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A method for structure sharing to enhance resource effectiveness

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Structure sharing is said to be observed in a product when more than one function is performed by the same structure at the same time and it is claimed to make a product more resource effective. While understood at an intuitive level, however, and although some initial measures are mooted, unless the concepts of structure sharing and resource effectiveness are understood at a more concrete level, their relationships are hard to establish, and harder to instil in a product. Being able to develop measures of, and relationships between, these two concepts should help develop products that are better structure-shared and resource-effective, and hence more innovative yet competitive. This is because structure-shared products are often considered more innovative than non-structure-shared products, and being more resource effective should amount to being simpler and less expensive. The goal of this paper is to develop a method for assessing resource effectiveness and structure sharing in a product, and enhancing resource effectiveness through structure sharing.

Keywords: Structure sharing; Resource effectiveness; Simplicity; Integration; Cost

1. Aims and objectives

Structure sharing (Ulrich 1988, Chakrabarti 2001, Chakrabarti and Regno 2001) is one of the four types of sharing that can be found in a product (Chakrabarti 2001). The other types of sharing are multi-modal integration, structure redundancy and function sharing (Chakrabarti 2001). This research aims at achieving a better understanding of the definitions of function, structure, structure sharing (SS) and resource effectiveness (RE) in the light of physical implementation of design solutions, developing a systematic approach for computing and evaluating SS and resulting RE in a given product, and guidelines for improving the RE through SS. There are four objectives.

1. To define the concepts of function and structure at a level of concreteness adequate for using them to define the concepts of SS and RE so that it is possible to assess the degree to which these are fulfilled in a product.
2. To compare these definitions.

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3. To develop a method for assessing and enhancing RE.
4. To evaluate this method for its effectiveness.

2. Research methodology

The following are the research questions pertaining to each objective:

1. Understanding the concepts: What is function? What is structure? What is SS? What is RE? To clarify these concepts, a literature review was used to form a preliminary understanding along with an interview of designers to understand their intuitive notions of these concepts, especially SS and RE. This was done by analysing the views of designers about the value of a set of common products given to them, which they were asked to evaluate for these values.
2. The definitions were adapted to be consistent with these views.
3. Develop a method for assessing and subsequently enhancing RE: How can we use the above concepts to create a measure for assessing these values? What steps should be provided in this method so that more SS leads to more RE? This was based on translation of the measures into steps for product enhancement.
4. Evaluate the effectiveness of these methods: How can we tell whether the methods are effective? This was based on using the methods to improve the RE and getting these evaluated by other designers for consistent agreement.

3. Developing understanding and measures

To develop the initial understanding, an interview-based survey with designers at a master's level of training was carried out alongside a study of the existing literature to check for current understanding of the concept of SS. The aims of the survey were to identify the perceived understanding of function, structure and SS, and the degree of consistency between these observations.

3.1 *Initial study*

Five designers were given a brief introduction of the concept of SS based on Chakrabarti (2001), and then four different artefacts were individually introduced to 10 more participants, who were then asked to exercise their judgement, based on their perception of the products, to answer the following questions:

- What are the functions of these products?
- What are the structures in these products?
- Did the subject observe SS in these products? If yes, then where in the product did SS occur?

The products used for this survey are shown in Figure 1. For the details of the survey, see Singh (2003).

3.2 *Main conclusions*

The main conclusions from the survey are as follows:

- There was considerable disagreement of views among the participants as to what qualifies as a single structure. Often people identified a monolithic or single-piece artefact or part

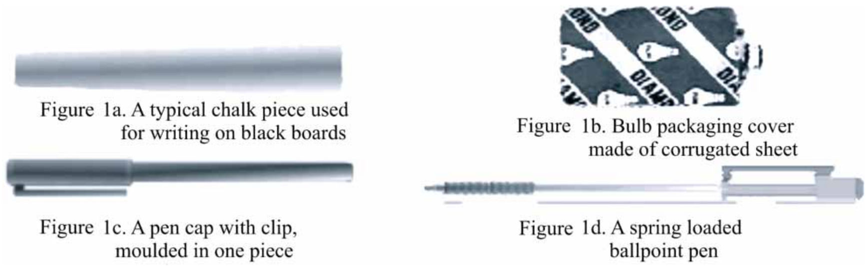
Figure 1a. A typical chalk piece used for writing on black boards
Figure 1b. Bulb packaging cover made of corrugated sheet
Figure 1c. A pen cap with clip, moulded in one piece
Figure 1d. A spring loaded ballpoint pen

Figure 1. Artefacts used for the survey.

as a single structure. For example, the chalk piece. This is not universal, however, and contradictions existed. For example, the pen cap. Some considered the single moulded pen cap as a single structure, while others believed it to have two structures, namely the cap and the projected clip arm.

- Identification of functions and the hierarchy in which they relate to the structure of the product was an issue. There was general agreement that the main function relates to the intended or desired effect. This is seen as the black box representing the transformation from the input to the output; for example, in the case of the chalk piece the main function was that of making a mark on the board. Besides this, the relative importance of functions observed in a product must also be taken into account. For example, in the case of the chalk piece some of the functions were those of: marking on the board, providing a surface to hold, transmitting force, providing a medium to mark, storing a medium and allowing transfer of a medium. In such case, the relative importance of various functions is important for measuring the performance of the product in terms of SS and RE.
- There were some doubts raised as to how the changing state of a structure affects the structure–function relationship. For example, as the chalk piece becomes smaller it affects its functioning.

3.3 *Further discussions based on the literature*

Any product is an assembly of various components (Pahl and Beitz, 1996, Otto and Wood, 2001, Ulrich and Eppinger, 1995, Lindbeck and Wygant, 1995). It can be represented functionally or structurally depending on the way the product is looked at (Andreasen 1980, Andreasen, 1992, Hubker and Eder, 1988). While evaluating a product in terms of its functions, the representation can be in terms of:

- the desired effect and the processes therein, and
- the physical implementation for bringing in the required effect.

This representation is a complex process needing a structured method for identifying the various parts or components forming the overall product. One-way to do this is to start with the main function of the product and break down the line. This would typically involve organs[†], processes[‡] and means[§], which would relate to physical elements, technology[¶] and principles,

[†]An organ is a material element or an interaction between several material elements based on a physical regularity, which create the desired effect. Organs may include a set of structures participating together in bringing an effect.

[‡]Any step in the transformation of the various operands, namely materials, energy or information, that alters one or more properties of the operand in an appropriate direction is a process or operation.

[§]Means are the principles, laws or phenomenon that are responsible for the occurrence of the function.

[¶]Technology is the interaction between the operands and the necessary effects (force, the effects of heat, movements, flow changes, etc.), which affect the operand (Andreasen, 1992).

respectively (Andreasen, 1992). The function-means (FM) tree is an effective and simple way of breaking down a complex system into smaller and simpler components.

SS has been identified as a desirable quality for products (Chakrabarti 2001) and therefore demands greater attention and understanding. SS, by definition, relates directly to the functions and structures in a product. This means that the definition of function and structure and their measures have a bearing on the accuracy and reliability with which SS and RE of a product can be estimated.

A particular issue to be resolved is that functions and structures can be found at various levels of abstraction in a product (Hubker and Eder 2001), which brings ambiguity in choice of the functions and structures to be considered for the purpose of computing SS and RE. Such an ambiguity needs to be removed. Any methodology so developed should consider the broadest range of solutions and give an accurate and reliable measure for assessing a product for its degree of SS and RE.

4. Discussion on the measures developed

SS, by definition, relates to the number of functions and structures in a given design solution (figure 2). The phenomenon of SS is said to exist where there is more than one function fulfilled by the same structure at the same time.

SS is calculated here as the ratio of the number of functions at the lowest level of abstraction to the number of structures in a product:

$$\text{Degree of SS} = \frac{\text{number of functions at the lowest level of abstraction}}{\text{number of structures}} \tag{1}$$

Please note that SS was earlier mentioned as the ratio of number of structures to the number of functions in a product (Chakrabarti 2001). Defining SS as ratio of the number of functions to the number of structures brings consistency with understanding of SS. The higher the average number of functions per structure, the greater the SS should be. Since functions at the lowest level of abstraction are considered, the ambiguity in choice of functions is removed. The definitions of function and structure as used here are now given.

Function is defined as the intended effect, given the input conditions. The input conditions include the typical environment in which the product is expected to work. In order to account for the level of abstraction, we use the term '*main function*' (MF).

Main functions are defined as the intended effects from the system at its highest level. In case a system has more than one MF, which are independent of each other, it needs to be taken as having several MFs (Hubka and Eder 2001). For example, a screwdriver is designed to fasten/unfasten a screw; that is, there is a distinct single desired effect from the product. Contrast this with a screwdriver-cum-wrench that has two independent functions, 'fasten/unfasten a screw' and 'fasten/unfasten a bolt'. These functions are the desired outputs at the highest level as well as independent of each other. Each independent function will generate an independent FM tree.

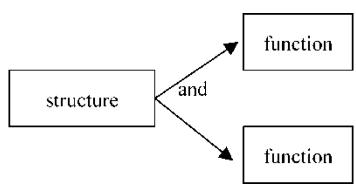

Figure 2. Structure sharing. Adapted from (Chakrabarti 2001).

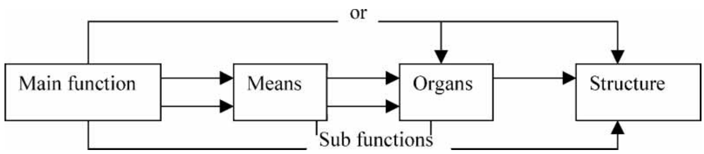

Figure 3. The process of generating a function means tree.

In this work, any physical entity or feature capable of being identified independently is called a *structure*. For example, even a hole or a bend provided in a design constitutes a structure.

4.1 *Steps for generating an FM tree*

The steps for generating an FM tree are the following (figure 3):

1. Identify the MF. For the cases where there is more than one MF, each will have a separate FM tree. Each FM tree starts with a MF.
2. Identify the immediate next link, which can be a subfunction, means, an organ or a process. Asking the question 'HOW' leads to the next level.
3. At each stage look for further branching until a structure is reached.
4. The total number of end points in an FM tree gives the total number of structures for the purpose of computing the degree of SS and RE.

All functions evolving in a branch for the fulfilment of some other function at an immediately higher level of abstraction are called *subfunctions* (SFs).

4.1.1 Example 1. In order to understand the terms subfunction, means and organs let us consider the electric bulb (see figure 4). The FM tree for it is given in figure 5.

Here, the main function of providing light is broken into three SFs by asking the question 'how to provide light?'. In the following levels, once again asking a similar type of question leads us to the next level. For example, by asking the question 'How to allow light through?' we get the 'Glass container' in the next level. It is noticeable that a number of associated functions emerge alongside while moving down the FM tree. For example, the need for holding the container comes into picture only after the container surfaces in the FM tree. Please note that, the metallic holder is marked as an organ (O) since it is an assembly of many different structures, which can be identified, as we break down further. Such a breaking down would also lead to identification of many SFs coming along these structures.

Figure 4. An electric bulb.

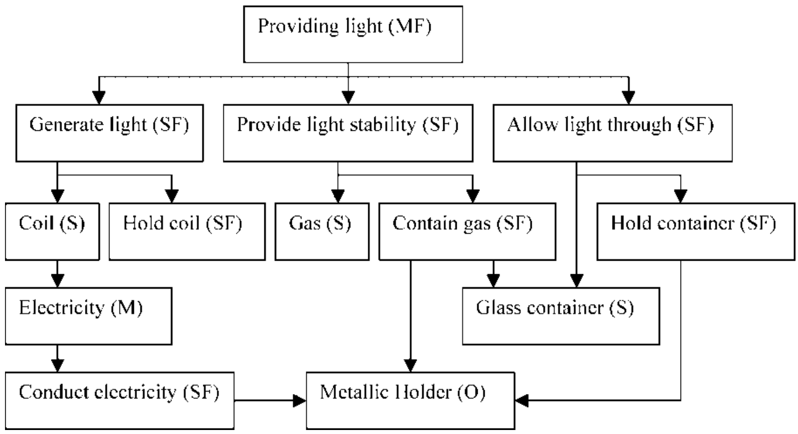

Figure 5. FM tree for the electric bulb shown in figure 4. MF = main function, SF = subfunction, S = structure, O = organ.

4.1.2 Example 2. To understand the process of generating an FM tree better, let us see the FM tree for a screwdriver-cum-wrench (figure 6). In this case, the MFs are fastening/unfastening of a screw and fastening/unfastening of a bolt. Since there are two MFs, two different FM trees are to be generated (figures 7 and 8).

In this case there are four functions at the end of the network and altogether three structures. We can map the structure set onto the function set (see figure 9).

Using equation (1), the degree of SS = 4/3.

4.2 *Resource effectiveness*

In earlier research the following has been said about RE:

- In general, RE increases with the increase in SS (Chakrabarti 2001, Chakrabarti and Regno 2001).
- RE is defined as the ratio of number of structures to the number of functions these structures fulfil (Chakrabarti 2001).

Figure 6. Schematic drawing of a screwdriver-cum-wrench.

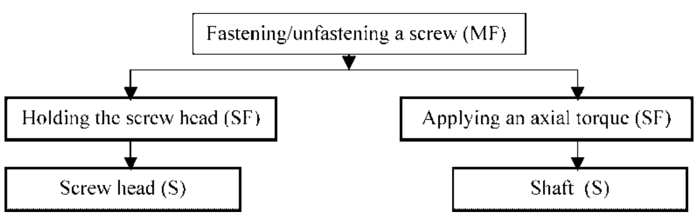

Figure 7. FM tree for screwdriver. MF = main function, SF = subfunction, S = structure.

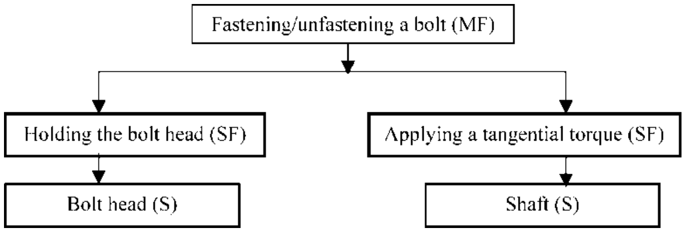

Figure 8. FM tree for wrench.

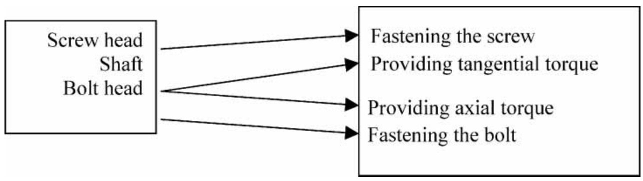

Figure 9. Mapping of structure set onto subfunction set.

Here:

$$\mathrm{RE} = \frac{\text{number of main functions}}{\text{number of structures}} \tag{2}$$

Philosophically, RE is approached with the view to achieve efficiency in terms of the number of distinct physical entities used in attaining the desired functions. This may not translate into efficiency in generic terms. In order to evaluate the validity of this definition we have evaluated the link between this RE and cost-effectiveness of a product (see section 7).

For the example considered earlier (screwdriver-cum-wrench), we have RE $= 2/3$. According to this definition, RE is:

- Directly proportional to the number of main functions of a product.
- Inversely proportional to the total number of structures that appear at the end of the FM tree.
- Independent of the number of SFs appearing at intermediate levels of abstraction.
- The measure of RE cannot be directly inferred from the degree of SS. Rather, it depends entirely on the MFs and the structures.

RE should in general be higher with mere simplification of a design. This means that for the same MF, a design with the least branching of its FM tree should have more RE. A design with lesser number of SFs and structures should be more efficient.

5. Examples of SS and RE

5.1 *Example 1: corrosion rate testing vessel*

Here, case 1 has an acid-filled container with samples of alloy dipped inside to check the rate of corrosion of the sample (figure 10). The MF is to measure the rate of corrosion. Again, using the FM tree, the structures and SFs can be identified. Here, the corresponding mapping is shown in figure 11.

Using equations (1) and (2), the values of the parameters in this case are: degree of SS $= 3/3$ (three SFs, three structures) (i.e. no SS is seen here) and RE $= 1/3$ (one MF, three structures).

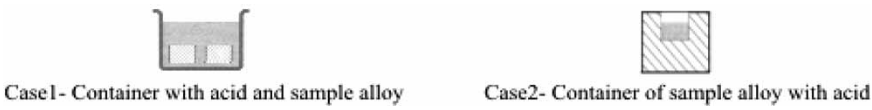

Figure 10. Corrosion rate testing vessel.

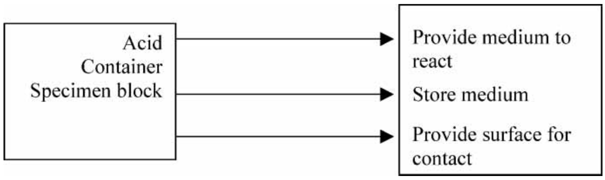

Figure 11. Structure to subfunction mapping for the system in case 1 (figure 10).

In the second case, the container is made of sample alloy and filled with acid. Here again, the MF is to measure rate of corrosion. Similarly we have case 2 (figure 12).

Here, the values are: degree of SS = $3/2$ (three SFs, two structures) and RE = $1/2$ (one MF, two structures).

5.2 *Example 2: writing board*

The first case involves a writing board with a hole and a separable elastic band to wrap around (figure 13). The MFs are: provide base to support, hold papers, and hang the board. From the corresponding three FM trees we can identify the SFs and associated structures. The structure to SF mapping is shown in figure 14.

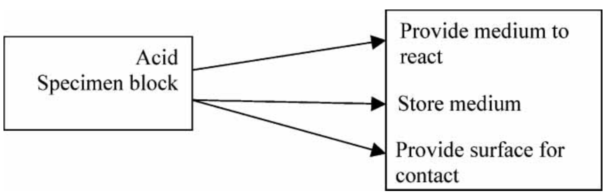

Figure 12. Structure to subfunction mapping for the system in case 2 (figure 10).

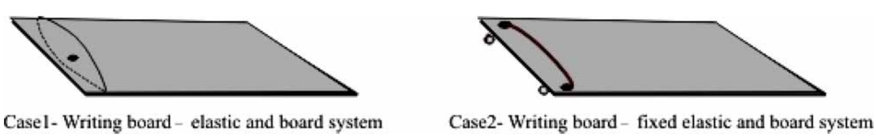

Figure 13. Writing boards.

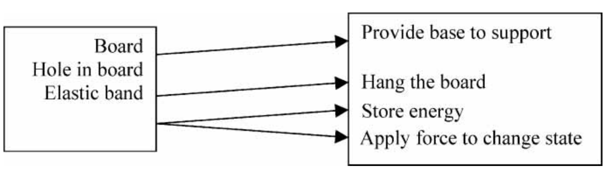

Figure 14. Structure to subfunction mapping for the system in case 1 (figure 13).

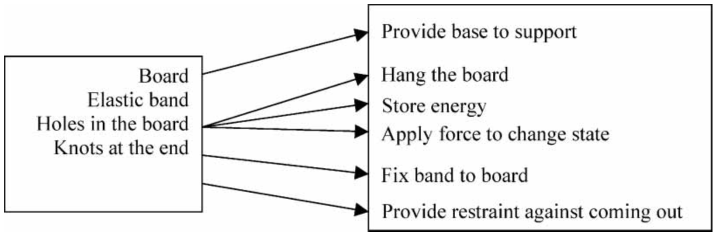

Figure 15. Structure to subfunction mapping for the system in case 2 (figure 13).

The values of the parameters in this case are: SS $= 4/3$ and RE $= 3/3$. In the other design, the board has two holes to fix the elastic band (figure 13). The MFs are: provide base to support, hold papers and hang the board. Mapping for case 2 is shown in figure 15.

The values of the parameters in this case are: SS $= 6/4$ and RE $= 3/4$. Here, the degree of SS is more even though it has less RE than in the first case. This supports our earlier inference that RE cannot always be said to be increasing with increase in SS. Keeping this in mind, guidelines for generating a more structure shared and resource effective solution have been developed.

6. SS guidelines for enhancing RE

The guidelines proposed here are more of a checklist of steps to ensure that the problem has been approached from different directions towards achieving the same goal of increasing RE through SS. For problems of smaller scale where the structures and corresponding functions are easier to find, one can skip the first step, although it is still recommended so as to ensure a better understanding of the problem.

1. Make a Bill of Materials (BOM) for the product and list the various functions and structures within it. The format of the BOM should be as following:

Sl.no.	Assembly Components Structures	Quantity	Function (S) corresponding to each structure	Materials and manufacturing process

2. Identify MFs in the product and make an FM tree for each MF separately.
3. Use the BOM as a checklist to verify the completeness of the FM tree.
4. Apply one of the following to generate more structure-shared solutions.
   a. Look out for alternative solutions (principles and corresponding means, *e.g.*, function of ‘apply forces’ can be achieved in different ways like nuclear, gravitational, electromagnetic, etc.) to achieve the functions occurring at different levels of abstraction.
   b. Identify the properties of the structures responsible for their corresponding functions. Look for commonalities of properties in different structures within the same FM tree. Try eliminating one of the structures by using the property common with the other structure for fulfilling the function(s) performed by the former. This is applicable to overlapping properties across the different FM trees within the product.
   c. Apply the earlier steps in various branches within the tree. For this purpose one can move either bottom up or top down.

d. Reduce the number of repeating elements for the same function (multiple elements resulting in function sharing).
e. Within a given part try integration through creative designs and selection of appropriate manufacturing processes.
f. Try reducing the number of assemblies by appropriate integration at the assembly interface.
g. Reduce the need for separate fasteners by appropriate connectors like snaps and fits.
h. Try reducing the variety in the use of different manufacturing processes within a product.

Various creative design techniques such as brainstorming, SCAMPER (Michalko 1991), lateral thinking (de Bono 1970), TRIZ (Altshuller 1984, Savransky 2000), and analogy (Goel 1997, McAdams and Wood 2000) can be used alongside at different levels of abstraction.

7. Experimental evaluation

In order to evaluate the guidelines, experiments were conducted in three phases:

- Phase 1—with researchers: to check the usability of the guidelines. This checks the clarity of communicating the guidelines to the user.
- Phase 2—with groups of non-experienced designers: to compare the method effect with group effect. This was done to check the effectiveness of the guidelines across different groups.
- Phase 3—with experienced designers: to check whether the guidelines can help generate more and better concepts (in expected terms) than otherwise. This helped in comparing the design solutions generated with and without the guidelines.

Once the guidelines were found usable by trying them on given problems by the researchers involved, these were ready to be taken to the next phase.

7.1 *Experiments in phase 2*

In the second phase two teams of two members each were used. Two design problems were selected and each team was asked to solve each of these problems, one without any guidelines and the other with the help of these guidelines. In order to reduce the influence on the result due to the inherent difference in creative ability of the teams, the problems were swapped as shown in table 1.

Problem 1 involved the redesign of a given camera tripod stand. Problem 2 was about redesigning a given clipboard. The first session involved problem-solving without guidelines, while the second session involved problem-solving with guidelines.

Table 1. Matrix showing the problems and the groups involved.

	Group 1	Group 2
Problem 1	With guidelines	Without guidelines
Problem 2	Without guidelines	With guidelines

7.1.1 Findings from the experiments in phase 2. Findings from the experiments in phase 2 are as follows.

- There was not much difference in the number of concepts generated with or without guidelines (5 against 4 in experiment 1, 8 against 5 in experiment 2).
- A number of concepts generated without guidelines were not as resource effective as the given solution (3 out of 9 solutions in experiments 1 and 2 generated without the guidelines were less RE than the given solution).
- The concepts generated with the help of guidelines were focused and similar in nature. The concepts generated here were more resource effective than the given solution. Many a times the concepts generated later were an improved version of the ones generated earlier.
- In all cases a better structure-shared solution was also more resource effective. Besides, a more resource effective solution was also more cost effective.
- Tables 2 and 3 summarize the results from these experiments. The tables list the design solutions generated in corresponding cases and the main features, degree of SS, RE and cost of each of these solutions.

7.1.2 Experiment 1: redesign of given tripod stand. A regular stainless steel camera tripod stand was given (see figure 16). The values of the parameters for the given tripod stand are: SS $= 71/53$, RE $= 3/53$, approximate cost = Rs.780.

The vacant cells marked with a dash mean that the concepts were not detailed enough to calculate the number of structures correctly. The costs shown here are the approximate direct variable cost (Pahl and Beitz, 1996, Otto and Wood, 2001), and include material costs, processing costs, labour costs and the assembly costs (Malvade, 2003).

Group 1, working without the method, generated four solutions, of which, only one was detailed enough to calculate the SS and RE values. While three of the four solutions had lesser number of structures than the given design, the fourth used more number of structures but reduced the volume of material used and hence a marginal reduction in cost. On the other hand, group 2, working with the method, generated five solutions, all of which had lesser number of structures than the given solution. Here, the two solutions, which were detailed enough, had better SS, greater RE and were more cost-effective than the given solution.

7.1.3 Experiment 2: redesign of given writing board. A regular hard board-writing pad (see figure 17) with a sheet metal clip was given. The values for the given writing board are: SS $= 7/13$, RE $= 3/13$, approximate cost = Rs. 850.

In experiment 2, the same groups were used as in experiment 1. However, here group 2 worked with the method while group 1 worked without the method, opposite to experiment 1. The two experiments were conducted simultaneously, where the sessions without the method were finished first.

In experiment 2, group 2, working without the method, generated five solutions of which only three were better SS and had greater RE than the given design solution, while four out of five solutions were more cost-effective. In contrast, group 1, working with the method, generated eight solutions, which were all better SS and had greater RE than the given design solution. All of these solutions generated with the method were also more cost-effective than the given solution.

Comparing the results from experiment 1 and experiment 2, we see that the method is effective in helping to generate more number of solutions in a given time, which are also better SS and have greater RE and cost-effectiveness as compared with the solutions generated without a method. The designs generated using the method were also found to be simpler.

Table 2. Solutions generated for the tripod stand shown in figure 16.

Number	Group 1 (without method)					Group 2 (with method)				
	Solution	Features	SS	RE	Cost	Solution	Features	SS	RE	Cost
1	Ball and socket		–	–	–	Ball and socket		–	–	–
2	Material reduction	More structures	71/55	3/55	760	Modified legs	Fewer structures	71/50	3/50	760
3	Remove a tier of extension	Function quality reduced	–	–	–	Remove a tier of extension	Function quality reduced.	–	–	–
4	Flexible tube	Novel concept, fewer structures	–	–	–	Pedestal type	Simpler, function quality reduced	57/36	3/36	725
5				Modified locking	Use of fits	–	–	–		

Table 3. Solutions generated for the writing board shown in figure 17.

	Group 2 (without method)					Group 1 (with method)				
Number	Solution	Features	SS	RE	Cost	Solution	Features	SS	RE	Cost
1	Profile change	More complex	8/15	3/15	8.5	Base-pad integrated	Fewer structures	6/10	3/10	6.0
2	Cut and bend	Fewer structures	5/5	3/5	5.5	Moulded parts	Fewer structures	6/5	3/5	5.0
3	Different clamping system	Same complexity	9/15	3/15	6.5	Different clamping system	Fewer structures	6/8	3/8	6.5
4	Plate clamp	Fewer structures	7/5	3/5	5.0	Holder type	Integrated, simpler	4/4	3/4	4.5
5	Push ball	Fewer structures	7/6	3/6	5.0	Plate clamp	Fewer structures	6/6	3/6	5.0
6				Bar clip	Fewer structures	9/7	3/7	6.0		
7				Pad elastic band	Simpler, fewer structures	4/3	3/3	4.0		
8				Corner pockets	Repeating structures	4/3	3/3	4.0		

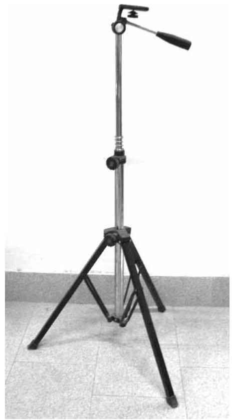

Figure 16. Tripod stand used in the experiment.

Figure 17. Writing pad used in experiment 2.

7.2 *Experiments in phase 3*

In third phase, experienced designers were used. The individual designers were given the same problem in both the sessions. Guidelines were introduced to them only in the second session. This was done to see whether the guidelines could help them generate further concepts on the same problem on which they have already worked. Furthermore, it would also facilitate the comparison of the solutions generated in the two sessions. The results of the experiments are presented in Tables 4 and 5.

7.2.1 Experiment: redesign of given spotlight. An aluminium lampshade with a mounting system was given (see figure 18). The values for the given spotlight are: SS $= 28/26$, RE $= 4/26$, approximate cost = Rs. 125.

In experiment 3, participant 1 generated five solutions without the method and four solutions after the method was introduced. While all the solutions generated were better SS and had greater RE, at least one solution generated using the method was remarkably more cost-effective than the other solutions. Participant 2, on the other hand, generated six solutions without the method and three solutions after the introduction of the method. Here again, all the solutions generated were better SS, had higher RE and were more cost-effective than the given solution. Noticeably, there was no remarkable difference in the solutions generated by participant 2 between the two sessions.

Experiment 3 exhibited the ability of the method to help the designer generate additional solutions that were not generated by the same designer in the session without the method. However, in the second session, although the solutions generated with the method were not

Table 4. Solutions generated for the spotlight in phase 3 without the method.

	Participant 1					Participant 2				
Number	Solution	Features	SS	RE	Cost	Solution	Features	SS	RE	Cost
1	Spherical shade	Function quality reduced	–	–	–	Vacuum clamping	Reduced complexity	27/21	4/21	105
2	Coiled wire shade	Fewer structures	22/16	4/16	80	Integrate bulb and shade	Complex	–	–	–
3	Modified clamp	Function quality reduced	–	–	–	Thick insulated wire	Fewer structures	20/17	4/17	95
4	Eye ball shade	Function quality reduced	–	–	–	Eye ball shade	Function quality reduced	–	–	–
5	Flexi-shade	Fewer structures	24/19	4/19	95	Flexi-holder	Fewer structures	28/26	4/26	115
6						Reflecting mirror	More structures	20/18	4/18	80

Table 5. Solutions generated for the spotlight shown in figure 18.

	Participant 1					Participant 2				
Number	Solution	Features	SS	RE	Cost	Solution	Features	SS	RE	Cost
1	Ball joint-changed base	Fewer structures	–	–	–	Holder and shade integrated	Fewer structures	24/22	4/22	90
2	Thick wire	Fewer structures, simple	20/17	4/17	95	Holder-bulb integrated	Complex	–	–	–
3	Moulded shade	Fewer structures,	–	–	–	Modified bulb	Integration	–	–	–
4	Flexi-tube, coating	Physical shade removed	16/16	4/16	40					

Figure 18. Spotlight used in experiment 3.

necessarily remarkably improved for both the participants, they were still better than the given solution in terms of SS, RE and cost.

Some of the feedback received from the participating designers was:

- Although the BOM and FM tree help in understanding the given design better, they consumed a significant proportion of time allocated for the experiments.
- It was generally felt that generating the FM tree needs some practice.
- An earlier exposure to methods such as Design For Manufacture and Assembly (DFMA) was helpful in understanding the guidelines.

8. Comparison with related methods

A discussion on these guidelines would remain incomplete without an appropriate comparison with the related methods, namely Value Analysis (VA), DFMA, the Function Analysis System Technique (FAST) and Subtract and Operate (SOP) (Pahl and Beitz, 1996, Otto and Wood, 2001, Ulrich and Eppinger, 1995, Lindbeck and Wygant, 1995). VA is based on the application of function analysis to the component parts of a product. It supports cost reduction activities by relating the cost of components to their function contributions.

FAST builds upon VA by linking the simply expressed, verb–noun functions to describe complex systems. FAST differs from VA in the use of intuitive logic to determine and test function dependencies and the graphical display of the system in a function dependency model. Another major difference is in analysing a system as a complete unit, rather than analysing the components of a system. Unlike the FM tree, FAST does not give structures at the end of the tree. It only shows the MF and SFs. The importance of identifying the structures can be established based on earlier literature (Lawson 1990, Schon 1992), which suggest that designers often work reflecting on the materials, details and constructions within the design task through drawings or in real world.

On the other hand, SOP focuses on component elimination. This not only narrows down concept exploration, but also inherently misses the function details that would otherwise be understood at a structure level.

VA or Function Analysis provide methods for identifying the problem and defining the functions that need to be performed. It does not suggest guidelines or methods to generate solutions. Performing VA or producing the FAST model and analysing functions with the VA matrix are only the first steps in the process. Further work must involve developing and analysing potential improvements in the product.

The guidelines therefore should work well in conjunction with the VA process and build on from where function analysis ends.

DFMA guidelines look similar at first glance. However, the difference lies in the fact that we are primarily interested in looking at structure level rather than component level. The DFMA guidelines also talk about integration and part reduction but do not suggest methods and approaches to do the same. DFMA guidelines should work well with the guidelines proposed above to make design solutions more resource effective.

Once the concepts have been generated, the measure of RE should help concept evaluation better and in a more objective way. This ability to objectively analyse and compare the generated concepts makes the method particularly useful. During the design evaluation this measure can also be applied to different subtasks of the design to assess which sections need greater emphasis and rework.

9. Conclusions and future work

Functions and structures in a product can be identified using an FM tree. The FM tree for a product also helps in evaluating its degree of SS and RE. The functions and structures occur at various levels of abstraction in an FM tree. While for evaluation of SS the structures at the lowest level of abstraction are used, RE is calculated using the total number of functions at the highest level of abstraction. It is important to note that in cases where the MF also relates immediately to a structure, then for the purpose of calculation of SS it is also considered as an SF; that is, functions considered for the purpose of evaluating SS are those that immediately precede a structure.

SS is the ratio of number of functions at the lowest level of abstraction to the number of structures in a product. RE is the ratio of number of functions at the highest level of abstraction to the total number of structures. This implies that the measure of RE cannot be directly inferred from the degree of SS. Rather, it depends on MFs and structures. However, RE of a product can usually be increased through improved SS, which has also been found to increase the cost-effectiveness of the product in general.

The following are some of the limitations of the current status of the guidelines, which are likely to modify the values of SS as well as RE:

- Accounting for the quality of function (QOF): QOF refers to the nature of function, the extent to which a structure fulfils a function and how efficiently the function is fulfilled. The QOF has not so far been considered. However, there seems to be a clear indication that the QOF has a definite role to play while considering RE. This area needs to be explored.
- Accounting for the harmful functions in the design: so far only the positive functions are considered (i.e. harmful functions do not feature in the discussions and they are not accounted for).
- Currently there is no provision for penalizing the design solutions that generate additional SFs. This needs to be explored and incorporated.
- RE has so far been discussed with respect to the function module only. However, it has also to be looked from production and retirement phases of the lifecycle so as to obtain a more integrated assessment.

Finally, relationships of this method and its concepts with that of other, possibly related methods need investigation, and triangulation of its results using other cost estimation methods. These include axiomatic design theory (Lawson 1990, Schon 1992), robustness methods (for example, Olvander 2005), reliability methods (for example, Tsai 2005), and cost estimation (for example, Hicks *et al.* 2002).

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