STRUCTURE SHARING AND MULTI-MODE INTEGRATION IN SUCCESSFUL DESIGNS: AN EMPIRICAL STUDY

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ABSTRACT

Structure sharing (SS) and multi-mode integration (MMI) are types of sharing in designs that help in resource effectiveness. This research explores their prevalence in successful designs. To do this: (a) 5 award-winning designs from International Design Excellence Awards are chosen, information of these designs is used to construct their Function-Means Tree and this is used to check whether they exhibit SS or MMI, and (b) 250+ award-winning designs are examined via a longitudinal study to check whether they exhibit SS or MMI. The following observations are made: (a) both SS and MMI are seen at systemic and sub-systemic levels, (b) both SS and MMI are and can be present in designs and (c) close to 35% of 250+ designs examined exhibited SS or MMI. These are fundamental insights, have not been reported earlier and build on the existing work on SS and MMI.

Keywords: Case study, Design methods, Product structuring, Resource effectiveness, Sustainability

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1 INTRODUCTION

Design is defined as a purposeful, goal-oriented activity that generally results in the plan for at least an artefact that can meet the desired purpose(s) (Gero, 1990). The purpose(s) is/are explained as the function(s) of the artefact (Gero, 1990; Chakrabarti et al., 2013), which is/are typically realized through a set of structures(s) that fulfil the functions. Consequently, it is common to discuss design in terms of functions and structures (Hubka and Eder, 1988; Gero, 1990; Andreasen, 1992).

Researchers have posited the notion of sharing in designs and explained it in terms of the possible mapping between functions and structures associated with the designs (Chakrabarti, 2001, Chakrabarti and Regno, 2001, Chakrabarti and Singh, 2007). Sharing in designs seems to be exhibited in daily life in diverse forms, ranging from multi-purpose designs to sharing-based product-service systems to the ideas of shared economy. That is, the concept of sharing in designs can have wide ranging implications. Although sharing appears to be common, no empirical investigation has been done to check the prevalence of sharing in designs.

Since the different types of sharing in designs are distinguished in terms of function-structure mapping, any method that seeks to elicit sharing in a design will require to decompose the design in terms of its functions and structures. There are several models in literature that use Function and Structure to explain designs. Previous work on sharing in designs (e.g. Chakrabarti and Singh 2007, Ghazanfari and Singh 2017) has used the Function-Means decomposition (FMD) approach of Andreasen (1992).

Therefore, the broad objective of this research is to investigate the prevalence of sharing in designs that are typically considered to be successful. This research builds on the existing work, while raising some fundamental questions on this topic.

2 LITERATURE REVIEW AND OBJECTIVES

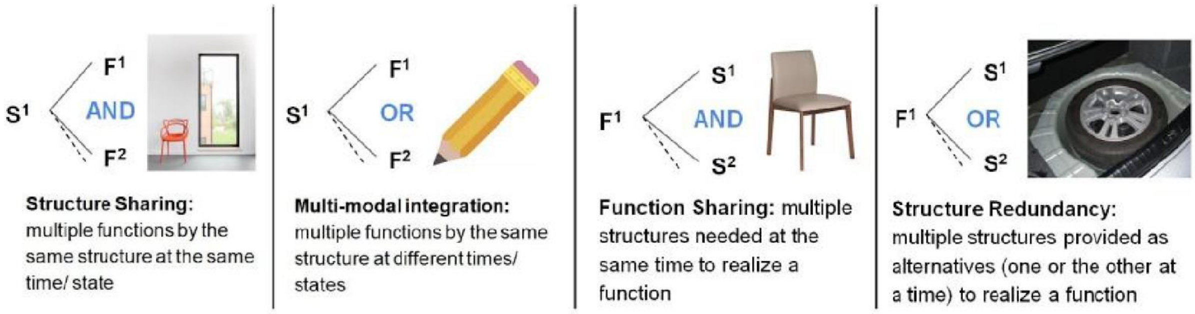
This section reviews literature on sharing in designs, measures & desirability of sharing and function-means tree.

2.1 Types of sharing in designs

Based on the function-structure mapping, Chakrabarti (2001) distinguishes four kinds of sharing in designs, as shown in Figure 1. Structure sharing refers to the case where more than one function is achieved by a structure at the same time. That is, there is one-to-many relation between some structure and associated functions, where multiple functions are simultaneously active. While Multi-mode integration also includes one-to-many relation between some structure and associated functions, only one function or some functions but not all are actively achievable at any given time. In contrast to structure sharing and multi-modal integration, the other two sharing modes refer to designs that demonstrate one-to-many relation between some function and associated structures. In function sharing, more than one structure collectively combines at the same time to achieve one function. On the other hand, in structure redundancy, even though multiple structures are available to achieve the function, at any given time, only one or more of the structures is needed to achieve the function, while the other structure(s) serve as a back-up. Examples for the four kinds of sharing are shown in Figure 1. A fixed glass pane window exhibits structure sharing because the glass panel provides a physical barrier and allows light to pass through at the same time. The pencil in Figure 1 exhibits multi-mode integration because at any given time one can either use it to write or to erase, while holding the shaft that is shared. The four legs in the chair exhibit function sharing because they collectively provide the function of transferring load while providing stability. And finally, the spare wheel provides a backup for the function that is already provided by the wheels on which the vehicle is running.

2.2 Measures for sharing in design, and the desirability of sharing

Following the classification of the four types of sharing in designs, Chakarabrti (2001) argues that structure sharing and multi-mode integration are more desirable, especially the former, because both these approaches are more resource effective than the other two modes. Accordingly, the work (for instance, Chakrabarti and Singh (2007), Ghazanfari and Singh (2017), etc.) that followed has investigated measures for assessing the role of structure sharing in generating resource effective solutions. However, Singh and Srinivasan (2021) observed that some of the examples used in the previous studies (Chakrabarti and Singh, 2007; Ghazanfari and Singh, 2017) of structure sharing were in fact multi-mode integration. Hence, they argue that both structure sharing and multi-mode integration, collectively under the umbrella of multi-functional designs, could be assessed using the same measures for their levels of resource effectiveness and desirability. A number of factors that could be considered in assessing the desirability, level of resource effectiveness of such multifunctional designs have been identified in the literature (Chakrabarti and Singh, 2007; Ghazanfari and Singh, 2017), including the number of functions and structures, the Relative Importance (RI) of the different functions performed, the Quality of Functions (QoF), and the emergent Negative Functions (NF) in a multifunctional design that do not exist when the separate functions are not combined in the same design.



Structure Sharing: multiple functions by the same structure at the same time/ state

Multi-modal integration: multiple functions by the same structure at different times/ states

Function Sharing: multiple structures needed at the same time to realize a function

Structure Redundancy: multiple structures provided as alternatives (one or the other at a time) to realize a function

Figure 1. Four types of sharing in design based on Function-Structure mapping

Therefore, with further investigation into sharing in designs, the factors affecting the assessment of sharing and desirability have gone beyond the simple mapping of the number of functions and structures to the quality of functions, which is typically associated with the behaviours associated with the structures enabling those functions. This is further illustrated in the work of Ghazanfari and Singh (2017) on behaviour-related affordance-based opportunities and their implications for sharing in designs. With this increasing significance of behaviour-based discussion in literature on sharing in designs, it is reasonable to investigate the efficacy of the current default approach of FMD of designs.

2.3 Function-Means Tree

The Function-Structure mapping is a complex process that needs a methodological approach to identify the various functions and structures in a design. One of the ways to do so is to begin with the identification of the main function(s) (MF) of a design and proceed down the path along each main function. Main functions are intended effects/purposes from the system at its highest level (Chakrabarti and Singh, 2007). In case a system has more than one MF, these functions are not only the desired purposes at the highest level, but also independent of each other. Each independent main function will generate an independent FM tree. Based on Chakrabarti and Singh (2007), all functions evolving in a branch for the fulfilment of some other function at an immediately higher level of abstraction are called subfunctions (SFs).

A full FM tree may involve organs, processes and means, which relate to physical elements, technology, and principles, respectively (Andreasen, 1992). 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 a function. Means are the principles, laws or phenomenon that are responsible for the occurrence of the function. As outlined by Chakrabarti and Singh (2007), the key steps in generating a FM tree for a design are:

1. Each FM tree starts with a separate Main Function (MF). For designs that have only one MF, there will be a single FM tree, while for those with multiple MFs, there will be as many FM trees as the number of MFs.
2. By asking the question ‘HOW’, identify the immediate next node(s) branching from a MF. The immediate node(s) can either be a sub-function, a means, an organ, or a process.
3. For each node, unless it is a non-divisible structure (at the acceptable level of detail, i.e., not a combination of structures with sub-functions), look for further branching until a structure is reached. Thus, all the leaf nodes in the FM tree must be a structure.
4. The total number of leaf nodes (i.e., end points) in an FM tree gives the total number of structures for the purpose of computing the degree of sharing.

2.4 Research Objective

The objective of this research is to assess the prevalence of structure sharing and multi-mode sharing in award-winning designs which can deemed to be successful in some aspects, using the FMD approach of Andreasen (1992).

3 METHODOLOGY

To answer the research question, 5 designs that won the Industrial Design Excellence Awards (IDEA) organised by Industrial Designers Society of America (IDSA) (IDEA Gallery, 2020), are chosen (see Fig. 2). These designs are: (a) LG Dual Ceiling Fan (LG Dual Ceiling Fan, 2020 a,b) (Fig. 2a), (b) LifeStraw home glass water filter pitcher (Lifestraw Home Glass Water Filter Pitcher (2020 a,b) (Fig. 2b), (c) Dream Ring Concept (Dream Ring Concept, 2020) (Fig. 2c), (d) Zip Top reusable containers (Zip Top Reusable Containers, 2020 a,b) (Fig. 2d), and (e) Y Bell exercise equipment (Y Bell, 2020 a,b) (Fig. 2e). The choice of 5 designs for this research was based on satisfying all the following criteria: availability of sufficient information to construct a Function-Means Tree (FMT), simplicity of designs for effective communication for readers, and effectiveness of representation of FMT within the manuscript limits. In IDEA, the designs are judged by a Jury appointed by IDSA, based on the following criteria: (a) Design Innovation (newness, criticality of the problem being solved, cleverness of solution), (b) Benefit to User (improvement of a user's life through the design, accomplish things not previously possible), (c) Benefit to Client/Brand (business impact of the design, design as a key market differentiator), (d) Benefit to Society (consideration of social and cultural factors, design and manufacture with sustainable methods/materials) and (e) Appropriate Aesthetics (relation of form of the design adequately to its use/function, use of colours/materials/finishes to fit design's purpose) (Judging Criteria, 2020). From the textual and video description of these designs, the following are identified: (a) the various main functions and sub-functions, (b) the various structures that together constitute the design, and (c) the relationships between them. By using the FMD and the information of functions and structures of these designs, a FMT is created; using FMT, structure sharing and multi-mode integration are identified.

Figure 2. Five examples of awarded designs that exhibit sharing in design

To check the desirability of sharing in designs, a larger pool of designs drawn from the IDSA design awards is analysed to check how many of the awarded designs exhibit some form of sharing. The five design concepts shown in Figure 2 belong to the same pool of designs. This approach is built on the premise that design solutions that have been listed in the design awards, and judged by a jury of experts, can be deemed successful based on the criteria listed earlier. Furthermore, in analysing the awarded designs for sharing, the description of the awarded solution is also evaluated. Only those entries in which sharing in design is visible (qualitative judgement by the authors) the reason for the solution's unique selling point(s) was counted as a positive case (see Fig. 3).

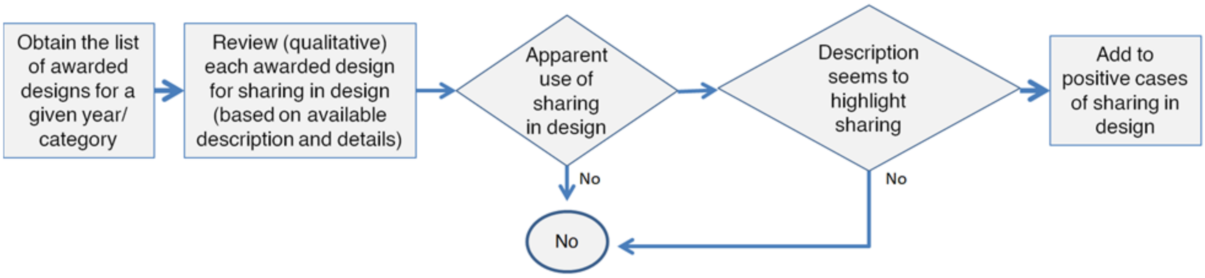


Figure 3. Process to identify how many of the awarded designs exhibit sharing in design

4 FINDINGS

In this section we describe our findings related to the research objective:

4.1 Function-Means Tree of Existing Designs

The function-means tree of the 5 designs can be seen in Figures 4-8. A main function is represented by a rectangular box, a sub-function by a box with rounded edges and a means by a circle.

Designs exhibit structure sharing or multi-modal integration at multiple levels. In this research, only two levels are explored: systemic and sub-systemic. Examples of structure sharing at systemic level are: (a) the LG dual ceiling fan is able to perform the functions of circulating air, reducing dead zone and driving mosquitoes away, simultaneously, and (b) the Lifestraw homeglass water filter pitcher is able to store tap water, filter tap water and store filtered water at the same time. Instances of structure sharing at sub-systemic level are: (a) the 7-cup borosilicate structure (a sub-system of the Lifestraw homeglass water filter pitcher) is able to perform the functions of removing microplastics, bacteria and parasites, reducing concentration of some heavy metals, and reducing chemical contaminants, and (b) the Si-Pt material, a sub-system of Zip Top Containers, allows the containers to withstand the high temperatures of microwave, oven and low temperatures of freezer without any alterations. Some cases of multi-mode integration at systemic level are: (a) the Dream Ring Concept allows either collecting or disposing the menstrual discharge, but not both simultaneously, and (b) the Y Bell allows training muscles with one hand grip, two hand outer grip or in the push-up mode. Some instances of multi-mode integration at sub-systemic level are: (a) the sugarcane vinyl cup (a sub-system of the Dream Ring Concept) can collect menstrual discharge (by virtue of its shape) and allows disposability (by virtue of its biodegradability), but both these are not possible simultaneously, and (b) the silicone ring (a sub-system of the Dream Ring Concept) allows inserting and removing the menstrual cup (by virtue of its flexibility and elasticity), but not both the functions simultaneously.

Some designs exhibit both structure sharing and multi-mode integration. The Y Bell has multi-mode integration at the systemic level as explained earlier but the (centre and outer) handles - a sub-system of Y Bell - provide grip and have weight; these are required to perform various exercises. In other words, the handles have structure sharing at the sub-systemic level. This identification may not have been possible without identifying sharing at multiple levels (systemic and sub-systemic).

4.2 Sharing in award finalists and winning designs

To understand how often sharing in design is observed in designs that are appreciated by other stakeholders, all the finalists in the IDSA Design Awards 2019 were assessed qualitatively for potential sharing in design, namely structure sharing and multi-modal integration. As explained in Figure 3, the assessment was qualitative and subjective because of the limited amount of details that were available for each of the designs. Altogether 253 designs across different awards categories such as consumer technology, automotive and transportation, commercial & industrial products, etc. were analysed. Wherever there was adequate clarity to conclude with confidence that a specific case demonstrated sharing in design or not, it was either classified as ‘Yes’ or ‘No’ respectively. However, in cases where it was likely that sharing in design is a possibility, but there was uncertainty, the specific case was classified under the ‘NA’ category. Thus, based on this preliminary approach, out of the 253 design solutions that were reviewed, 89 demonstrated sharing in design (approx. 35.2%), 85 did not have any sharing in design (approx. 33.6%), and the remaining (31.2%) were inconclusive. That is, more than one third of the solutions that were chosen among the finalists, and hence, appreciated by the reviewers and critics, demonstrated sharing in design, particularly structure sharing and multi-modal integration. Thus, it appears that sharing in design is a desirable approach, which is either explicitly or implicitly incorporated by the designers in their solutions, and which are appreciated by others who are either experts or critics of design.

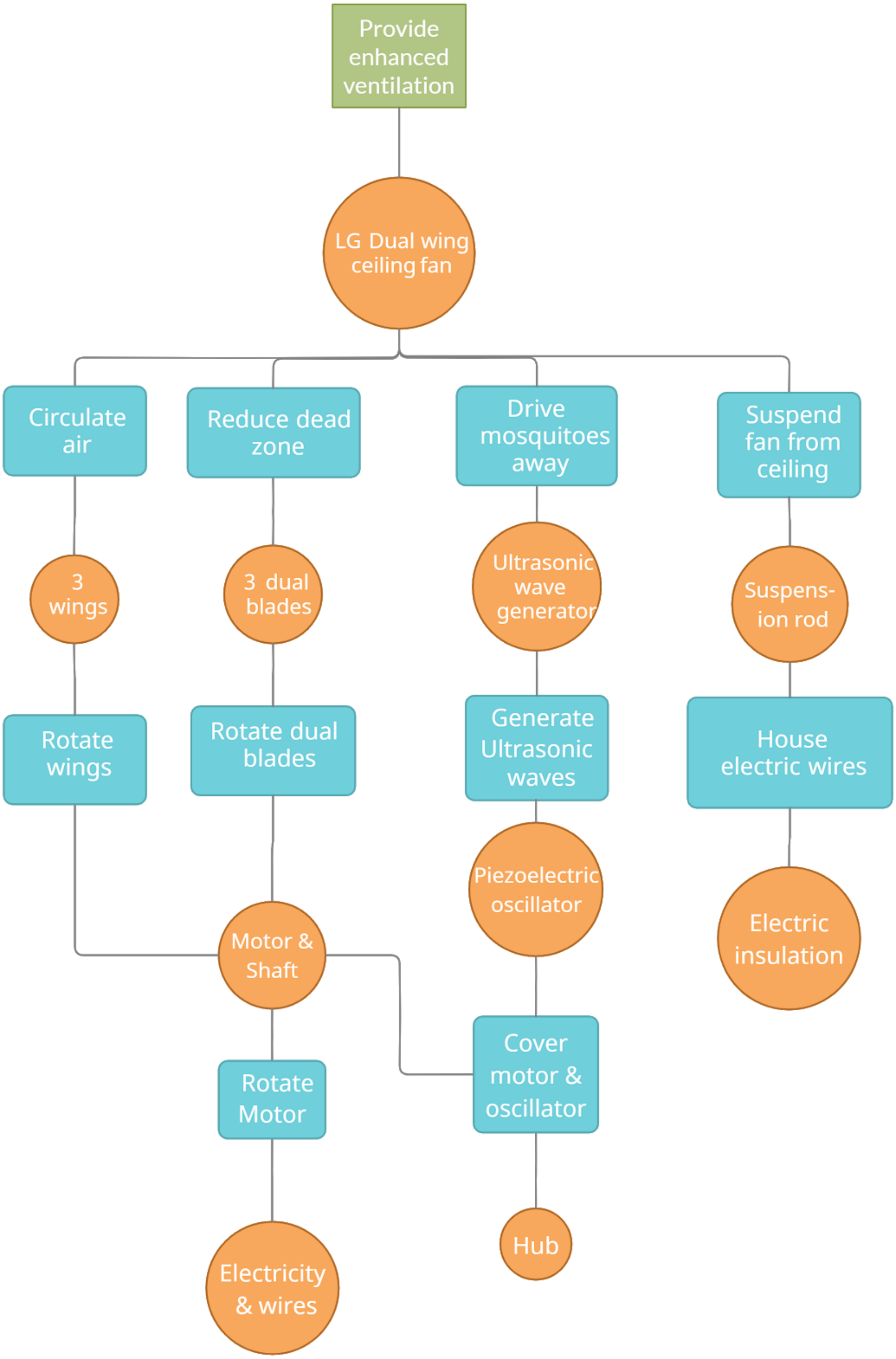


Figure 4. FM tree for the LG dual wing ceiling fan

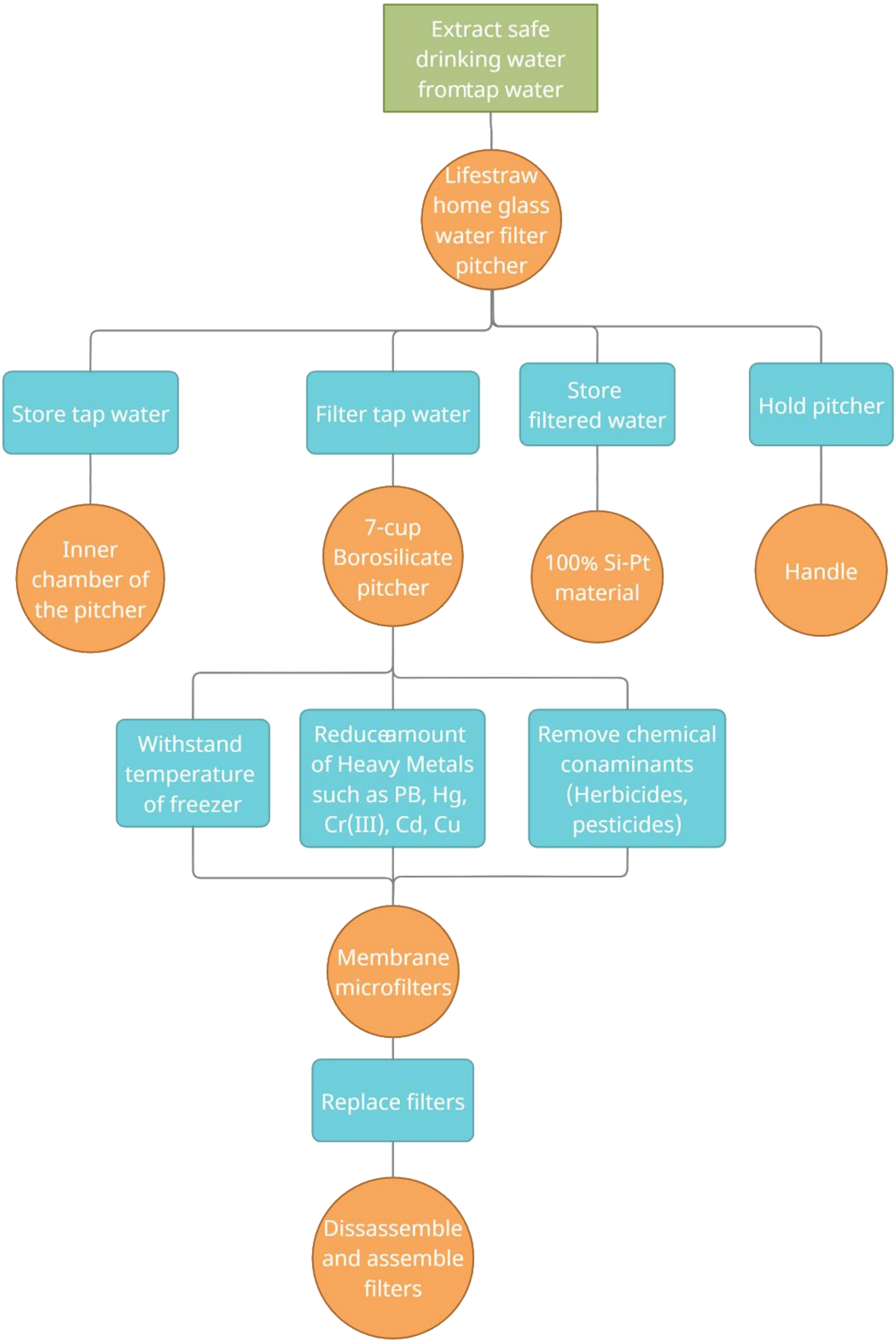


Figure 5. FM tree for the Lifestraw Home Glass Water Filter Pitcher

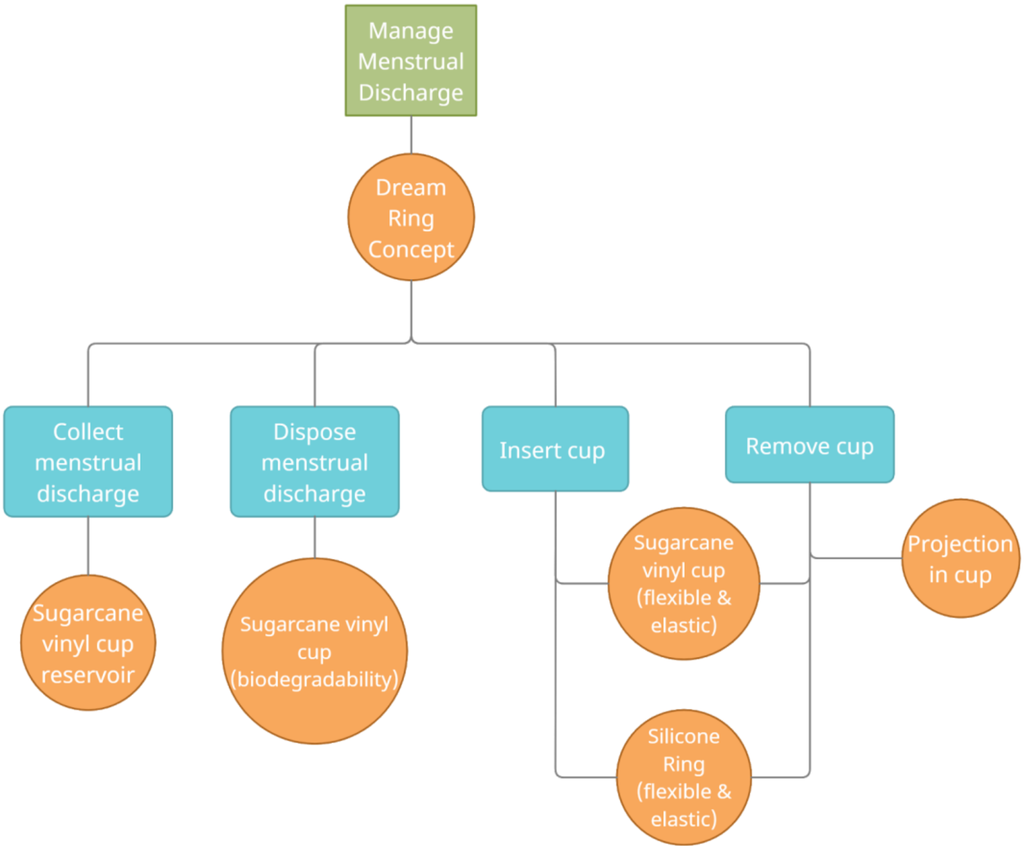


Figure 6. FM tree for the Dream Ring Concept

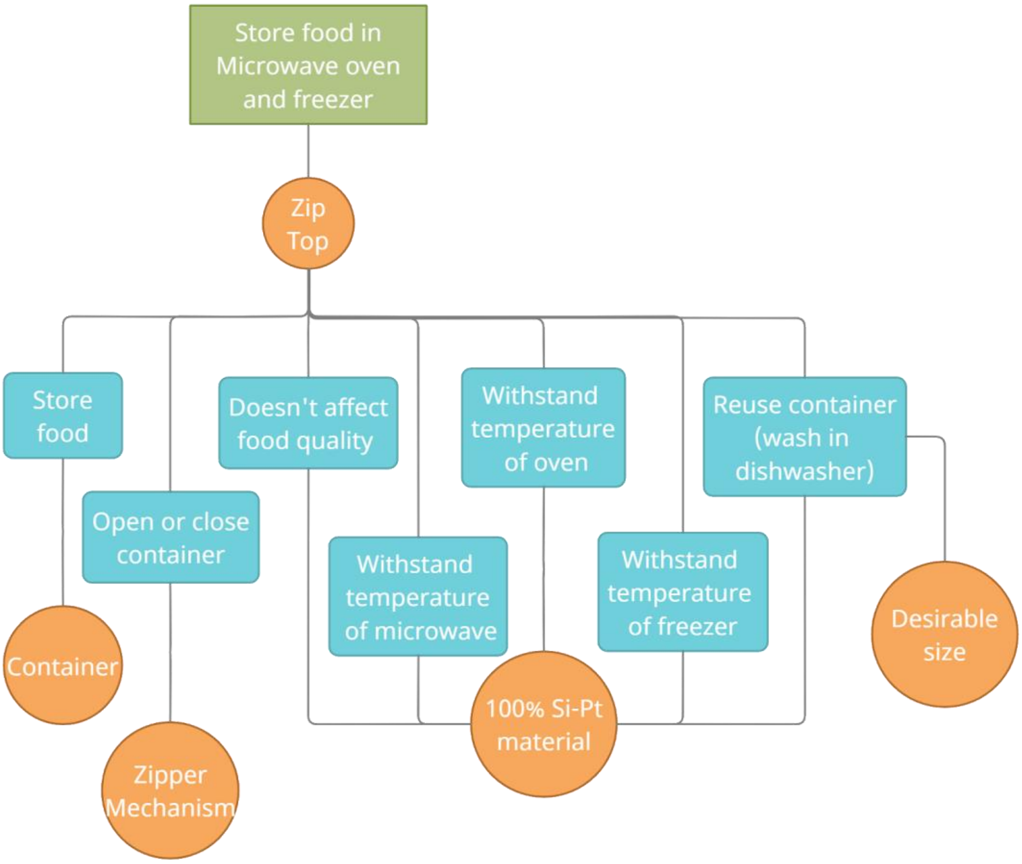


Figure 7. FM tree for the Zip Top Reusable Containers

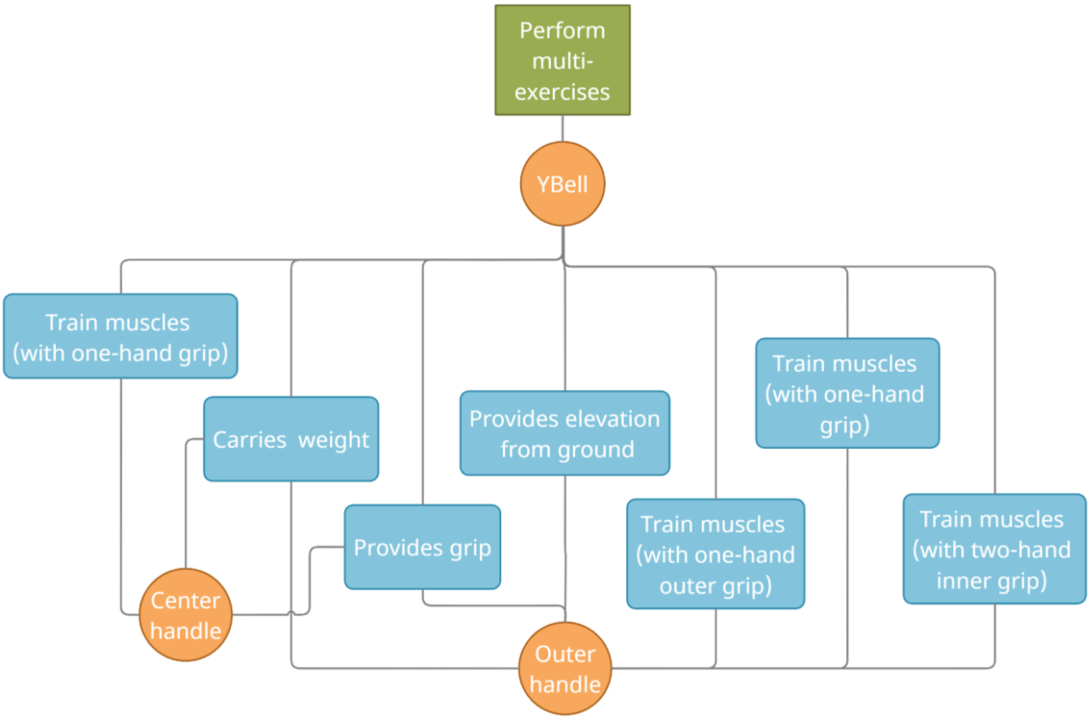


Figure 8. FM tree for YBell (gym and fitness equipment)

5 DISCUSSION

Structure sharing or multimodal integration can be observed at multiple levels (see Sec. 4.1). Therefore, it is not adequate to mention that a design uses structure sharing or multimodal integration without specifying at what levels this is observed. Earlier work (e.g., Chakrabarti and Singh 2007, Ghazanfari and Singh 2017) does not make this distinction. Sharing at multiple levels enables a design to exhibit both structure sharing and multi-mode sharing. Previous work does not explore this aspect.

The preliminary findings in Section 4.2 suggest a significant number of design finalists exhibit sharing in design, signifying that sharing in designs is appreciated. However, there are two important points to consider in interpreting the patterns observed. First, the analysis was based on a broad overview, with limited information, and without creating a FMT for the different cases. Second, we only know that nearly one third of the solutions within this pool of design finalists demonstrated sharing in design, but we do not have any benchmark to compare this proportion against. That is, we have not assessed this sample against a random sample of design solutions to check what percentage of typical design solutions exhibit sharing in design. It is only when we know the typical patterns in a random set that we can conclude whether one third is a good ratio or not. For instance, if we find that only 20% of the random design solutions exhibit sharing in design, while 35% of award finalists exhibit sharing in design, we can conclude that sharing in design is preferred. In contrast, if we find that 50% of typical designs demonstrate sharing in design, but only 35% of the award finalists exhibit sharing in design, it could mean that sharing in design may not necessarily be desirable. Therefore, while the findings are encouraging, it needs further benchmarking.

Based on the review of literature on sharing, only the FMD has been used to explain sharing in designs. However, the efficacy of FMD in assessing and developing sharing in designs has not been explored yet. There are other models of designs, such as the Theory of Technical Systems (Hubka & Eder, 1988), FBS model (Gero, 1990), SAPPhIRE model (Srinivasan & Chakrabarti, 2009), etc. that can also explain designs through their various levels of abstraction, including function and structure. A comparison of the descriptions of the shared designs through these models will help identify their pros & cons to explain sharing in designs, and this will help assess their individual efficacy.

In the first part of this research, the FMTs of 5 designs are constructed, based on the available information, to identify structure sharing and/or multimodal integration, at various levels of the system (see Sec. 4.1). The rationale for choosing these 5 designs is explained earlier (see Sec. 3). A limitation of this approach is that this sample is only a small representation of the award-winning designs.

However, the insights obtained through the analysis of these designs are interesting and deserve further exploration. In the second part of this research, 250+ designs from IDEA are examined in a cross-sectional study to assess whether they exhibit either structure sharing or multimodal integration. Though this examination is not robust, it draws experience from creating the FMTs in the first part of this research, in deciding whether structure sharing or multimodal integration is present in the designs.

In summary, both structure sharing and multimodal integration contribute to resource effectiveness. It is our conjecture that if more sharing happens at systemic than sub-systemic levels, it contributes better to resource effectiveness. This conjecture needs a detailed investigation. However, this also assigns additional burden on the bearing structures (means) to fulfil all the functions they are allotted. This may lead to higher wear and tear, shorter lifespan, more repair, service or replacements, etc. A systematic approach is needed to methodically assess how structure sharing influences a design from various viewpoints such as resource effectiveness, quality of functions, longevity, etc. Similarly, further investigation is needed on intuitive and perceived desirability of sharing in design across different stakeholders, ranging from designers to potential users, customers and independent critics and observers.

6 SUMMARY

The authors investigate the prevalence of sharing in designs by: (a) developing Function-Means Tree of 5 award-winning designs to identify structure sharing and multimodal integration at systemic and sub-systemic levels, and (b) conducting a longitudinal study of 250+ award-winning designs to check whether they exhibit structure sharing or multimodal integration.

REFERENCES

Andreasen, M.M. (1992), “The theory of domains”, Proceedings of Workshop on Understanding Function and Function-to-Form Evolution, Cambridge University.

Chakrabarti, A. (2001), “Sharing in design-categories, importance and issues”, ICED01, Glasgow.

Chakrabarti, A. and Regno, R. (2001), “Sharing in Design: Categories, Importance and Issues”, ICED01, 563–570, Glasgow.

Chakrabarti, A. and Singh, V. (2007), “A method for structure sharing to enhance resource effectiveness”, Journal of Engineering Design, 18(1), 73-91.

Chakrabarti, A., Srinivasan, V., Ranjan, B.S.C. and Lindemann, U., 2013. A case for multiple views of function in design based on a common definition. AI EDAM, 27(3), pp. 271-279.

Dream Ring Concept (2020), https://www.idsa.org/awards/idea/social-impact-design/dream-ringconcept. (Accessed in Jul, 2020)

Gero, J.S. (1990), “Design prototypes: a knowledge representation schema for design”, AI Magazine, 11(4), 26–36.

Ghazanfari, E. and Singh, V. (2017), “Structure sharing for resource effective solutions: Improving measures to account for importance and quality of functions”, ICED 17, Vol 7: Vancouver, Canada.

Hubka, V. and Eder,W.E. (1988), Theory of Technical Systems, Springer-Verlag: NewYork.

Hubka, V. and Eder,W.E. (2001) “Functions revisited”, in ICED 01, Glasgow, 21–23 August 2001.

IDEA Gallery (2020), https://www.idsa.org/IDEAgallery (Accessed in Jul, 2020)

Judging Criteria (2020), https://www.idsa.org/faqs. (Accessed in Jul, 2020)

LG Dual Ceiling Fan (2020a), https://www.idsa.org/awards/idea/home/lg-dual-wing-ceiling-fan. (Accessed in Jul, 2020)

LG Dual Ceiling Fan (2020b), https://www.youtube.com/watch?v=fys2qMEZjWg. (Acc. in Jul, 2020)

Lifestraw Home Glass Water Filter Pitcher (2020a) https://www.idsa.org/awards/idea/home/lifestraw-home-glass-water-filter-pitcher. (Acc. in Jul, 2020)

Lifestraw Home Glass Water Filter Pitcher (2020b) https://www.youtube.com/watch?v=rnG8XTPGotY (Accessed in Jul, 2020)

Singh, V. and Srinivasan, V. (2021), “Design of multifunctional artifacts as perceived by potential users: Findings from a preliminary investigation”, Int’l Conf. on Res. Into Design, Jan 2021, Mumbai, India. (accepted)

Srinivasan, V., and Chakrabarti, A. (2009), "SAPPhIRE–an approach to analysis and synthesis", 17th International Conference on Engineering Design, 417-428, Palo Alto.

Y Bell (2020a), https://www.idsa.org/awards/idea/sports-leisure-recreation/ybell. (Acc. in Jul, 2020)

Y Bell (2020b), https://youtu.be/hZOezL-_Eqo. (Accessed in Jul, 2020)

Zip Top Reusable Containers (2020a), https://www.idsa.org/awards/idea/home/zip-top-reusable-containers. (Accessed in Jul, 2020)

Zip Top Reusable Containers (2020b), https://youtu.be/5Qt0H8xHhlY. (Accessed in Jul, 2020)