Effectiveness of Color-Coded CAD Models Value Visualization in PSS Conceptual Design

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Abstract. The paper presents the results of testing activities aiming to verify the effectiveness of an approach that uses color-coded 3D CAD models to visualize value in the conceptual design stage of PSS. The paper describes setting and findings of a series of PSS Design Experiments involving 8 design teams composed by students participating to the Master Programme in Product Development. Through the application of protocol analysis to the recorded design sessions, the paper compares the behavior of those teams using color-coded CAD models, against those using color-coded numerical tables. The design teams using color-coded models have been found to dedicate significantly more time in the analysis of the value information provided, and to follow a more structured approach in problem analysis and solving.

Keywords: Product Service Systems, Protocol Analysis, Conceptual Design, Color-coded CAD models.

1 Introduction

Conceptual Design is one of the most critical steps in the product development process [1]. At this stage, designers take decisions that determine a large share of the final value of the product [2], often dealing with requirements that are vague, poorly defined or not existing. This problem is exacerbated when designing PSS, because the design space becomes wider and the analysis of the future solutions goes beyond merely product-related characteristics, encompassing service and lifecycle aspects outside the horizon of the engineering team [3]. Lacking of a holistic perspective, designers tend to follow their *'normal specification'* and optimize the system locally, making decisions based on their own preferences [4].

A Stage-Gate® approach [5] is commonly adopted to cope with the issues generated by long and complex development processes to facilitate projects from idea conception to product launch. However, as far as the system grows in complexity, it becomes less straightforward to understand which solution is the most value adding. Hence decisions at the gate become more difficult and working guidelines during the stages less clear. Innovative methods and tools are needed to stimulate the discussion about the system-level contribution of a component design, to eventually trigger

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better decisions. One of the major issues in this domain relates to the capability of representing value-related information in a way to foster such a collaborative process.

Value-related information relates to the operational life of future design concepts, and encompasses dimensions that complement a purely technical and requirements-related perspective. The literature provides several examples of the multifaceted aspects that influence the value of a forthcoming solution. Kowalkowski and Kindström [6] represent the value of PSS as the merging of three dimensions: Product, Service and Relationship. Declining these dimensions at a lower level of granularity, product-based value encompasses aspects such as cost and quality, but also environmental impact and sustainability [7]. Service-based value encompasses aspects such as operation cost, customisation benefits, service consistency [6] or ilities [8], capturing for instance, by the capability of a system of to maintain its functions in the presence of changes. Relationship-based values includes proactivity, trust, long-term commitment and shared norms and mind-sets [6], thus encompasses more intangibles aspects, such as knowledge, emotions or experiences [9-11]. Building on these concepts, Bertoni et al. [12] propose six layers of categorization in an effort to summarize all the aspects relevant for the value assessment of a PSS in the aerospace industry, namely: Performance attributes, risk, profitability, operational performances, ilities and intangibles. In a nutshell value-related information can be seen as a way to represent the system characteristics, i.e. a way to represent the multifaceted factors and interactions which have an impact on the design and the behavior of the product and therefore on the design decision-making process

At the 3rd CIRP IPS2 Conference, the authors presented an approach to support decision-making at the gate, by increasing the decision makers' awareness about the value of a set of PSS alternatives [13]. The paper proposed an approach for displaying the value contribution of a part/assembly through color-coded 3D models in a CAD environment, which were exemplified in a case study related to the development of an aero-engine sub-system. The models aimed at improving the design teams' awareness on the problem to be solved, leveraging the way value-related information was considered during conceptual design.

This paper presents the results of a testing activity performed to verify such hypothesis. The researchers have applied protocol analysis to evaluate the performances of eight design teams working on the same design task, four using value reports in the form of color-coded 3D models, and four using value reports in the form of color-coded QFD-like tables. Eventually, conclusions are drawn about the effectiveness of the proposed visualization approach for PSS design.

2 Research Method

The research has been conducted within a European Commission's Seventh Framework Programme (FP7) project named CRESCENDO (Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation – http://www.crescendo-fp7.eu/) between May 2009 and October 2012.

The research adopts protocol analysis, in the form of Gero and Mc Neill [14], to investigate the behaviors of the designers during the design episodes. Protocol analysis has its roots in the “think aloud” method, which was introduced by Ericsson and Simon [15] and further detailed by van Someren et al. [16], where designers are literally asked to think aloud, so to record the verbalization for later analysis. The protocol technique extends the think aloud method through the use of a domain-dependent coding scheme based on generic models of designing and a robust coding methodology [14]. This approach makes possible to observe the temporal aspect of the design process [17] and to capture designers’ behaviors as a sequence of activities.

Protocol Analysis considers the designer's activity as composed by a sequence of actions, each typically lasting for a few seconds. During the course of the work, designers engage in the design problem calling up a series of micro strategies, which can be recorded, grouped, categorized and analyzed [6]. The testing activity has been conducted in a laboratory environment involving students from a second year master in mechanical engineering.

3 PSS Dimensions for Conceptual Design

The PSS dimensions have been defined emerging from the PSS Layer method first developed by Müller et al. [18], and later adopted by Sakao [19]. The method defines nine dimensions, namely: Lifecycle activities, Needs, Values, Deliverables, Actors, Core Products, Periphery, Contract and Finance. Such layers served as a guidance to define a set of PSS dimension to be used in the protocol analysis. Within the present study, 5 of the original dimensions were better defined and renamed in order to avoid inconsistencies and to limit the risk of mistaken interpretation by the encoders. Namely Deliverables and Customer Value were reworked into Usage Phase and Service, to detail how the design teams intend to deliver value, either by directly impacting the usage phase of the product or by creating synergies or benefits in the servicing activities. Core Product was reworked into Engineering Characteristics, to better capture hardware-related instances, making explicit that this dimension was limited to technical specification. Eventually, Knowledge Reuse and Design Rationale were added and Actors and Contract removed, to analyze the impact of the visualization approach on the use of knowledge in PSS conceptual design, where discussions about contract specifications are premature and actors involved are not yet defined. The 9 PSS dimensions used for the analysis are defined as follows:

- *Needs* captures the discussion related to the definition or clarification of customers’ and stakeholders’ needs. It also considers the discussion related to the information made available from the previous assessment, as it represents a way to clarify the needs of the forthcoming solution. (e.g.: ‘…yes, but what is the need we focus on when we want it inside?...´)
- *Knowledge Reuse* captures the discussion related to the personal knowledge of the designers that was recalled during the experiment in order to fulfill the design task. (e.g.: ´The plastic may melt if you put something on it, so I think is not the best´)

- *Design Rationale* refers to explicit documentation, discussions, argumentations or reasons behind decisions made when designing a system or artifact. (e.g.: ´Why was it better with plastic?´)
- *Engineering Characteristics* captures the discussion related to the structure, mechanical characteristics, technical features or material related to the PSS hardware. (e.g.: ´…if we take away the welding and try to make it more…´)
- *Usage Phase* includes all the statements related to the operating phase of the product when the customer is physically using the artifact. (e.g. ´If you look at what is here, if you talk about ergonomics, it should be easier to use´)
- *Service* embeds all those statements related to activities activated by the customer's request to benefit of the product, but that are not directly visible by the customers, such as transportation or in-site assembly. (e.g.: ´It would take a lot of less time instead of pushing it into the garden…´)
- *Lifecycle Activities* contains all those statements related to the lifecycle of the product, from the production to the dismissal, with the exception of the statements concerning Usage Phase and Service. (e.g.: ´We can have a foldable one that is easier to store, but then is harder to assemble´)
- *Periphery* captures the statements about support equipment, technical periphery, tools and infrastructure related to the PSS execution system, similarly to what defined by Muller et al. [18]. (e.g.: ´I am thinking not roll it into the truck, but having a small crane that can..´)
- *Finance* includes all the discussions about cost-related aspects, either related to production, maintenance or servicing of the PSS. (e.g. ´Perhaps the burners are the most expensive part, those ones…´)

To facilitate the analysis at an higher level of granularity, the dimensions have also been grouped based on their area of relevance: Knowledge Reuse and Design Rationale referred to the Knowledge field, while Lifecycle Activities, Usage Phase, Periphery and Service have been grouped into the Service System field. The grouped categories are those not considered as main evaluation metrics for the experiment, and the decision to group them is driven by the necessity to make the result more readable. A description of the key metrics of the experiment is provided in section 4.3.

4 Experiment Set-Up

The testing activity was conducted in a laboratory environment at the university facilities. The rooms during all the experiments were equipped with the same material, i.e., papers, pencils, pens, tape and prototyping materials; the walls of the rooms were empty and no whiteboards were available. The equipment for both audio and video recording were available at DO. Eight experiments, in four different sessions took place between January and February 2012. A pilot session also took place in December 2011 and served the purpose of verifying and adjusting the variables for the study. All the sessions featured the same schedule. The task was explained in a 20 minutes meeting where the company, its PSS offer, and the rating system for the value assessment were presented. Each design team had then 25 minutes to analyze the report and come up with a new design. Additional 15 minutes were given to prototype a solution to be later presented to the other groups. The presentations lasted for 10 minutes, including short question and answer sessions. The last 15 minutes were spent to fill in individual questionnaires focusing on the use of the value assessment report. The analysis in this study has been limited to the problem analysis and idea generation phase (25 minutes).

4.1 Assignment and Instructions

The experiment featured a fictional design problem, which considered a barbeque equipment manufacturer aiming to shift its business focus, from selling the equipment through its retail network to provide it as a PSS solution. Despite the approach being first developed in the aerospace industry [13], it was preferred not to use the example of an aerospace component, since students might have perceived it as too complex and difficult to related to their direct knowledge. In the new scenario the ownership of the product stays with the manufacturer, which has to take care of all the service-related aspects, e.g. maintenance, cleaning, delivery and storage. The participants were asked to redesign the grills to make them more value adding in a situation where they are rented and delivered "just in time" to the customer.

The design sessions involved 26 students, who were split in 8 design teams of either 3 or 4 persons. The participants were allocated randomly to the teams with the only concern to uniformly assign the international students in order to use English as the only language. No particular method for PSS design was taught to the students prior to the experiments, in order not to influence the design session. Information about the company previous products was available to all the participants. Especially two different designs were described: The "old BBQ solution" (the old, outdated design) and "the actual BBQ solution" (the As-Is design). The two solutions had a similar structure based on six main components: A frame, a case, a grill, a lid, two supports, and a gas cylinder. The actual BBQ solution differed from the old one in terms of shape, materials and components, as it also featured an air system.

The value assessment reports, distributed to all the teams, represented the "knowledge baseline" for the redesign activity. The reports contained information about the capability of the old and actual design to fulfill the customer value scale, providing value-related information to the designers. The old and As-Is designs were compared against a set of value dimensions and value drivers, which were intended to translate stakeholders expectations and needs into understandable and actionable design objectives. Five value dimensions were defined, each of them built up by two to five specific value drivers. The 5 value dimensions were defined as: Operational Performances (i.e. Warming speed, Cooling speed, Ergonomics, Heat distribution, Safety), Service (i.e. Reparability, Cleaning, Mean time between failure, Assembly time, Logistic (i.e. Packaging, Weight, Size, Foldability), Production costs (i.e. Material cost, Manufacturing cost, Assembly cost), Intangibles (i.e. Brand acknowledgement, Environmental impact). In total six papers in an A3 format were provided in each report. Each paper reported the results of the benchmarking of a specific value dimension with its related value drivers, while the sixth paper reported an aggregate view of the 5 value dimensions without the detailed value drivers.

4.2 Implementing the Visualization Approach in the Design Problem Scenario

The value contribution of the ´Actual BBQ’ was assessed by the authors using the same 1-9 scale proposed by the value visualization approach [5], considering the ‘Old BBQ’ as baseline. In case the ´Actual BBQ´ was found more value adding than the old solution for a given driver, a score form 6 to 9 was assigned. In the opposite case a score between 1 and 4 was assigned. A score of 5 meant that no difference was found between the old and the As-Is solution. A color scale from red to white to dark green was associated to the numerical scale. White was associated to the neutral value (5), nuances of red to scores from 1 to 4 (pink=4, red=1), nuances of green to scores from 6 to 9 (light green=6, dark green=9).

Color-coded tables

	Reparability	Cleaning
Cover	7	7
Case	5	3
Frame	2	3
Support	3	7
Grill	4	8
Air system	3	3
Gas Cylinder	4	3

Color-coded 3D models

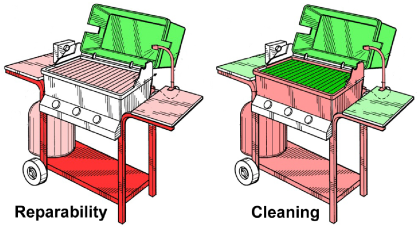

Fig. 1. Color-coded tables vs. color-coded 3D models

The value assessment report featured two alternative visualizations (Figure 1). Four teams received value-related information in a QFD-like format, i.e. the results of the benchmarking were visualized as numbers from one to nine in an excel table, and each table cell was filled with the corresponding color. The other 4 teams received the value assessment results as color-coded 3D models. In this case the report did not show any number, but the benchmark information were directly visualized as components colors in the printout of the BBQ CAD model. To avoid bias during the experiments the students were not aware of the difference in the value visualization between the teams.

4.3 Evaluation Metrics

The shift toward the design of PSS forces designers to make decisions based on a wider set of customer and stakeholder needs and expectation [20]. Being able to identify such needs earlier at a conceptual stage would save time and rework in later phases of the development process [20]. Therefore the author identified in the increase of the total time spent on discussing needs a success criterion for the evaluation of the visualization approach. Moreover research has shown that when a sample design is available to designers, the range of ideas produced in a conceptual design session suffers by design fixation [21]. Building on this finding, the discussion of specific engineering characteristics of the future products in the very initial phase of a conceptual design was considered as a proxy to evaluate the early fixation on a specific preformed idea of product to be developed, making designers' scarcely considering the new aspects related to the service dimension. By consequence the decrease of the total time spent in discussing engineering characteristics in the first quarter of the experiments has been identified as a success criterion to be investigated.

5 Data Analysis

The experiments were transcribed and codified separately by two encoders. This was done to grant the coding consistency. The percentage of agreement between the encoders after the first round of coding was of 65.2%. This result showed the necessity of describing with major detail the definition of the PSS dimensions into consideration. A second coding activity was later performed jointly by the two encoders, which led to the final version of the coding presented in the paper.

The scheduled duration for the idea generation and report analysis phase was of 25 minutes, however small discrepancies, up to 2-3 minutes, were found during the transcription. To overcome this problem the time spent on each PSS dimension has not been considered in absolute terms, but has been translated into percentage of the total time spent in the experiment.

5.1 High Level Results

Initially, the analysis has focused on the total time spent on each dimension during the experiment. The first column of Table 1 lists the 9 PSS dimensions considered for the analysis, plus an additional dimension that gathers all those statements that were not related to any dimension. The second column shows the average time percentage spent on each dimension by the teams with QFD-like value reports. The third column shows the average time percentage spent on each dimension by the teams with color-coded CAD models. Finally the last column shows the difference between column 2 and column 3.

Table 1. Percentage of time spent on each Value Dimension

DIMENSION	Tables	CAD	CAD-tables
Needs	13.45%	25.46%	**12.01%**
Knowledge Reuse	6.07%	6.28%	**0.21%**
Design Rationale	5.42%	3.50%	**-1.92%**
Engineering Characteristics	32.37%	28.75%	**-3.63%**
Lifecycle Activities	6.83%	4.33%	**-2.50%**
Usage phase	9.60%	4.07%	**-5.53%**
Periphery	2.53%	0.66%	**-1.87%**
Service	5.09%	7.53%	**2.44%**
Finance	5.34%	4.35%	**-0.99%**
No dimension	13.29%	15.07%	**1.78%**

Table 1 shows a relevant change in the behavior of the design teams. The teams using color-coded CAD models have spent 12% more of the total time in discussing about clarification and definition of needs, also related to the analysis of the previous value related information. This behavior causes the reduction of the time spent on all the other PSS dimensions with the only exception of the Service dimension, which has been discussed for the 2.44% more of the total time.

The analysis at this stage did not suggest the reasons for such behavior, neither it allowed analyzing in detail the behavior and the trends generated by the difference in the visualization. Therefore a second step of the analysis focused on the evolution of the topic of the discussion along the timeline of the session.

5.2 Analysis along Experiments Timeframe

To analyze in which sequence different activities were undertaken during the sessions, the experiments were temporally divided in four quarters. Each quarter lasted from 5 to 7 minutes according to the length of the experiment. It is worth notice that the time not allocated to any PSS dimension did not differ much between the two categories (see Table 1). For this reason such percentage of time were not considered in the analysis that follows.

Figure 2 displays the results of the analysis along the 4 quarters of the experiment, and shows that the teams using color-coded models initially approached the design problem strongly analyzing the needs (more that 50% of the time). As opposite teams with tabular reports dedicated to this task less that 15% of their time, focusing more on the engineering characteristics of the new product to develop. Concerning Finance and Knowledge no significant difference was found, while the aspects related to the Service System were deeper discussed by subjects with tables. The same trend related

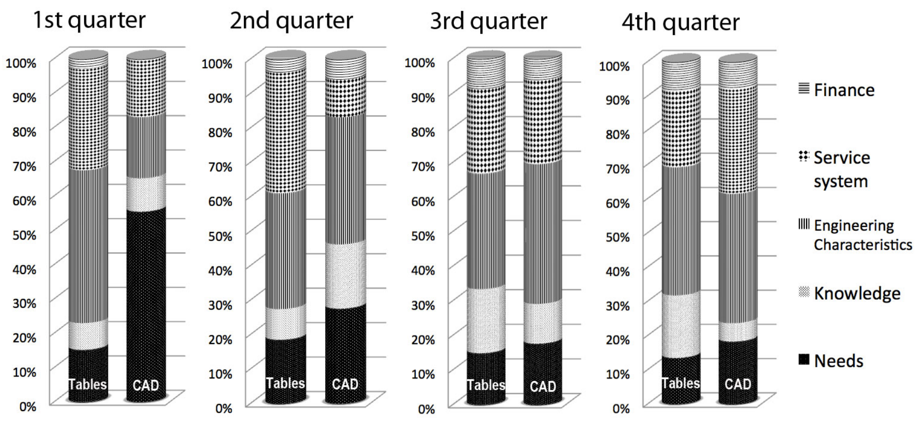

Fig. 2. Length (in percentage) of the time spent on each PSS dimension along the timeline

to the Service System was visible in the second quarter, where no relevant difference in behavior for teams with tables is recognized. CAD models teams instead switched their focus, reducing the time dedicated to investigate needs and spending an increasing time for Knowledge and Engineering Characteristics. In the third quarter a slightly increase in the Knowledge dimension for the teams with tables is visible, together with a continuous increase in the Engineering Characteristics dimension for the CAD model teams. In this quarter the teams with color-coded models started to significantly discuss Service System with more intensity. Finally in the last quarter the CAD models teams mainly focus on Service System and Engineering Characteristics, while the teams dealing with tabular reports did not show any significant change from the 3rd quarter. It has to be noted that after the first quarter, designers with color-coded models did not abandon the discussion about the needs, but kept focus on this dimension, conserving a percentage higher than the teams with tabular visualization all along the experiment.

6 Discussion

The results of the tests indicate that the use of color-coded CAD models drive the design team in a more detailed discussion of the needs of the solution to be developed. This finding is particularly relevant since the dimension Needs covers all the discussions related to the value assessment reports made available to the design team. Such finding strengths the hypothesis that the value visualization approach in color-coded CAD models enhances the awareness about the problem to be solved, leveraging the way value-related information is used in conceptual design.

From the analysis of the discussion along the timeline a clear trend seems to emerge. Teams using tabular reports did not significantly change their behavior during the experiment, i.e. the time spent on the PSS dimensions did not differ significantly in the quarters. As opposite teams with color-coded CAD reports followed a more structured approach. Initially they focus on the needs, and then they recalled previous knowledge and rationale to feed the discussion about the engineering characteristics of the hardware. In the third quarter the Service System dimension was emphasized concurrently to the technical discussion about engineering characteristics. The process is completed by the fourth quarter when the discussion about the Service Systems was brought up to more than 30%, equalizing those related to the engineering characteristics.

6.1 Discussion about the Method

The experiments have featured 26 participants from the Master Programme in Product Development. Protocol analysis is a widely know and proven approach, and despite some limitation [22] and the limited set of data, previous studies have shown the method to be applied also for a smaller number of experiments (see [19]). In authors' advice the sample represents the target population for the visualization approach, as they are soon becoming novice engineers in industry, and they will be actively involved in development projects featuring similar boundary conditions (intensity of teamwork, limitations in the knowledge baseline, deadlines) and problem statements. In terms of possibility of observing similar results in an industrial context, as highlighted by Coley [23], the main difference between experts and novices is that experts pay frequent attention to the reformulation of the problem, while this is completely ignored by the novices [24], which have been found to use a pattern of trial and error [25] although they seem to use similar working backward strategies [26]. These suggest that the results in an industrial contest might differ in absolute terms from what observed in the artificial scenario, although in relative terms the difference between the two settings might not be particularly evident. Furthermore, as recognized in the information visualization literature, most information visualization tools are still verified and validated in lab settings [27]. In spite of the drawbacks of artificial scenarios [28], a main advantage of conducting experiments with students in a laboratory environment is that industrial companies may not permit video and audio recording, and this restricts the amount and relevancy of the data collected.

7 Conclusion

The paper has presented the results of a set of experiments run in a laboratory environment aiming at analyzing the impact of color-coded 3D CAD models to improve communication and value-related information processing in PSS conceptual design.

The experiments have shown that design teams using such models have spent significantly more time, compared to teams using color-coded tabular reports, on analyzing the needs of the new solution in the light of the value information communicated to the design teams. Additionally the teams with color-coded CAD models have followed a more structured approach in analyzing the multifaceted aspects of the design problem into consideration. The experiments thereby confirm the hypothesis that color-coded 3D CAD visualization enhances the awareness of design teams on the problem to be solved, leveraging the way value-related information are used during conceptual design. Such finding suggests that the use of color coded CAD models to visualize the value of a forthcoming solution would improve the stage-gate process during early design, by triggering better decisions thanks to an improved understanding of the system level contribution of a component design.

Future work will focus on new codification of the existing recordings after the selection of categories targeting different aspects of the design activity. Finally additional experiments will be planned involving a larger number of product stakeholders and featuring cross-functional teams with different backgrounds.

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