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STRUCTURE SHARING FOR RESOURCE EFFECTIVE SOLUTIONS: IMPROVING MEASURES TO ACCOUNT FOR IMPORTANCE AND QUALITY OF FUNCTIONS

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Abstract

Structured sharing is believed to improve resource effectiveness of design solutions by allowing multiple functions to be achieved from the same shared structure. The current measures for assessing structure sharing and resource effectiveness account for the number of functions and structures in the solutions, but they do not take into account some of the basic aspects of functions from the customer and user perspective, which may determine whether the structure shared solution is desirable or not. This paper addresses this gap by improving the existing measures of structure sharing and resource effectiveness to take into account: (1) Relative importance of the different functions performed by the product (2) Quality of functions, which answers how well are the functions in the structure shared products performed when compared to a typical non-structured product serving the same function, and (3) emergent negative functions in the shared product that did not exist in the non-shared counterparts. The paper presents the derived equation, findings from the empirical tests conducted to test and validate the developed measures, and implications and recommendations for future research.

Keywords: Design for X (DfX), Decision making, Design methodology, Design process

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1 INTRODUCTION

Structured sharing is believed to improve resource effectiveness of design solutions by allowing multiple functions to be achieved from the same shared structure (Ulrich, 1988; Chakrabarti, 2001). The current measures for assessing structure sharing and resource effectiveness account for the number of functions and structures in the solutions (Chakrabarti and Singh, 2007), but they do not take into account some of the basic aspects of functions from the customer and user perspective, which may determine whether the structure shared solution is desirable or not. This may also lead to waste of resources. Therefore, this research builds on previous research on methodologies for estimating the resource effectiveness of structure shared solutions, focussing this time on customer satisfaction and the functional performance of the structure shared solution.

1.1 Limitations of Current Measures of Structural Sharing

The existing measures for the degree of structure sharing and resource effectiveness of solutions have some critical limitations that render the measures limited and non-reliable for effective design decision making. Firstly, the existing measures do not take into account the quality of function (Chakrabarti and Singh, 2007). That is, in the existing measures there is no way to assess that by achieving multiple functions through sharing of structures whether the functions are getting compromised in terms of how well they are achieved or not? And if the quality of function is adversely affected, then by how much? Secondly, the current measures also do not account for any emergent effects (Goldenberg et al., 2001) in the structured shared solutions. That is, the sharing of structures may also result in the emergence of intended and unintended functions and behaviours that may adversely affect the overall level of customer satisfaction (Chakrabarti and Singh, 2007). In this paper, we improve the existing methodology such that it attracts the attention of the designer towards these issues, leading to an improved measure for structure sharing and resource effectiveness.

2 DEVELOPING A NEW MEASURE OF STRUCTURE SHARING

In this paper we have considered the effects of factors such as Relative Importance (RI), Relative Quality of Function (RQOF), and Number of Negative Effects (NNE) in the design decision making. In many studied cases the designers come up with innovative structure shared solutions, but the users have not necessarily been interested in them, because the users do not see these solutions to be important enough for them to pay more for the many other functions that the structured shared solution offers. Therefore, it is important to have some decision making tools that allow designers to look into the target market and gather the preferences and feedbacks of the users on the relative importance of the different functions before integrating them through structure sharing into one single product. Therefore, one factor that we consider is the Relative Importance (RI) of Functions.

Relative Importance: Relative Importance of each main-function shows the degree to which it is effective in the final performance of the product and the degree that it can result in customer satisfaction. A relative importance value can be assigned to each of the main-functions by giving an importance rating from 1 to 5 to each function. As a more reliable approach to obtaining the relative importance of each main function, the Quality Function Deployment (QFD) customer requirements analysis (Akao, 1990) can be used and the ratings of experts and target customers can be gathered such that a weighted-average for importance can be derived.

Another factor that should be taken into account is the quality of function (QOF). It is very important to check how well the functions are being performed by the products (Matzler and Hinterhuber, 1998). Durability, robustness, ease of use, and other measurable aspects related to the performance and functioning of the product can be used to determine the quality of different functions in a product. The designers could compare the quality of functions in the shared and unshared cases. In this way, they can judge how much of the performance is being deteriorated or improved when structure sharing is done to increase resource effectiveness.

Relative Quality of Function: It is a value between 0 and 1 that the designer can allocate to a shared solution by assuming that the unshared solution has quality of function =1. Quality of function depends on multiple factors. RQOF can be numerically determined based on functional requirements of the design, derived from QFD Analysis or other methods in which the designer can measure how well a functional requirement is being satisfied. For instance, the functional requirements analysis in QFD can be used as one the alternatives to obtain RQOF. In this method, a target value or a minimum numerical value for different design characteristics is being set and these properties in the solutions can be measured and it can be seen how close they are to the target and whether they pass the minimum requirements or not. By summing over all the functional requirements, the overall performance of the shared and unshared solutions can be numerically compared.

Furthermore, it is important to be able to account for the negative effects that are generated in an unintentional manner during the course of the design. For example, structure sharing may impose new limitations and constraints on the effective use of the product. In such cases, the designer should be able to identify emergent limitations and assess whether these limitations are acceptable or not.

Number of Negative Effects: By counting the negative effects (Suh, 1995) that are the result of either sharing or not sharing the structures, the number of undesirable effects that each case (shared/unshared) is imposing on the environment of the product can be determined. It can have multiple forms like wasting space, clashing with other elements or products, affordance of the design, ease of use, mobility of the product, solution not being multi-purpose or any other negative effects that the designer can identify in the context of the solution and its surrounding environment. It can also be determined based on customer requirements in the QFD analysis, by taking into account the relationships between all of the customer requirements and functional requirements and their negative inter-relations. Negative effects of each individual main function can be thought of and also negative effects of sharing on the overall solution can be considered. Those overall negative effects will be considered in all the main functions, however, each main function is imposing its own negative effects. As another suggested method for deriving the number of negative effects, the QFD analysis can be utilized. By looking at all the customer requirements the design team can see if they are satisfying each or not. If satisfying one requirement has an adverse effect on satisfying another requirement, a negative effect can be spotted.

2.1 New Methodology: Checking the Admissibility of Structure-Shared Design

Based on the three factors, RI, RQOF and NNE discussed, we develop a measure to assess whether a proposed structure-shared design is admissible or not. The initial step is identifying all the structures, main functions, sub-functions, and behaviours of a product. At first a FM-tree is drawn for all the separate main functions of the product, as described in Chakrabarti and Singh (2007). Next, all the customer requirements and engineering requirements need to be gathered to create a QFD matrix. Next, now that a proper understanding of the structures that are involved in that particular design alternative is reached and the requirements of the customer are clarified, the designer can calculate the value of "Admissibility of Sharing" using the Equation (1).

As shown in Equation (1), Admissibility of Sharing is calculated by summing over all the sub-functions. Each term in the nominator corresponds to the shared solution and each term in the denominator corresponds to unshared solution. A value over 1.0 shows that the sharing is admissible and the bigger the value, the more logical is the design decision. A value below 1.0 tells the designer that not sharing the structure is more beneficial as it will result in customer dissatisfaction from the performance of the product.

$$Adm = \frac{\sum \mathrm{RI} \cdot \mathrm{RQOF} \cdot \frac{1}{\mathrm{S(s)}} \cdot \frac{1}{1+\mathrm{NNE(s)}}}{\sum \mathrm{RI} \cdot \frac{1}{\mathrm{S(u)}} \cdot \frac{1}{1+\mathrm{NNE(u)}}} \tag{1}$$

Where,

Adm: Admissibility of Structure Sharing.

RI: Relative Importance of Main Function.

RQOF: Relative Quality of Function.

S(s): total number of structures in the structure shared solution.

S(u): total number of structures in the unshared solutions.

NNE(s): total number of negative effects for the structure shared case.

NNE(u): total number of negative effects for the unshared case.

The number of structures can be obtained by counting all the terminal nodes of the FM tree (Chakrabarti and Singh, 2007). One important aspect that needs to be considered when counting the number of structures, is to check whether there are operations that need to be done on one single physical entity to make it a useful part. For example, cut-outs, holes and bends are needed in the manufacturing process to turn a solid piece of geometry into one part of an assembly. These operations also incur costs and must be counted as a separate structure. For instance, if there are 3 different manufacturing processes to be done on 1 part, that 1 part is counted as 3 in the above formula. The designer must try to reduce the complexity of the design to make it more efficient by not only reducing the amount of consumed material, but also reducing the number of manufacturing operations.

2.2 Example Case: Application of the New Methodology

Figures 1 shows an example case where we test applicability of the developed methodology. The structure-shared product combines the functionalities of a pen and that of a USB.

Figure 1. Example Design Case - Multipurpose Pen

By conducting an Admissibility of Sharing analysis the designer can check whether the shared solution is desirable or not. As explained, the first step is to construct FM trees of the products, one for each of the unshared products and one for the shared concept that has been developed. The higher the level of detail in the FM tree, the more reliable the results of the analysis will be. It is important to note that the FM trees that were used for the case example 1 were not necessarily accurate and complete. This is because we realized that it takes a few iterations for new users to start getting a better understanding of the FM tree, and to differentiate between what is a ´Function' and what is a 'Behaviour' as per the FBS ontology (Gero, 1990). Thus, despite the inaccuracies and incompleteness we accepted this FM tree created by one of the students because other respondents and students were able to understand it in the short time available during the workshops and the experiments (see Figure 2, 3 and 4). For the purpose of our research this preliminary evaluation was deemed as acceptable. Nonetheless, in real design cases constructing a very accurate FM tree is crucial in achieving reliable results.

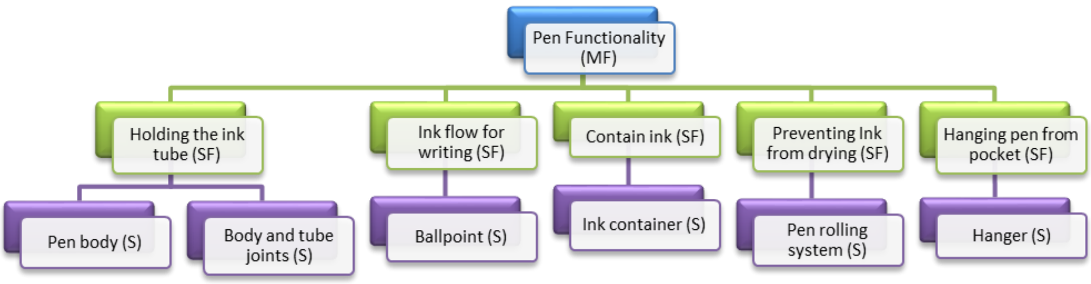

Figure 2. FM Tree of a Typical Pen

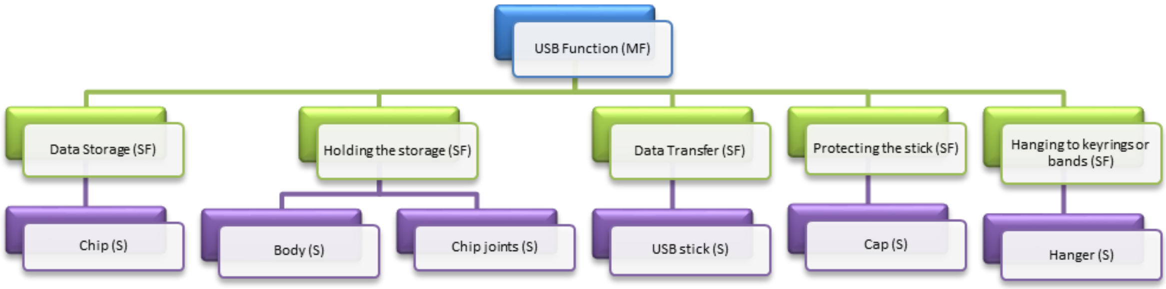

Figure 3. FM Tree of a Typical USB Memory Stick

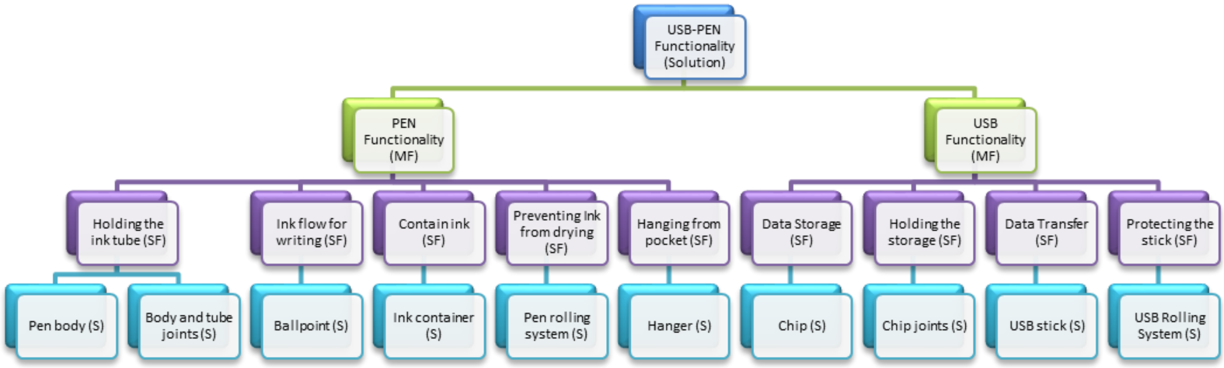

Figure 4. FM Tree of the Designed Structure-Shared Solution (USB + Pen)

These FM trees help to identify all of the main functions that should be performed by the product and the exact number of structures that are involved in the solution concept.

The next step is to determine the relative importance (RI) of each of the main functions for the end user. To assign a meaningful number to the RI values, individual designers and customers are asked to give a value of importance from 1 to 5 to each of the main functions, in this case functioning as a pen and functioning as a USB memory stick. Subsequently, by calculating an average value of their importance rating more reliable values can be obtained. An average value of 0.62 is derived for the RI of pen function and a value of 0.38 for the RI of USB function.

The next step is to estimate the relative quality of each of the main functions. In other words, to estimate how well the pen in this solution is performing in comparison to a typical pen, and how well the product is functioning as a data storage device in comparison to a regular USB memory stick. The designer or responder can subjectively allocate values of what they think, within a range from 0 and 1. To obtain a more reliable result, it is recommended that the QFD analysis of the product is used.

The value of quality of function (QOF) is derived by engineering comparisons made between the target values of the engineering requirements and their measured values in the design. In this example, because of the limitations on the shortened length of the pen due to the placement of the USB memory stick, the ink storage capacity is reduced. So, dividing the storage capacity in the solution by the storage capacity in a regular pen (which is the target value) a number between 0 and 1 is achieved. This process is repeated for all the other engineering requirements in the solution. Using QFD, Figure 5, we get the value of importance of the engineering requirements and relating them to the customer requirements and the importance of the customer requirements. Deriving a weighted average over all the engineering requirements, including the importance of each of the engineering requirements, can produce more accurate and reliable value for the relative quality of the main functions.

In Figure 5, an unshared normal pen is taken to be Competitor 1 and an unshared normal USB memory stick is taken to be Competitor 2. This way a qualitative rating for the structure shared concept is obtained with respect to the unshared solutions. Thus, the established QFD approach is adopted to derive the relative quality of main functions. In this case example, the value of QOF is derived numerically by taking into account the target (or limit) values and the weight/importance of functional requirements, as follows:

Measured USB memory limit: 4 GB, Target value for USB memory limit: 8 GB.
Measured ink storage limit: 6 cm, Target value for the ink storage limit: 10 cm.

Measured value for the diameter of pen: 12 mm, Target value for the diameter of pen: 8 mm.
Measured weight: 70 gr, Target weight: 50 gr.

$$Relative\ QOF\ of\ pen\ function\ = \frac{454}{454+593+593}\times\frac{6cm}{10cm}+\frac{593}{454+593+593}\times\frac{8mm}{12mm}+\frac{593}{454+593+593}\times\frac{50gr}{70gr}=0.66 \quad (2)$$

So the pen functionality in the shared solution has a 66 percent performance rating compared to a regular pen. Similarly, for the USB function, the shared solution is half as good of a regular USB stick.

$$Relative\ QOF\ of\ USB\ function = \frac{439}{439}\times\frac{4GB}{8GB}=0.5 \quad (3)$$

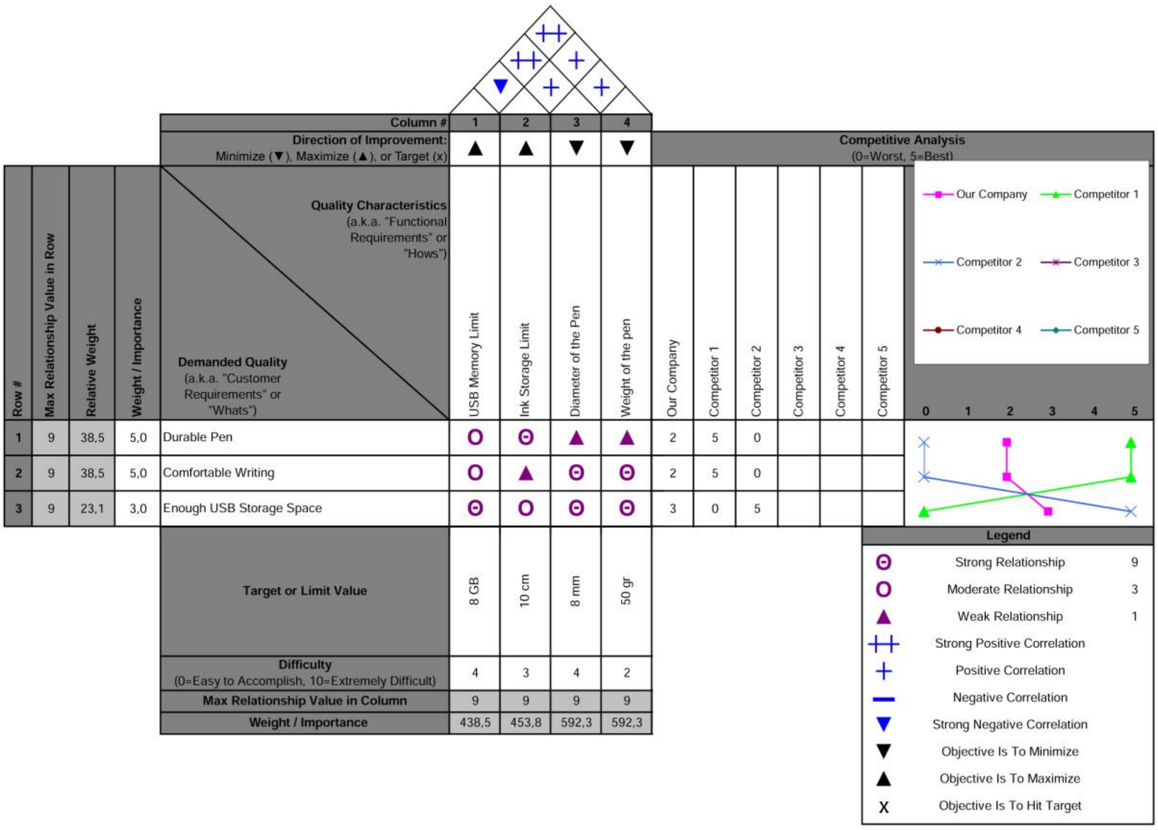

Figure 5. QFD Analysis of the USB-PEN

There is one more step to take to be able to calculate the overall admissibility of sharing and that is to identify the negative effects. By looking into each individual customer requirement, the different types of interactions of the end user with the product can be identified and a list of all the negative types of behaviors that this structure sharing is creating for the users can be identified. These negative effects are more or less context dependent and it is important to know what exactly will be the environments where users are interacting with the product, and what are the other products that might be interacting with this product. In the case example, the following negative effects were identified for the unshared and shared scenarios:
Negative effects of using unshared pen: You need to carry it separately in case you need it.
Negative effects of using unshared USB memory stick: You need to carry it separately in case you need it; It is more probable that you lose it somewhere.
Negative effects of using the shared solution: It is not comfortable while writing; Cannot use both pen and USB at the same time; When the ink runs out half of the performance is gone and the structure is useless.
So, we have 3 (=2+1) total number of negative effects of using the unshared solutions, and 3 total number of negative effects of using the shared solution.
Lastly, the value of admissibility of sharing can be derived by applying Eq. (1), which gives a value of 0.39 for the admissibility of sharing in pen-USB product.

Analysis of the result: Since the Admissibility value is less than one, it shows that from the perspective of potential customers this may not be a desirable product even though it is more resource effective than buying a pen and a USB memory stick as two separate products.

3 VALIDATION OF THE NEW METHODOLOGY

To validate if the proposed methodology and model is applicable in the different fields of engineering design, different methods were used. First, a set of different designed products were analysed to check if the methodology is understandable and applicable. Then, a set of guidelines was composed to explain the methodology to other researchers and designers to check if the methodology is comprehensible. Additionally, these subjects were asked to do the analysis of the same products that were analysed earlier to see how subject dependent would be the results, and to check if the model is giving consistent results. After that the methodology itself and its guidelines were revised, and the results were tested by analysing two sets of products. One set that seemed to be desirable products from a market success point of view and according to customer satisfaction ratings. And another set of undesirable products that had utilized the structure sharing techniques but had failed to gain customer satisfaction and good sales in the market. In this phase, we intended to check if the formula gives results that are consistent with the successful acceptance of the product. In the next phase, the methodology was explained and the guidelines were handed out to a group of master's level students of structural design and architectural design and they were asked to do the calculations and determine if the methodology is helpful in giving them a perspective for the design. In addition, with this approach it was possible to compare the results with the previous analysis conducted by the authors. The results from the validation studies in each phase are presented here:

Phase one: A list of products were analysed with the methodology and checked whether the predictions of the methodology for the success of the product align with the market success of the products. Below you can see the admissibility values calculated for the chosen products. As seen in Table 1, the admissibility results see to predict whether a structure-shared product would have been desirable or non-desirable in the target market.

Table 1. Results of the Analysis for Some Desirable and Undesirable Products

	Products	Admissibility Value
Desirable/ successful	Smartphone	2.97
	Passenger Seat	4.12
Non-desirable/ non-successful	USB-PEN	0.39
	Laptop-Table	0.65

Phase two: The methodology was explained to a group of researchers and they were asked to perform the analysis for some example cases as well as give their opinion about the clarity of the guidelines, and their suggestions for the improvement. Results of the workshop were as follows:

- Other researchers believed that the methodology was straightforward to understand, but a bit time consuming to do the calculations by hand and on paper.
- They pointed out that there must be more clear definition of structure in the guidelines.
- Their FM trees for the same products had some differences that could result in different answers.
- Overall, it was possible for them to broadly learn and apply the methodology in less than 2 hours.

After the workshop, a brainstorming meeting was conducted with other researchers to ask for their ideas to improve the methodology further and to find more applications for it.

Phase three: A group of master's degree students of structural and architectural engineering were recruited to perform the analysis for two given products. Almost all of the students had at least two years of work experience in design related tasks. The students were given FM trees and a basic QFD sheet pre-filled with requirements for the two products, but not the ratings and weightages. The students were asked to complete it if they thought it was necessary. They were asked to add or remove any items that they thought was necessary from the FM trees and QFD matrices before running the analysis. They had to fill in a table containing all the parameters that are needed for calculating the admissibility value, and later the value of admissibility of sharing could be calculated with an excel spread sheet. They were also asked to write down their thoughts and especially the list of negative effects that they were thinking about.

The key findings from these experiments are:

- The methodology was easy to learn and to apply in less than 2 hours for the two products, provided the basic FM tree was given.
- For the first case (Pen-USB), it can be noticed in Figure 8 that 6 out of 7 students obtained a value below 1 which is similar to the lead author's own assessment that the design was not desirable.
- In the second case (smartphone), it is observed that 5 out of 7 students derived a value over 1, and 2 students derived a value below 1. Again, the mid value and the average value are over 1 and similar to the lead author's own finding it shows that this sharing is desirable.

However, it is worth noting that the result of the analysis is up to a point subjective and it is always good to have as many inputs from different people as possible to have reliable values. Also, the drawing of FM trees and identification of negative effects can differ based on the concept, context and the designer's attention to details. So, one way to achieve more reliable results is to use polls, surveys, and batches of analysis in design groups so that statistically significant and reliable values can be obtained. The validation methods used in this paper were only the initial trials and more study needs to be done for further validation of the methodology.

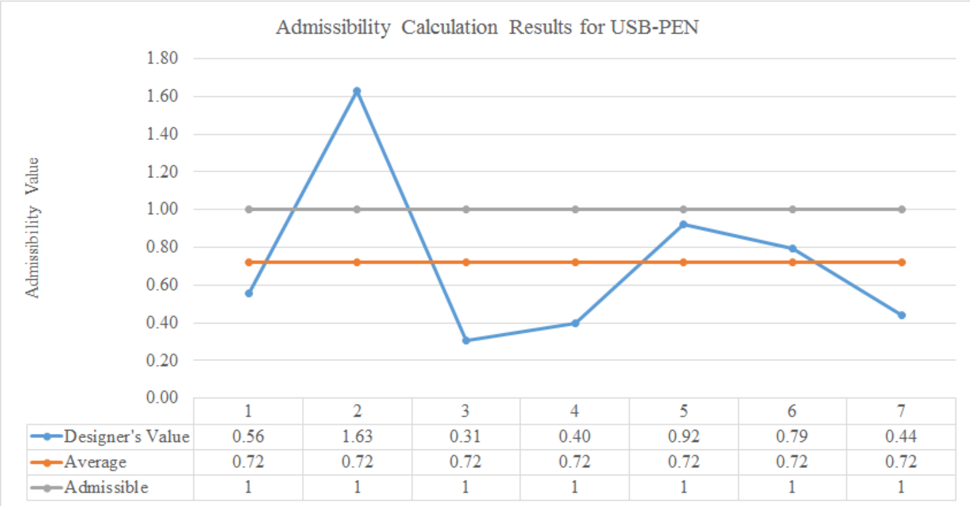

Figure 6. Results of Analysis in the Workshop (USB-PEN)

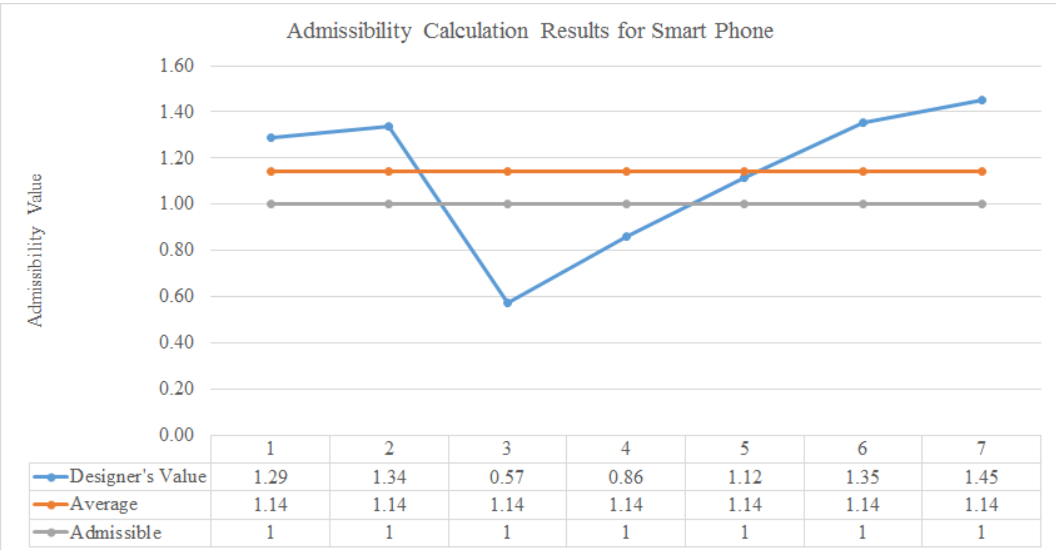

Figure 7. Results of Analysis in the Workshop (Smartphone)

4 REFINING THE METHODOLOGY FOR FURTHER APPLICATIONS

4.1 Simplifications and Automation for Quick Practical Use

The guidelines were found to be a bit hard and laborious to be applied with rigour within a reasonable amount of time. Therefore, some simplifications to the methodology may be required. In addition, for the methodology to be usable in practice, it should be scalable so that all potential functions, sub-functions, behaviours and structures could be assessed. Even for a simple product these numbers can be fairly high, while in complex products it may not be manageable manually. Automation and computational implementation should increase the usability in practice. For example, we developed and tested on such plug-in written in a Building Information Modelling software, for products designed and used in construction sector. Figure 5 shows the user interface of the developed plugin.

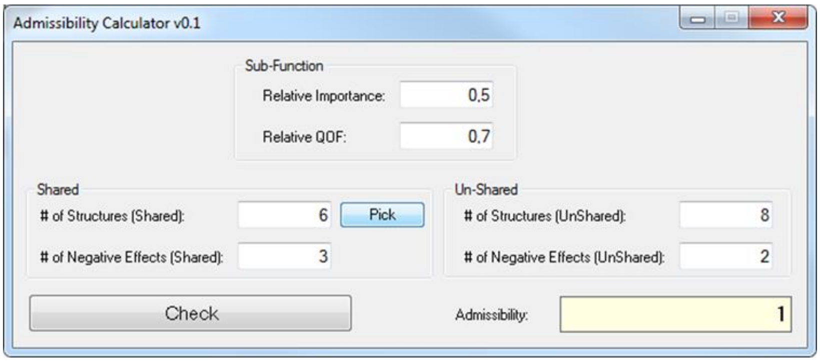

Figure 8. User Interface of the assessment plug-in for a design software

In addition, some simplifications can be made to proceed faster with the methodology. The designer can personally identify the main functions of the product, count the number of structures using the design software. For the negative effects, the designer can take the role of a customer and see what are the limitations that this structure shared solution can impose. For the values of relative importance one simple assumption can be that all of the main functions have the same weight of importance for the customer. These simplifications make the analysis much faster, but at the same time they reduce the level of accuracy and reliability of the results of the analysis. Therefore, depending on the scale of the design project, a balanced approach can be taken that results in a reasonably fast but reliable analysis. This also requires iterations and calibration in developing the equations further.

4.2 Usability in Different Stages of Design

It is also important to define the phases of the design in which the methodology can be applied. The methodology is not intended to be a design tool, rather it is an analysis tool. To be able to use the methodology, there should be one or more concepts already at hand. The methodology can be used to reengineer the design through iterations. However, one may ask if the methodology is applicable in the early stages of conceptual design where there is no solution at hand. In such scenarios, the designer can begin by using the most typical and conventional engineering solutions that exist and quickly develop a preliminary concept and then by applying the structure sharing techniques he/she can improve the concept to come up with more innovative solutions.

4.3 Introducing and Calibrating Coefficients in the Equation

One of the open questions with the current equation is whether the linear relationship between all the terms of the function is adequate? In the current model all the terms (number of structures, number of negative effects, etc.) have equal weightage, which may not be the case in practice. For example, the current equation is highly sensitive to the number of negative effects, and any subjective variation in the count of negative effects for the same product by different respondents can significantly alter the results. Therefore, in the next phase of the research we are working with weighted coefficients as well as exploring non-linear relationships to investigate if we get more consistent results.

4.4 Using the Methodology for Increasing the Affordance of the Structure Shared Products

Affordance of a product shows the ability of the user to use a product for a purpose other than the main purpose that it has been designed for. The designer can use the same presented methodology to check if these additional functions are worth designing for. However, this needs more research and experiments, and will be covered in a separate paper.

5 CONCLUSION

This paper presents new measures for assessing the effectiveness of structure shared solutions focussing on how well the conceived solutions meet the target function requirements, while enhancing resource effectiveness. The new measure for assessing the admissibility of the conceived solution accounts for the relative importance of the multiple functions performed by the product, quality of the functions that are performed, and the potential negative effects that may have emerged due to the sharing of structures. The developed measures are tested through empirical studies with designers, researchers and students for their applicability and comprehension. Initial findings suggest that the developed methods do provide some indication of admissibility of structured shared solutions in terms of their potential desirability from customer point of view. However, further experiments are needed to test the usefulness of the methodology. Opportunities for further refinements of the developed measures are outlined as well.

REFERENCES

Akao, Y. (Ed.) (1990), "Quality Function Deployment: Integrating Customer Requirements into Product Design", *Productivity Press*, Cambridge, MA.

Chakrabarti, A. (2001), ''Sharing in Design: Categories, Importance and Issues'', *Proceedings of International Conference on Engineering Design (ICED01)*, pp. 563–570, Glasgow.

Chakrabarti, A. and Singh, V. (2007), ''A method for structure sharing to enhance resource effectiveness, '' *Journal of Engineering Design* Vol. 18 No. 1, pp.73–91.

Gero, J.S. (1990), ''Design prototypes: a knowledge representation schema for design, '' *AI Magazine*, Vol. 11 No.4, pp. 26–36.

Goldenberg, J., Lehmann, D.R. and Mazursky, D. (2001), ''The idea itself and the circumstances of its emergence as predictors of new product success,'' *Management Science* Vol. 47 No. 1, pp.69–84.

Matzler, K., and Hinterhuber, H.H. (1998), ''How to make product development projects more successful by integrating Kano's model of customer satisfaction into quality function deployment'', *Technovation* Vol.18 No. 1, 25–38.

Suh, N.P. (1995), "Designing-in of quality through axiomatic design", IEEE Trans. Reliability, Vol. 44 No. 2, 256–262.

Ulrich, K. (1988), ''Computational and Pre-Parametric Design,'' PhD Thesis, Artificial Intelligence Laboratory, MIT Cambridge.