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ANALYSING THE EFFECTS OF VALUE DRIVERS AND KNOWLEDGE MATURITY IN PRELIMINARY DESIGN DECISION-MAKING

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Abstract

The paper presents the results of a three-days experiment to test the use of information from a value assessment model and from a knowledge maturity scale in decision-making in preliminary design. A visual analogue scale was used to collect individual information from designers through questionnaires. Bivariate statistical analysis was applied to study the correlations between both the use of value drivers and knowledge maturity and the designers' awareness of the design problem to be addressed. Results show that value drivers and knowledge maturity information increase the decision makers' awareness of (1) the different perceptions of design team members about the needs to be satisfied and (2) the technical solution to be developed in the product concept under consideration.

Keywords: Early design phases, Decision making, Teamwork, Knowledge Maturity, Value model

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1 INTRODUCTION AND OBJECTIVES

Competitive pressure has pushed manufacturing companies, over the last few decades, to progressively move from a traditional product-oriented vision towards incorporating more services and support activities in their products. This "servitization" process is an expression of the need to add value to the traditional core product offerings (Vandermerwe & Rada, 1989) by fulfilling specific client demands (Manzini & Vezzoli, 2003). Designers and engineers working in this context focus their attention in finding the right combination of technical features and services characteristics to ultimately deliver the "best" design. However, observations (e.g., Cheung at al., 2012) show that engineers find it difficult to talk about what "best" means, and to identify the best design in a way that is objective, repeatable, and transparent. A recent stream of literature (e.g., Collopy and Hollingsworth, 2009; Curran et al., 2010) have suggested the use of value models as a way to solve such trade-offs. Yet, these models are highly data intensive, which poses problems when performing a preliminary screening of new hardware-service combinations (Isaksson et al., 2013), because data are ambiguous or incomplete. Hence, when assumptions and forecasts prevail, the use of a qualitative definition of value is found to be more appropriate (Soban et al., 2011)(Isaksson et al., 2013). Qualitative value models (Bertoni et al., 2013a)(Eres et al., 2014) are based on the notion of "value drivers": these are intended as system characteristics that are less formalized and more volatile than requirements, and that carry contextual information on solution directions influencing the customer /end user value perception. These models are seldom precise, so Knowledge Maturity (see: Johansson et al., 2011) has been proposed as a mechanism to simultaneously state the level of reliability and fidelity of the knowledge on which they are built.
While the concept of 'value' becomes appealing for designers to elaborate a concise, overarching cross-system requirement specifications list, providing a summary of the most important requirements for a project, there is still little evidence that "value drivers" and "knowledge maturity" could work as 'coordinative artefacts' (Schmidt and Wagner, 2002) or 'boundary objects' (BOs) (Star and Griesemer, 1989) able to facilitate knowledge sharing in engineering design teams. The usefulness of such concept has also to deal with the risk of generating information overload (Tegarden, 1999) and, as shown by the theory of cue-summation (Severin, 1967), with the risk of evoking irrelevant cues adding extraneous association. The main purpose of this paper is to verify the ability of "value drivers" and "knowledge maturity" to trigger the debate around the team members' understanding of different design alternatives and hardware choices. The objective is to present the results of an experiment conducted in a laboratory setting and related to the use of the two constructs presented above in a design session. The experiment aimed at testing the following four hypotheses:

- Value drivers enhance decision makers' awareness on the different individual perceptions of the needs to be satisfied.
- Value drivers enhance decision makers' awareness on the different individual perceptions of the new concept technical features.
- Knowledge maturity enhances decision makers' awareness on the different individual perceptions of the needs to be satisfied.
- Knowledge maturity enhances decision makers' awareness on the different individual perceptions of the new concept technical features.

In order to test the hypotheses, data on individual perception were collected by means of questionnaires at the end of the design session, and statistical regression models were used to highlight the relationship between the variables and to answer the given hypotheses.

2 THEORETICAL FOUNDATION

This section reports on the related literature about value assessment and knowledge maturity, including the main references, that constitutes the theoretical foundation of this paper.

2.1 Value

Research both in Systems Engineering (INCOSE 2006) and Product Service System design (e.g., Kowalkowski and Kindström, 2009) focuses on highlighting what properties are relevant to determining the value of a design solution. Early definitions of value point to the ratio between performance and cost (Miles and Boehm, 1967), and to the customer willingness to pay for an artifact (Shapiro & Jackson, 1978). Further definitions highlight the perceived worth in monetary units received by a customer (Anderson et al., 1993). These units somewhat measure the customer's desire to obtain or retain a product/service (Kelly & Male, 1993). More recent works emphasize the subjective nature of value, linking it to the personal perception of each customer (e.g. Grönroos & Voima, 2012). The latter, while seemingly suitable from a marketing perspective, does not provide useful guidelines for early stages of design, when customers are far from experiencing the final product. Further examples include the intangible value layer proposed by Steiner and Harmon (2002) and the evaluation of ilities proposed by McManus et al. (2007). Bertoni et al (2013b) recently proposed a definition of value that focuses on the level to which a product, or a technical solution, fulfills internal and external stakeholders' needs along its lifecycle (Bertoni et al. 2013b*)*. This interpretation looks at the level to which stakeholders' needs are impacted or satisfied by a particular design, taking care of trade-offs between different needs and stakeholders. Following this definition, *Value Drivers* are then defined as the metrics representing need fulfillment in a design decision situation. Ideally, a solution should fulfill all needs of all stakeholders, rendering the highest possible score for every Value Driver. In practice, any decision in such context is based on a trade-off between different needs that might be positively or negatively correlated (Bertoni et al., 2013a).

2.2 Knowledge Maturity

Design decisions involve uncertainty that needs to be handled, perhaps not by directly reducing it, but rather by providing decision makers with a better understanding of the uncertainty (Stacey & Eckert, 2003). In early design, the lack of factual data is often replaced by assumptions (to be concretized) that may be mistaken for knowledge. Johansson (2011) proposes the use of a scale (see Table 1) from 1 to 5 to rate the maturity level of knowledge entering a decision gate. This *Knowledge Maturity* scale, which based on three dimensions –input, methods (and tools), and expertise (and experience)- can *"assist the identification and assessment of assumptions that are ingrained in the process*" and facilitates decision makers to highlight (and eventually addressing) assumptions, ambiguities and uncertainties (Johansson, 2011).

Table 1. The Knowledge Maturity scale (Johansson, 2011)

KM LEVEL		**Input**	**Method**	**Experience**
5	*Excellent*	*Input is detailed and verified*	*Tested, standardized and verified methods that are under continuous review and development*	*Long verified experience and expertise within area of concern*
4	*Good*			
3	*Acceptable*	*Input is available in detailed form, but is not verified*	*Standardized and tested methods have been used*	*Proven experience and competence within area of concern*
2	*Dubious*			
1	*Inferior*	*Risk of incorrect input*	*Untried methods have been used (ad-hoc)*	*Person doing the work is inexperienced (first time)*

3 EXPERIMENT DESIGN

The experiment involved 35 students enrolled in the Master Course of Systems Engineering at Blekinge Institute of Technology. All students shared a preliminary knowledge of decision-making theories, stakeholder analysis, requirements definition, concept selection and trade-off analysis.

The aim of the design task was the conceptualization, the design and the selection of a portable barbecue. The students could either decide to incrementally or radically innovate an existing model. Along the course of the experiment each team was asked to:

- generate the functional model of a portable barbecue;
- analyse the product functions based on a list of customer statements provided by the controller;
- generate a candidate concept for a new portable barbecue;
- evaluate the concepts proposed by the other teams and rank the three favourite design concepts.

The students were randomly divided in 11 teams. The dimension of the teams was set to either 3 or 4 individuals, with the aim of balancing the eventual presence of strong or weak participants and to avoid the presence of parallel discussions amongst team participants (Cash et al. 2012). While the goal of the design task was shared among the students, the teams were unaware of the purpose of the experiment (i.e., teams did not know that their behaviour was going to be studied). This was done to avoid biases in their performances. Each team worked on the task independently without interaction with other teams. An external person played the role of "experiment controller", as suggested by Cash et al. (2012), to facilitate the design session. The role of the controller was to introduce the design problem and manage the progress of the experiments on the basis of the scheduled duration. The controller had a passive role in the experiment and the participants were not allowed to ask him questions related to specific aspects of the design, to the decision making task, or to a design configuration. The experiment featured 3 modules running in 3 separate days. Each module lasted between 1 hour 30 minutes and 2 hours.

Functional analysis and brainstorming. Day 1 started with an introduction to the design task. A list of customer statements concerning an existing off-the-shelves barbecue was presented. The list highlighted six main aspects perceived as important by the customers, which were further translated into the following needs for the new solution: easy to clean, resistant to rust, safe and easy to move and carry, homogeneous heat distribution on the grilling surface. After the introduction, the participants were divided into groups, and each group received a physical barbecue together with its original packaging. About 50 minutes were then dedicated to the product functional decomposition, 30 minutes to brainstorm new design ideas, and 10 minutes to document the outcomes of these analyses, for later use in day 2.

Concept screening and refinement. On day 2 each team was asked to select one of the concepts generated in the brainstorming phase, and to extensively describe it according to a provided template. The template aimed at collecting information about value and knowledge maturity. This template also embedded additional information about internal company needs that was not available on day 1, such as logistics, production and marketing needs. One and a half hours was dedicated to concept selection and description. The groups were asked to upload all the documentation to an online database used as common repository for all the groups.

Decision making for concept selection. On day 3 each team was given 1 hour to rank the design concepts proposed by all teams and to indicate the three most valuable ones. This activity included both accessing the information about the different designs in the shared on line database, and ranking the three most promising ideas to bring forward in the design process. The teams were not allowed to consider their own design proposal in the selection. At the end of the process each team was asked to provide a written rationale for the decision, and each individual was asked to fill in the experiment questionnaire.

3.1 Generating value and knowledge maturity information

During day 2, the participants were asked to self assess the value of the new concept, and to provide feedback on the reliability of the assessment itself. To guide the team in conveying information about the value and knowledge maturity, an assessment spread sheet template was provided. The template consisted of two parts: the first collecting value-related information in the form proposed by Bertoni et al. (2014) and the second collecting information about knowledge maturity in the form proposed by Johansson et al. (2011).

Concerning value, the assessment was based on a set of 14 value drivers belonging to 4 main families: customer, logistics, production and marketing needs (Table 2). Each need has an "ideal goal" associated, representing the ideal way to satisfy the related need. The teams were asked to assess the expected value of their concept in relation to the different 'drivers', basing their judgment on the benchmarking between the actual commercial portable barbecue and the ideal goal. Each value driver was ranked on scale from 1 to 9, considering the current barbecue to score 5 in all the needs. If a proposed design was believed to perform worse than the actual solution, each team was asked to choose a score from 1 to 4, identifying with 1 the level of needs dissatisfaction that would prevent the product to be commercialized into the market. If the design was believed to be better of the actual solution, each team was asked to choose a score from 6 to 9, with 9 reflecting the "ideal goal" indicated in the Table 2.

Table 2: List of value drivers and ideal goals used during day 2

Family	*Value drivers*	*Ideal goal*
Customer needs	*Resistance to rust*	*No rust possible*
	Easy to clean	*Clean in 1 second*
	Heat distribution	*Homogeneous in cooking area*
	Safety	*Impossible to get burned*
	Easy to carry	*As comfortable as a backpack*
	Avoid to get dirty	*It does not get dirty at all*
Logistics needs	*Reduce Packaging*	*No packaging needed*
	Reduce Weight	*Ultra light BBQ (<100grams)*
	Reduce Size	*As big as a shoe box*
Production needs	*Reduce material cost*	*Almost zero*
	Reduce manufacturing cost	*Almost zero*
	Reduce No. of components	*Only 1 component*
Marketing needs	*Brand acknowledgment*	*Be perceived as extremely innovative*
	Environmental Impact	*No environmental impact*

Knowledge maturity was assessed, using a scale from 1 to 5, on the basis of the quality of the input and on the experience of the designers (Table 3). The first concerned an indication of how much to trust the expected value set for each need. The second assessment concerned the individual experience about barbecues of each participant. To allow a coherent estimation, the frequency of use of a barbecue was considered as a good proxy of the knowledge about the product, thus each team member was asked to rate its personal knowledge. Information about value and knowledge maturity was visualized in a single spreadsheet. Conditional formatting was applied to the table cells to associate a scale of colour from red to green to each number.

Table 3: The Knowledge Maturity scales (adopted from Johansson et al 2011)

KM score	*1*	*2*	*3*	*4*	*5*
Quality of the input	*INFERIOR Risk of not correct assessment*	*in between 1 and 3*	*INTERMEDIATE The assessment shall be trustable but it is difficult to verify*	*in between 3 and 5*	*HIGH The assessment is reliable and can be verified*
Experience of the designer	*INFERIOR (e.g., I never grill, I don´t know much about barbeque)*	*in between 1 and 3*	*INTERMEDIATE (e.g., I grill a couple of time per year without many expectations on results)*	*in between 3 and 5*	*HIGH (e.g., I am a barbeque master!)*

4 QUESTIONNAIRE DESIGN

The questionnaire consisted of two parts; the first one featured 3 open-ended questions, while the second one asked the respondents to indicate their agreement to 25 statements covering 4 main topics (experiment results, decision making process, group collaboration, group discussion). Agreement was indicated using a visual analogue scale (VAS) (Aitken, 1969), see Figure 1.

Figure 1: Visual Analogue Scale (VAS) used in the questionnaire.

VAS was selected to allow participants to more intuitively and precisely express their personal impressions. Bivariate analysis has been used to test the correlation of the variables two at a time. The calculation of the coefficient of determination (R^2) and of the P-value has been run to each set of data. The coefficient R^2 is an indication of the strength of the relationship between variables: a R^2 with value 0 indicates no relationship between variables while a R^2 with value 1 indicates a perfect linear relationship. The P-value was used as a second measure of correlation. A P-value resulting lower than the significance level set to 0.05 means that the consideration of the first variable in the prediction model is significantly improving the ability to predict the result of the second variable. In total 31 students answered the questionnaire.

5 RESULTS

Table 4 lists the 25 questions showing the average score of the answers and the standard deviation. Overall, participants expressed a general satisfaction regarding the final design (average score > 3.1). Also, they felt that agreement within the team was relatively easy to reach, and that the final ranking provided mirrored well the value of solutions. Low scores, i.e. below the 3.1 medium score, are found in two questions: “I feel in the group we had different understanding about the underlying problem (needs)” and “I feel in the group we had different understanding of the product concepts (technical solutions)”. Still, standard deviation is quite high for both questions, meaning that students had very different perceptions on this matter.

Concerning the way participants were individually guided in the decision making, Table 4 highlights a quite wide range of answers as indicated by the average values and the standard deviations. The only data that emerge more clearly is the fact that participants seem to disagree with the fact that the timeframe of the experiment did not allow them to make use of the information provided.

Table 4: Average and standard deviation results for each questions in the questionnaire

Maximum value 6.2, minimum value 0		***Average***	***Standard Deviation***
About decision making and selection	*I am satisfied with the result*	*4.53*	*1.14*
	I am personally confident with the ranking provided.	*4.68*	*0.81*
	I feel that everybody in the team is confident with the ranking provided.	*4.81*	*0.88*
	I feel that the information provided was all what the group needed to create the ranking.	*3.50*	*1.66*
	I feel it was easy to find an agreement within the group upon the best concepts.	*5.05*	*1.22*
	I feel that the people in the group have built on each other’s ideas.	*4.69*	*1.07*
	I feel in the group we had different understanding about the underlying problem (needs).	*3.00*	*1.89*
	I feel in the group we had different understanding of the product concepts (technical solutions).	*2.85*	*1.78*
About the way YOU have been guided in the decision making process	*When deciding about the best concepts I personally paid attention to the VALUE scores.*	*3.94*	*1.74*
	When deciding about the best concepts I personally paid attention to the RELIABILITY of the value scores.	*4.11*	*1.40*
	When deciding about the best concepts I personally paid attention to the EXPERIENCE of the persons setting the scores.	*3.17*	*1.96*
	The product SKETCH was for me the main source of information for the decision-making.	*4.34*	*1.42*
	When deciding about the best concepts I had no time to look at all the information provided.	*2.62*	*1.78*
About the way the group collaborated	*I feel that information about VALUE made it easier to find an agreement upon the best concepts.*	*4.19*	*1.43*
	I feel that information about RELIABILITY of the value scores made it easier to find an agreement upon the best concepts.	*3.84*	*1.36*
	I feel that information about people’s EXPERIENCE made it easier to find an agreement upon the best concepts.	*3.05*	*1.93*

	I feel that the product SKETCH made it easier to find an agreement upon the best concepts.	*5.02*	*1.15*
The group was mainly concerned and discussed situations where:	*VALUE and RELIABILITY were low*	*2.62*	*1.40*
	VALUE and RELIABILITY were high	*4.01*	*1.44*
	VALUE and EXPERIENCE were low	*2.48*	*1.20*
	VALUE and EXPERIENCE were high	*3.47*	*1.42*
	VALUE was high and RELIABILITY low	*3.45*	*1.16*
	VALUE was low and RELIABILITY high	*3.07*	*1.49*
	VALUE was high and EXPERIENCE low	*3.36*	*1.21*
	VALUE was low and EXPERIENCE high	*3.15*	*1.40*

The authors further applied bivariate statistical analysis to the VAS data to understand if, and how much, the use of value drivers and knowledge maturity influenced the perception of the designers when working in teams. The first set of correlations studied concerned the analysis of the impact of value scores in the decision-making. The analysis focused on the following statement:

a. "When deciding about the best concepts I personally paid attention to the value scores"

to verify if a strong or weak attention to the 'value drivers' score had an impact on the answers of the other questions. A relevant statistical correlation emerged between this statement and two statements concerning the different understanding of the problem in the team. The two statement were:

1. "I feel in the group we had different understanding about the underlying problem (needs)"; and
2. "I feel in the group we had different understanding of the product concepts (technical solutions)".

As shown in Figure 2, the correlation between (a) and (2) features a P-value=0,0011 (well below the 0,05 confidence level) and a R^2 score of 0,3105, calculated assuming a linear relationships between the data. The correlation between (a) and (3) features a P-value=0,0469 (close to the 0,05 confidence level) and a R^2 score of 0,12644, having a linear relationship as closest approximation.

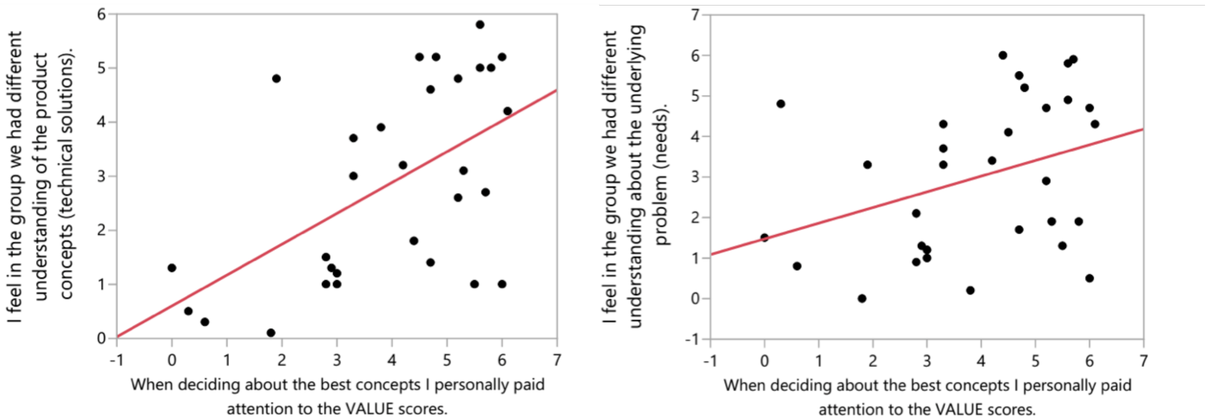

Figure 2: Correlation between attention paid to the value scores and (a) understanding of the concept technical solution / (b) understanding of the underlying problem (needs)

The analysis of the impact of Knowledge Maturity focused on how the teams made use of the information about the reliability of the value score. The analysis focused on the statement:

b. "When deciding about the best concepts I personally paid attention to the reliability of the value scores".

to verify if a strong or weak attention to the reliability had an impact on the answers of the other questions. As for the analysis of the use of the value scores, a relevant statistical correlation emerged between this statement and the two statements previously described, that is (1) and (2).

As shown in Figure 3, the correlation between (b) and (1) features a P-value=0,0081 with an R^2 of 0,2178. The correlation between (b) and (2) features a P-value=0,0278 with an R^2 of 0,156.

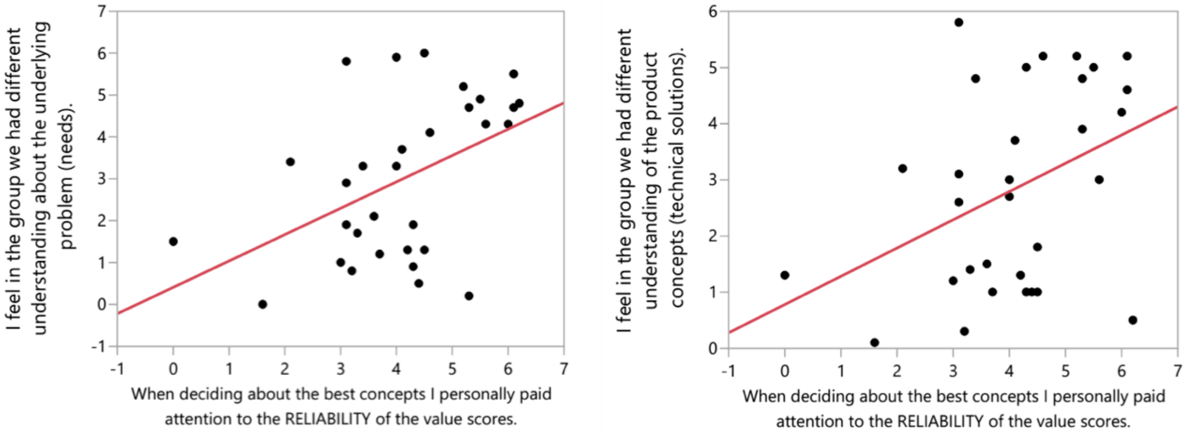

Figure 3: Correlation between attention paid to the reliability (i.e., KM) of the value scores and (a) understanding of the concept technical solution / (b) understanding of the underlying problem (needs)

Reflecting on the hypothesis presented above, the results suggest that, if more attention is paid to the value scores, the individual awareness of the different perceptions of the same product technical features in the design team is increased. Also, but to a minor extent, a higher consideration of the value scores brings a higher awareness of the different understanding of the underlying problem to be solved. Looking at knowledge maturity, a higher consideration of the reliability of the value score increases the awareness of both the different individual perceptions of the underlying problem to be solved and the different individual understanding of the technical features of the new product.
Still, even if a relationship is detected between the analysed variables, R^2 values do not show a very high linear relationship, rather a certain level of variance.

6 DISCUSSION

The experiment was conducted in an artificial setting, which is with students in a university environment and not with practitioners in a real industrial environment, and this might represent a limitation to the generalization of the results. Nevertheless, literature shows that a big part of the research experiments testing new tools and methods are still conducted in artificial settings (Ellis & Dix, 2006), and recognise master students as "advanced beginners" that understand how to design and take situational factors into account (Kleinsmann et al., 2012). Master students can be considered the target population for the development of new methods and tools, 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 (Bertoni, 2013).
A simplification has been introduced in the experiment concerning the interpretation of knowledge maturity. The knowledge maturity scores were qualitatively set by the teams during the design session, this represents a reduction compared to the original definition of knowledge maturity consisting of an assessment of input, methods and experience. Such simplification was introduced for two practical reasons: first to make possible the determination and the use of the information in the timeframe of the experiment, and second because it was believed that making each design team determining the knowledge maturity scores of its own assessment would have facilitated their use during decision making, preventing students to work on data whose meaning was not clear, or on concepts to which they were not accustomed to. This reduction can be also seen as a limitation of the experiment, since the individual willingness to use the knowledge maturity information might be influenced by the individual perception of how much such knowledge maturity information is reliable. Nevertheless the experiment focused on the effect of using such information irrespective of the quality of the information itself, so the authors believe that, in this case, the nature of the knowledge maturity calculation has not critically biased the results of the experiment.

It shall be noted that the experiment focused only on the study of the effect of value drivers and knowledge maturity, which are only a partial representation of all the information that can be communicated to designers. Additional information during the design activity might generate similar phenomena or improve specific designers' performances. An example is given by the participants' use of product sketches that were found particularly relevant for the decision making to convey information and find agreement. Knowledge maturity and value drivers shall therefore be considered as a part of the criteria used to guide the designers' reflections. What is the best set of information to be communicated to designers would ultimately depend by the objective of the final design.

7 CONCLUSIONS AND FUTURE WORK

The work has focused on the problem of enhancing the awareness of designers in preliminary design, in particular of the different perceptions that the design team members can have about the same design problem. The paper has presented the results of a three-day experimental activity aiming to analyse the effects of using a value assessment model and a knowledge maturity scale in preliminary design decision making. The experiment has been conducted with master students in a university environment and is a part of the testing activities planned for the experimental validation of the value assessment model and of the knowledge maturity scale (Bertoni et al., 2013a) developed within of a EU funded research projects (www.crescendo-fp7.eu), and a Swedish based research profile on model driven development.

To a greater extent, the results of the experiment support the hypotheses that value and knowledge maturity information increases the decision maker's awareness of (1) the different perceptions of the different design team members about the needs to be satisfied and (2) the technical solution to be developed in the product concept under discussion. This experimental evidence further supports the claim that both constructs could work as 'coordinative artefacts' or 'boundary objects' during the early stages of design, facilitating knowledge sharing in engineering design teams.

Future work will focus on the possibility to run additional experiments on a larger scale in a real industrial environment with a design problem fitting the needs and competences of the company hosting the experiment. An extended version of the experiment, featuring the definition of more mature design concepts, will allow to measure quality and improvement of performances of the design, thus providing opportunities for the triangulation of the results. Future research will also investigate the applicability of the value assessment model and of the knowledge maturity scale to design concepts that have tighter connection with a service network - that is, in the presence of service-intense product service systems. The use of protocol analysis to study design teams behaviours in such a context is valuable of being investigated.

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