed design activities (Figure 1). These indicators might serve as a proxy for understanding the use of VPs during such type of distributed collaborative activities.

The first step is to review the existing literature for possible indicators. After that, a collaborative design activity should be captured in terms of recording each TM's screen as well as the verbal conversation among them. These recordings should be used as the main data for validating but also for using the indicators. After conducting the design activity, a qualitative data collection method should be used (e.g., semi-structured interviews, focus groups) to get additional insights into the nature of using VPs. Together with the findings from existing literature, this qualitative data should be used as a resource for identifying the indicators. Based on the proposed description of the identified indicator, the researcher develops a procedure to validate its use. This procedure should consist of developing a coding scheme that will be used to segment the captured screen and conversation recordings and an analysis approach that will be used for data processing.

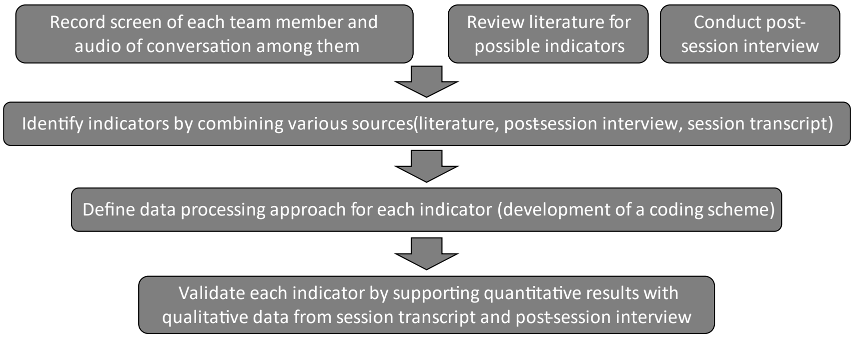

Figure 1: Approach to identify indicators for analysing the use of VPs.

Based on these quantitative results, the proposed indicators can be validated by analysing the recordings using methods such as protocol analysis. Protocol analysis is commonly used in the design field to analyse design sessions [3,20] and usually consists of defining the data to be analysed and an appropriate coding scheme for segmenting and coding the data [27]. As the data consist of more than one recording (e.g., several screens due to distributed nature of these activities), the first validation step is to synchronise them using video editing software (e.g., Adobe Premiere) or video annotation software (e.g., ELAN). After that, one or more independent coders annotate the video according to the predefined coding scheme, using the video annotation software (e.g., ELAN). To get familiar with the session context, coders usually watch recordings several times before annotating. Depending on the type of the codes (e.g., if they depend on semantic information), some indicators might require that two coders reach a certain level of agreement while coding the data. This coder reliability can be calculated using methods such as Cohen's Kappa. Although this process is laborious due to the manual annotation, it could later be automated by incorporating automatic segmentation algorithms, which would make the approach adaptable to larger sample sizes. After the segmentation and coding, the data is processed according to the analysis approach defined in the earlier steps and compared to the qualitative findings in order to validate the proposed indicators. This consolidation of quantitative data with qualitative findings is common in the design field (see, e.g. [12,17]) and represents an important step toward corroborating the quantitative findings and validating the proposed indicators.

4 IDENTIFYING INDICATORS TO ANALYSE THE USE OF VP IN A DESIGN REVIEW SESSION

To showcase the implementation of the proposed approach, this section develops indicators to analyse the use of a VP in a design review session. More specifically, Section 4.1. describes the case used to identify and develop the indicators, whereas Section 4.2. describes in detail the four indicators of VP use, following the procedure depicted in Figure 1.

4.1 Case Description

The studied case consists of a design review session, conducted as a part of an international design course in which an eight-member team has developed a solution for an industry partner. More specifically, two students from each of the four universities from Croatia, Italy, Slovenia, and Austria worked in a semester-long course to develop a solution for reusing the water from the rinsing cycle in washing machines. The final solution included a detailed 3D model, technical assembly drawings, and a bill of materials. During the course, a teaching assistant supported the team's work, primarily in management activities (monitoring the design process, managing conflicts, etc.). Moreover, the two industrial partners that proposed the task, Electrolux (www.electrolux.com/) and Elettrotecnica Rold (www.rold.com/), tracked the students' progress after each phase.

The observed design review session was organised after the course completion as a single 40-minute session of a student review team. The participants were instructed to check whether assembly and subassemblies meet the requirements, which they themselves have documented in the form of a list of requirements (represented in MS Excel Online) as part of the course. They also used a synchronous collaborative CAD software (Onshape) which has been used by the team to develop their design. The use of collaborative CAD software enabled TMs to manipulate the CAD model individually (personal view) and to follow the view of any other TM (shared view). For example, in Figure 2, TM1 and TM4 follow TM2 (indicated by examination of screen recordings), thus sharing the same viewpoint. On the other hand, TM3 has a different viewpoint, since they do not follow anyone. The following feature enabled the utilisation of personal and shared views, as reported in previous work [2]. To record their decisions, the team also had a review template (represented in MS Word Online), which was adapted based on Huet et al. [14]. The participants communicated using a video conferencing tool (Microsoft (MS) Teams).

Due to the voluntary participation in the review session, the review team consisted of four members out of the complete eight-member design team. The student team that reviewed the product consisted of two students from the Slovenian university, one student from the Croatian university, and one from the Italian university. These participants formed a team to review the design teams' solution based on the previously developed team requirements.

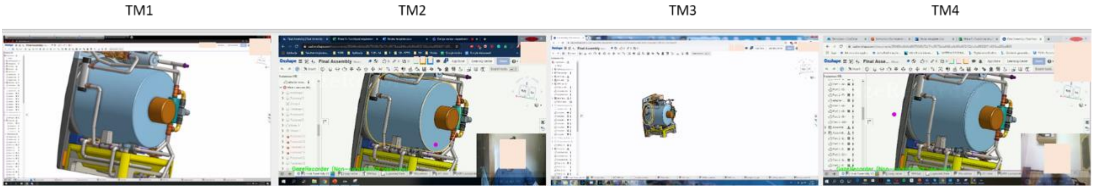

Figure 2: Personal (TM3) and shared view of the VP (TM1, TM2, TM4).

When preparing for the distributed design review, the participants installed a screen recording software (e.g., OBS Studio). Besides the recording software, the review preparation also included a brief introduction to the session goal and files to be used during the review. A researcher was present on the conference call at the beginning and the end of the session in order to provide the instructions, start the voice recording, and collect the data necessary for synchronising screen recordings across all participants (e.g., shared world clock). The TMs were allowed to modify the requirements list developed by the team during the course. After the review session, the researcher re-joined the conference call and asked participants several questions about their approach to the review. The interview questions are listed in Table 1.

Interview questions

• How much of the session time did you spend viewing the VP? • Why do you think you spent that amount of time and not more or less? • When did you use the VP? • Why did you use the VP in those situations? • For what purposes did you use the VP during this activity? • Explain the cases when you followed other TMs. Why did you follow them? • Explain the cases when others followed you. • Explain the cases when you wanted others to follow you. • Were there any differences in using the VP at the beginning, the middle, and the end of the session? • Are there any differences in using VP in different situations? • Do you know if you used the VP simultaneously for a similar purpose? Explain. • Do you know if you used the VP simultaneously, but for a different purpose? Explain.

Table 1: Post-session interview questions.

4.2 Indicators of VP Use in a Design Review Session

Building on the existing literature on using VPs during design reviews (Section 2.1), as well as on the transcript from the conducted design review session and post-session interviews, four indicators have been identified. These indicators might give insight into different aspects of the VP use during the design review session: *Time spent viewing the VP*, *Distribution of individual and simultaneous views of VP*, *Dynamics of viewing VP*, and *Time spent in personal and shared views of VP*. *Time spent viewing the VP* aims at evaluating the extent of VP use during the session, thus recognizing the VP's role during the design review. *Distribution of individual and simultaneous views of VP* provides insights into the VP use from the perspective of the virtual prototyping tool. It shows the extent to which more than one TM looks at the VP at the same time and how often TMs view the VP individually. *Dynamics of viewing VP* aims to express the VP use throughout the session and emphasise the periods of more extensive and less extensive use of the VP. Finally, *Time spent in personal and shared views of VP* determines what kind of mode is preferable when viewing the VP and to what extent TMs use shared views to help them develop shared mental models.

Each of these indicators can be utilised for analysing the data which have been obtained based on the recordings. These data consist of timestamps and durations of occurrences when each TM had opened the screen with the VP. These timestamps and durations of occurrences were split depending on whether each TM used the VP with the personal or the shared view, given the insights from the existing literature on personal and shared views [2]. Finally, the shared views have been divided into views when one TM follows another member and when one TM is being followed by another member. To obtain this type of data, four codes were developed for annotating the design review sessions (Table 2).

Code	Definition and coding rules
Viewing Virtual Prototype (VVP)	Team member has opened the screen with the VP.
VP – personal view (VPP)	Team member has opened the screen with the VP and does not follow anyone and is not being followed by anyone.
VP – shared view – following (VPF)	Team member has opened the screen with the VP and follows the viewpoint of another TM.
VP – shared view – being followed (VPBF)	Team member is being followed by another TM.

Table 2: Coding scheme for processing video recordings.

The developed codes have been used for the validation and as part of the quantitative procedure to analyse VP use by incorporating the suggested indicators. They can all be mapped to a certain indicator, as presented in Figure 3. Following the proposed approach, the next step was to validate each indicator by enriching the quantitative data with qualitative data from the interview and session transcripts. Quantitative data was gathered by synchronizing and annotating recordings using a predeveloped coding scheme (Table 2). None of the codes required a semantic understanding of the utterances, and the inter-coder reliability of non-semantic information is usually high [16], making this approach simple to implement. The following subsections present the validation of each of the proposed indicators.

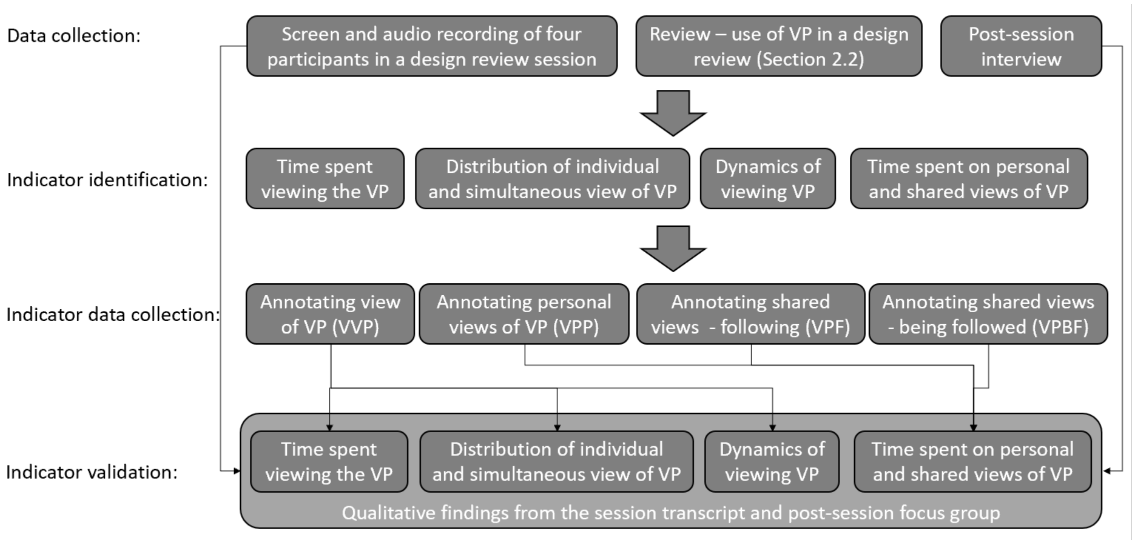

Figure 3: Mapping of the proposed VP use indicators with the collected data.

4.2.1 Time spent viewing the VP

The share of the session time that each member spent on viewing the VP and their mean average duration of viewing occurrence were calculated to obtain the results on the extent of VP use (Table 3). In total, TMs spent 18.9% to 31.9% of the session on viewing the VP (VVP code in Table 1). On average, the VVP code duration ranged from 16.7 to 25.1 seconds, suggesting that viewing of VP usually lasts for a brief period. These results suggest that TMs focused primarily on other screens they had available (e.g., requirements list, review template). The reason for the low percentage of VVP may lie in the composition of the review team, as they already had an understanding of the design under review. Another reason could be the limited information provided through VP, as some requirements could not be verified by analysing the VP (e.g., power of the machine pump). Post-session interview supports these interpretations:

"*Let's say for the storage space or something, for that kind of things, we went to the CAD models. Apart from that, we already knew the topics and the things which were covered in requirements.*" – TM4

"*For example, washing machine pump has maximum headlift. You were not going to get it from the CAD file.*" – TM3

TM	Viewing VP – total (VVP)	
	Share of the session time [%]	Average duration of occurrence [sec]
TM1	18.9 %	16.7

TM2	31.9 %	23.1
TM3	21.7 %	21.5
TM4	24.2%	25.1

Table 3: Descriptive statistics of viewing the VP (code VVP).

4.2.2 Distribution of individual and simultaneous view of VP

The distribution of viewing the VP shows that the individual view of the prototype (i.e., one TM at a time) covers about 1/4 of the overall session time (24.7%) (Figure 4). The individual percentages of viewing ranged from 2.9% (TM1) to 9.6% (TM2). As for the synchronous view of the VP (i.e., two or more members viewed the VP at the same time), the portion of session time equals 13.4% for two members, 9.2% for three, and 4.3% for all members. Such distribution suggests that as the number of simultaneous viewers of VP increases, the corresponding share in session time decreases. When summed up, the data shows that synchronous work on VP takes about 1/4 of the overall session time (26,9%). However, this share does not mean that TMs solved together the same problem, but rather that they worked synchronously on the VP, either on the same or on a different problem. These results further reveal that for 51.6 % of the session time, at least one TM has opened the screen with the VP (VVP code). For the rest of the session, none of the members had the VP opened, but rather focused on other screens (e.g., requirements' list, review template). The comparison of individual and synchronous work percentages suggests that TMs spent a similar amount of time on both interaction types. These results support the previous argument that all individuals should have accessibility to the 3D model [9] or physical prototype [10] during design reviews. The highest portion of session time for both the individual and simultaneous (shared) views is consistently related to TM2. This member was a team leader during the last phase of the course, which might affect their dominance in using the VP.

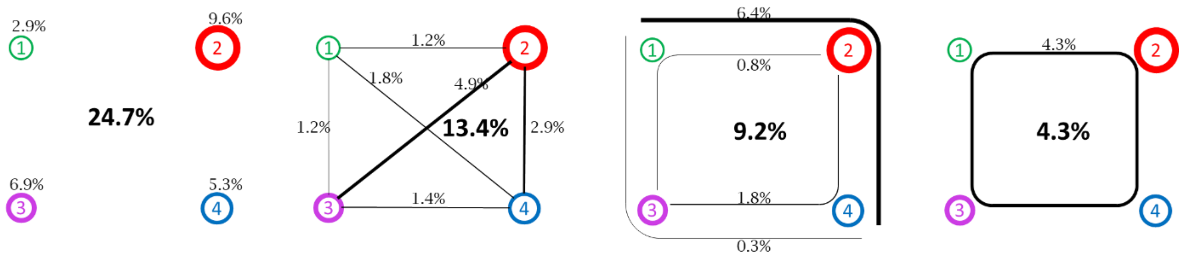

Figure 4: Distribution of (a) One at a time, and (b) – (d) Simultaneous view of VP (code VVP).

4.2.3 Dynamics of viewing VP

The indicator values throughout the session are shown in Figure 5. A moving average analysis was used with the window size corresponding to the average duration of TMs viewing the VP (22 s). This window size was selected to filter the data and get insights on the brief and long views of the VP. These viewing times were usually short, as a longer duration of viewing the VP (more than average – 22 s) occurred only a few times throughout the session. On the other hand, periods when TMs viewed the other screens (e.g., requirements list, review template) often lasted longer than the average viewing duration (indicated by the flat line on the bottom of Figure 5). These results suggest that reviewers viewed the VP for short periods throughout the session, while more time being spent on viewing other screens. Post-session interview supports this pattern, as one of the participants said that they viewed the VP to assess some of the requirements:

"The only time I opened CAD was if I wanted to check something, so like if all the components fit into the design. I checked that real quick, just to double-check." – TM3

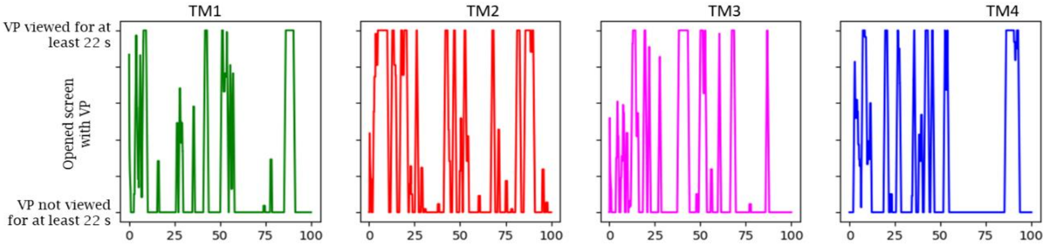

Figure 5: Moving average (22s) of the combined view of VP (code VVP).

Given the brief occurrences of VVP throughout the session, analysing transitions between the VP screen and other screens might result in valuable information about the occurrence of such transitions. Indeed, the transitions to the VP screen usually followed one of the two patterns: implicit call by mentioning CAD-related issue or explicit call by asking members to consult the VP. The former is shown in Table 4, where one team member asks a CAD-related question (lines 5 and 6), and others immediately open the VP. After the team reviews the VP based on the relevant requirement, some or all the members move to a new requirement which usually drags TMs to another screen (e.g., requirements screen).

Line	TM	Transcript	TM1	TM2	TM3	TM4
		Initial state		VP		
1	TM2	We actually didn't find this bacteria sensors. Just turbidity ones				
2	TM1	Yeah.				
3	TM4	Ok.				
4	TM2	What about putting it after the drum?				
5	TM2	Do we actually need this turbidity? At the bottom		VP	VP	
6	TM3	We are saying that yes				
7	TM3	Like what do you mean after the drum?				VP
8	TM2	After the drum so, hmmm, regarding the detection of this turbidity sensor [TM4: aha], the water will be moved either to drainage or storage tank.				
9	TM4	aha				
10	TM3	Yeah, but we said if we don't use the water for a while, we should have turbidity sensor in the tank [TM4: Yeah, yeah] so we know how if bacteria form.				
11	TM4	Yeah				
12	TM2	Aha				
13	TM3	So we said that on the last meeting yeah.				
14	TM4	I mean like if the bacteria is there, water will be unclear, and even turbidity sensor can get, can give us a result.				
15	TM3	Aha				
16	TM4	So, I think it's not required for the bacteria, separate bacterial sensor to be placed there				
17	TM1	So, what about this one? The washing machine's pump has maximum headlift of one meter. That's correct?				

Table 4: Transition to VP by contextual information (07:16 – 08:20).

The explicit call happened only once during the entire session (Table 5) and resulted in all TMs immediately accessing the VP. Although this happened only once, one TM considered asking for a shared view couple of times, as reported in a post-session interview:

"I think I actually said that [that others open the VP] one or two times. At some point I actually wanted to say for others to follow me, but I didn't. I don't know actually why. Maybe it was because we were in a hurry and we were discussing about other, more important things and I didn't want to interrupt anyone." – TM2

TM	Transcript	TM1	TM2	TM3	TM4
	Initial state		VP		
TM2	What about arrangement of the components?				
TM1	Hmm				
TM2	Inside. If you see on Onshape.	VP			VP
TM4	On Onshape? Let me…				
TM2	Yeah				
TM2	Do you think this is a good way to arrange them? Like pump at the top, microfilter beside the motor?			VP	
	Discussion continues with opened VP (three members) for 90 more seconds				

Table 5: Transition to VP by member request (33:44 – 34:18).

4.2.4 Time spent on personal and shared views of VP

The distribution of personal (VPP code) and shared (VPBF and VPF codes) views of the VP is shown in Table 6. The shared views are further divided into the shared view in which a particular TM is followed by one or more other TMs (followed by others) and the shared view in which particular TM follows any of the other TMs. Table 6 shows that TMs utilise both personal and shared views of the VP. Viewing the VP in the personal viewpoint mode was fairly consistent among the TMs and ranged from 10.2 % to 17.6 % of the session time. On the other hand, the extent of the VP shared viewpoints ranged from 3.4 % to 14.3 %. Furthermore, the type of shared viewpoint use differed between TMs, with some of them usually following others (TM1 and TM4), and some usually being followed by others (TM2 and TM3). Such use of shared viewpoints was discussed in the interview:

"When I was in CAD, I followed the members who actually tried to explain something. I did it a lot by myself because while we were discussing about potential improvements and everything, I was still searching in CAD and tried to figure something new or maybe look at the component or subsystem from the other perspective." – TM2

"I also didn't follow anyone. I just checked it on my own. Because I knew what the others were talking about if that was the case, because there are not many components. So, it's like: okay, we're talking about filter, you know where the filter is." – TM3

TM	**Personal view of VP (VPP)**	**Shared view of VP**		
		Followed by others (VPBF) [%]	Following others (VPF) [%]	Total shared view [%]
TM1	15.5 %	0 %	3.4 %	3.4 %
TM2	17.6 %	12.8 %	1.5 %	14.3 %
TM3	16.5 %	5.1 %	0 %	5.1 %
TM4	10.2 %	0.5 %	13.6 %	14.1 %

Table 6: Share of session time spent on personal and shared views of VP.

5 DISCUSSION OF THE PROPOSED APPROACH

The application of the proposed approach, as demonstrated in Section 4, provides preliminary evidence of its robustness. Despite this research being preliminary and limited in scope, the utility of the approach became evident given the conducted identification of measurable indicators (Figure 3). Therefore, the proposed approach can be used to identify indicators for assessing the effectiveness and the dynamics of a distributed collaborative design. These indicators provide analysts with a toolset to better understand the use of VPs in collaborative design sessions. The strengths and limitations of each indicator are given in Section 5.1, while the implications of the presented work are presented in Section 5.2.

5.1 Strengths and Limitations of the Proposed Indicators

The four identified indicators aim at providing different aspects of VP use during distributed design review activities. The VVP, i.e., the time spent viewing the VP, is a relevant indication of VP's importance in a design review session. The higher the value associated to that specific indicator (percentage of time of the review using the prototype), the stronger the role of the VP. This kind of behaviour could be easily associated with the VP's capability to convey all the relevant information that the participants need to share during a review session. On the other hand, the limited amount of time spent with the VP (low VVP) could also suggest other critical points. For example, the prototype version used in the review can lack the information necessary for the constructive design review discussion. Another point could be that the design review requires the integration of external tools (with reference to the VP visualiser/editor) that are not necessarily interoperable with the VP.

Studying the VVP across TMs can provide insights into VP-related collaboration within the team (Figure 4). This indicator provides the overall distribution of the individual and collaborative (shared) work and helps in understanding the team's way of working during the session. However, this indicator does not differentiate between synchronous and asynchronous collaboration among team members. Hence, to provide detailed insights into synchronous collaborative behaviour during the design review session, the VVP code can be split into three sub-codes to clarify whether the virtual prototype is considered personally (VPP) or if it plays a role in the collaboration (VPF and VPBF). As the sum of these three shares equals VVP, higher VPP (VPP/VVP) percentages reflect a lack of synchronous collaboration with the virtual prototype among the co-designers/co-reviewers. Vice versa, a stronger contribution of VPF and VPBF to VVP implies that the synchronous collaboration among the TMs was high. These indicators can assist in providing a general overview of collaboration efficiency during the design review session. More precisely, the differences between VPF and VPBF for each TM would also facilitate the identification of session leaders (co-reviewers whose VPBF overcomes VPF) and followers (VPF higher than VPBF). Moreover, the progression of these indicators in time can provide more than a single estimator of the whole session. As shown in Figure 5, their variations during the meeting can also show who is more active and when, thus providing another element for describing the engagement of co-reviewers.

The last important element is the triangulation of information from different sources to define the above indicators: from previous findings available in the background literature to the observations of real operational environments. The mentioned indicators thus introduce quantitative elements that shed light on how TMs collaborate and share information via the VP in design review meetings. However, the specific application proposed in Section 4 does not enable the generalisation of the results obtained experimentally. Nevertheless, the here-proposed approach enables the repetition of similar experiments through multiple co-design review sessions that would also involve larger cohorts of subjects, potentially spanning a larger number of profiles, which are not limited to mechanical engineering students.

5.2 Implications

Both the results presented in Section 4 and the general validity of the proposed approach have significant implications on the side of research as well as of industrial application.

Starting from the latter, there is a growing trend related to working in a geographically distributed environment. This begun to gain importance a few years ago, with the improvement of information and communication technologies (ICTs), as they allow companies to look for and hire the best human resources where they are available, going beyond the geographical span of the corporate business. The COVID-19 pandemics, on the other hand, stressed this because of the strong restrictions to live social interactions that many countries across the world put into force in order to contain the spread of the disease. Moreover, the growing co-design trend will also demand different stakeholders and profiles to collaborate and contribute to the ideation, development, and assessment of solutions to increase the chances of success for newly developed products. Shared design representations (e.g., VPs) help to overcome language barriers and jargon differences among different stakeholders. In a real operational environment, the use of relevant indicators and the proposed approach enable checking the effectiveness of the collaboration among TMs for design reviews as well as for other activities. Design teams, or companies, can retrospectively look at their behaviour during collaboration in order to highlight opportunities for improvement of the team dynamics or communication in general.

On the other hand, this approach also enables identification and definition of other indicators. These can focus on collaboration elements in environments that do not deal with VPs (for instance, preparing a presentation or textual document). Manufacturers of CAD tools and ICT can also exploit the opportunities of collecting user interactions with VPs and other kinds of representations in easier ways (e.g., by analysing log files) and then calculate the measures associated with the relevant indicators. These indicators can be used to check the effectiveness of their tools and identify opportunities to improve their products by means of relevant add-ons or extensions (e.g., live annotation of comments onto the VP, as it happens for comments in word processors).

On the side of the research, the essence of the proposed approach can be adapted to investigate the collaborative use of VPs in different stages of the design process, which are not limited to design reviews. The progressive diffusion of application that enables multiple users to modify the prototype can drive scholars towards the identification of blackspots in cognition and in design practice that could also have implications on the educational side. As a general example, further studies based on the proposed approach can explore the impact of shared design representations in collaborative settings. This could clarify if and how much the realism of a VP can foster cross-fertilisation (by means of frequent interaction) among design collaborators, or if, on the contrary, that works as a creativity killer.

6 CONCLUSION

This paper proposes and validates an approach to identify indicators of VP use during distributed design activities. Using the proposed approach, four indicators for a distributed design review session are proposed. Altogether, the indicators distinguish personal and shared views when using VPs, as well as individual (one-at-a-time) and synchronous viewing of VPs. Such categorisation enables the study of collaboration within a review session and might be used to assess collaboration efficiency during distributed co-design activities. The preliminary results based on the analysis of a team design review suggest that all TMs viewed VP throughout the session. Furthermore, viewing of VP varied between personal and shared viewpoints as well as between viewing by one TM at a time and simultaneous view by two or more TMs. However, the VP use was usually brief. Furthermore, even though often only a single member viewed the VP for a significant share of the session duration, the VP was also viewed simultaneously by two or more members at multiple occasions. Hence, the case study shows that using the proposed approach can result in a set of indicators that help in identifying relevant patterns of collaborative design activities. These patterns can then be related to the common design outcome metrics such as development time, number of failures, cost, etc.

Scholars and practitioners can utilise this approach to develop indicators for estimating the collaboration efficiency regarding the use of VPs. The application of the proposed approach, as well as the development of new indicators, can help practitioners to assess collaboration within co-design activities. These insights may then assist practitioners and scholars in developing workflows and ICTs optimised for the activity at hand. For example, the initial results suggest that the tools for viewing VPs (e.g., collaborative CAD, virtual reality) should allow enough flexibility for TMs (e.g., enabling utilisation of personal and shared views, enabling mapping of relevant documents to the review session). Hence, these technologies should be carefully implemented into the current workflows.

Future studies should develop a procedure for easier use of the proposed indicators. One approach would be to develop an automatic segmentation tool, which would be used to automatically annotate the design sessions with the proposed coding scheme. The development of such tool would reduce the coder subjectivity and the time needed for conducting the analysis. Furthermore, the tool would enable the analysis of a larger number of teams, thus providing results that could be generalised across contexts. Another stream of future work should identify other indicators for assessing the VP use in activities focused on creating and editing VPs, and activities focused on viewing the VPs. These indicators will provide practitioners and scholars with a toolset to assess and optimise their distributed design activities.

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