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EXPLORING STRUCTURE SHARING IN SERVICES AND USING THE PRINCIPLES OF PRODUCT DESIGN TO CONCEPTUALISE MODULAR WORKSTATIONS

Master's Thesis submitted to Aalto University in partial fulfilment of the requirements for the degree of Master of Science in Technology

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Abstract of Master's Thesis

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Abstract

The object of this thesis is to explore the design requirements of a modular and automated mobile workstation, and conceptualise it by exploring product design principles. During the thesis, a dynamic market survey has been conducted to explore existing competition and understand the user requirements for such a product. A thorough study was conducted to understand the rise and fall of open offices in the professional work environment and its relation to individual productivity. Engineering design principles such as Structure Sharing and Modularisation were effectively explored and utilized during this thesis. Structure sharing as a concept was used to explore sharing that occurs in the organisational structure of an industry providing shared services to the customers. AirBnB, a global shared-hospitality service provider, was used as the primary case-study for this purpose. An approach has been made to understand modularity and inclusive design, and find a common ground to apply the concepts of product development in the field of large-scale distributed construction. The results of this research can now be used for the conceptual design of a workstation for diverse users, by applying structure sharing at an organisational level, as studied for case specific services in this thesis. This design can then be evaluated for resource effectiveness using existing design methodologies or can be used to develop new methodologies.

Keywords Modular workstations, automated units, QFD, structure sharing, conceptual design, open office, product design, shared service, modularity, F/M tree

Foreword

The amount of work behind this thesis has been both invigorating and trying, both personally and professionally. In Spring 2016, the theme of the thesis was first presented by my colleague, Ehsan Ghazanfari. We started working on it together in Autumn 2015 at the Aalto BIM Lab. After that not a day has passed, that this work has not been on my mind. Now that the work is finally done, I feel both glad and dissatisfied. Glad, because it has taken a lot of effort to pen down the work that I have been doing for almost 15 months, and dissatisfied because I could not put my best work forward as well as I would have liked to.

There is a long list of people to thank for the almost timely execution of this thesis. First and foremost, I owe my most humble gratitude to Professor Vishal Singh for his unstinting support and unwavering confidence in me. His guidance and teachings have been remarkable in completing this journey. I would take this opportunity to thank Professor Amaresh Chakrabarti from the Indian Institute of Science, for guiding me through the concepts of structure sharing and product design.

I would like to thank the Aalto BIM Research Group, for sharing their research ideas and stepping forward whenever I needed help. A great amount of gratitude is owed to my colleague, Ehsan Ghazanfari, for sharing his knowledge and support at a time of great need. I would also like to thank my Study Coordinator at Aalto Learning Services, Virpi Ojala, for here relentless dedication and help towards finishing this thesis.

In the riveting 15 months of my thesis, through a lot of ups and downs, I owe a great amount of gratitude to my parents and my older brother who have been the actual motivation behind finishing this work. I would also like to thank my counsellor, Pia Nieminen, for helping me through all the difficulties faced during the completion of my thesis work. Last but not the least, I would like to thank my family away from home, Bijan Bayat Mokhtari, who has kept me sane through all the sleepless nights and hospital visits.

To anyone reading this foreword, who is yet to start working on their thesis, I have but one piece of cautionary advice. Please give enough time for writing down the thesis from the very beginning and leaving ample amount of time for multiple revisions. Sometimes things go wrong in the middle of your work and if you haven't written anything down, you wouldn't have anything to show for the work you have done.

Espoo, May 29th, 2017

Kalyani Kumar

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List of Abbreviations and Symbols

Abbreviations:

BIM	Building Information Modelling
QFD	Quality Function Development
FM Tree	Function Means Tree
IOT	Internet of Things

Symbols:

SS	Structure Sharing
RE	Resource Effectiveness
Adm	Admissibility of Structure Sharing
S	Number of Structures
RI	Relative Importance
RQOF	Relative Quality of Function

CHAPTER 1: Introduction

Scope of the Thesis

Exploring design requirements of a dynamic workstation

In the initial stages of this thesis, the requirement of an independent and mobile workstation was explored with utmost detail. An extensive study of existing office and personal working spaces was carried out to understand the diverse applications for such a product. Open offices were explored and the need for personal stations and their relation to improved productivity in specific environments was assessed. Requirements to facilitate the design of this product were enlisted from the perspective of the designer and the customers. Although intensive surveys could not be carried out for collecting these requirements, prolonged brain-storming sessions helped get a better picture of these requirements. A variety of users and design environments were identified and explored by carrying out a market survey, and the most dynamic features were proposed in the final product. The feasibility of these design features was thoroughly accessed by utilising existing methods and principles of engineering design.

Market survey of existing workstations and their design

A variety of workstations or office-pods have been introduced in the current market. This provided an insight into the customer expectations and reactions to the existing products. The market survey helped in studying the features of the products in the market and analyse the pros and cons of the current design. I could isolate the features that worked for a set of customers by studying the pros and enlist features that were missing or faulty by studying the cons. By evaluating the market size and scope for the product only in Europe, it was safe to assume that presently the market does not have a viable product to meet all its requirements, and that leaves a void for a better and affordable product.

Exploring modular design and the principles of product design

Modularity, as a concept for engineering design, was explored in this thesis. The idea of identifying modules was inspired by a Columbian start-up, which uses recycled plastic for small-scale construction. The modules in the design solution were isolated based on ease of assembly and repair, and by segregating similar technical features of the product.

Don Norman's Design principles were inculcated in the process of the conceptual design of this product. The concept of inclusive design was also explored. Since this product deals with a lot of independent technical features, I was trying to avoid any superfluous features that might inflict unnecessary increase in cost. QFDs proved to be an important tool in identifying the overlapping features and reduce redundancy.

Exploring structure sharing in services by evaluating existing organisations

In the latter stages of the thesis, the focus moved towards learning about and implementing the concept of structure sharing in services. Most of the existing research supporting this concept has been done to evaluate sharing in physical structures; by identifying the functions and finding a common ground for multiple functions to be used in the structure. Since I was working on conceptualising a product which performs multiple functions as an individual unit, and is part of a distributed network of units, it was important to learn about how structure sharing occurs in a product-service system. In this thesis, I have tried to explore structure sharing in the organisational framework of a service-providing industry that utilises sharing on a different platform. Use-case scenarios have been considered for the study, and observations have been recorded to facilitate their incorporation in the product. However, the scope of implementation and analysis of this concept is limited only to the core research ideas of structure sharing. New advances have been studied, but due to time constraint, they are not within the scope of this thesis.

Research problem and its significance in contemporary market

The research question I am trying to address with my thesis is the problem of space constraint. With industries growing and population increasing, the demand for space has increased by leaps and bounds. By developing a product with the primary focus of manipulating an existing space per the needs of the user, we are trying to solve one of the relevant problems in the service industry. This product is aimed to use any redundant or unused space for the duration of its use and transform that space per the given instructions. The fact that it does not require a space of its own for installation or storage serves as a big advantage. Although I have conducted the market survey for already tapped markets in Europe, developing countries with booming industries could also prove to be a potential market for this product.

The following chapters will describe the design thinking and processes involved in conceptualising this product. I have also explored similar existing products in detail to discuss their introduction and acceptance in the market. Although this thesis does not provide a finished product, the research and concept explorations provide a suitable platform for designers to start generating prototypes and testing it in the immediate market. SPACYPHY units are an example of possible market-ready products initiated by the Aalto BIM Lab. These units are designed to create a mobile physical space for diverse uses with an enhanced and automated infrastructure, and the possibility to connect distributed units with a common server. These units can be further modified to suit the market conditions and customer demands depending on the use case.

In the latter chapters, I have extensively explored the concept of structure sharing, and tried to project it on to a product-service system. The idea behind understanding and implementing this concept in this scenario is that we are talking about having a system of well-connected spatially distributed units serving an array of functions for the user. The whole unit as a structure and individual modular structures within one unit share different functions. I have observed and tabulated this sharing in the existing product-service system of AirBnB. As conclusion, I have mapped out parallels between resource efficiencies in products and services where structure sharing is observed. If a common structure performs multiple functions effectively, the resulting product is lean and cost efficient. This served as a strong motivation behind exploring this concept.

Goals and objectives of the thesis

Due to the long duration of the thesis, some of the pre-determined goals got modified with time. The thesis work has been divided into three segments and, in this section, I have discussed the objectives that I have tried to achieve in each segment.

Segment 1: Concept Exploration

Exploring the concept of modular design and its applications in structural design

Modularity in design has become an inherent part of cost-effective design in our times. From small-scale products to large scale construction, modular design has proved to be an effective way of reducing resource wastage and easing the process of design and construction. While modular design also makes off-site construction feasible, it also gives a lot of scope to experiment with the building material. Thus, making it an important inclusion in design of structures in the built environment.

In my use-case, modularity plays a key role in establishing grid-based functions by combining repetitions and eliminating redundancies. Modular design provides for ease in design, production and maintenance.

Implementing product development techniques and concepts in design

Inclusive design and design for variety are some of the product development principles that have been explored and implemented in generating a platform-based concept that can link an array of distributed units being accessed by different users per their requirements.

By exploring these concepts, the idea was to create a gateway for these principles to be utilised in contemporary design solutions of building and infrastructural projects.

Segment 2: Market Evaluation

Studying open offices, their relevance and drawbacks

It was important to explore the market before finalising the specifications of the product. For a workstation, we observed a myriad of applications, but what seemed to be the immediate and largest application was its use in the suddenly declining trend of open offices. As has been discussed in the latter chapters of this thesis, I have carried out a detailed evaluation of open offices in different European countries, with Finland as the primary market, using various case studies. This study was important in realising the relevance of this product in the said market.

Exploring the user base and their requirements for a functional workstation

An array of users was considered for this product. The idea was to identify different target users and their most basic requirements in a workstation. I have considered single-user and multi-user scenarios in indoor and outdoor conditions. After evaluating the specifications in these combinations, the most dynamic set has been proposed for the final conceptual design.

Studying the contemporary market and existing products and their drawback

A variety of products already exist that are used as alternatives for a workstation. It was important to explore these existing products to familiarise with the competition and their essential features. This thesis has considered every possible feature of the products in the contemporary market. The focus was to design the most resource effective product while considering the drawbacks of these existing products in parallel.

Segment 3: Structure Sharing

Exploring the concept of structural sharing on an organizational and developmental level

In this thesis, I have explored a different aspect of structure sharing. This aspect of sharing is observed in a product-service system. We are building a product to match a set of dynamic requirements mechanically, electrically, electronically and digitally. To avoid any redundancies and overlapping, F/M trees are to be constructed and sharing is assessed at various levels of organisation. In this thesis, I have explored this concept by assessing the organisational structure of AirBnB, a worldwide shared network of hospitality.

Research methodology

The research plan over the time span of this thesis has been discussed in the schematic diagram below.

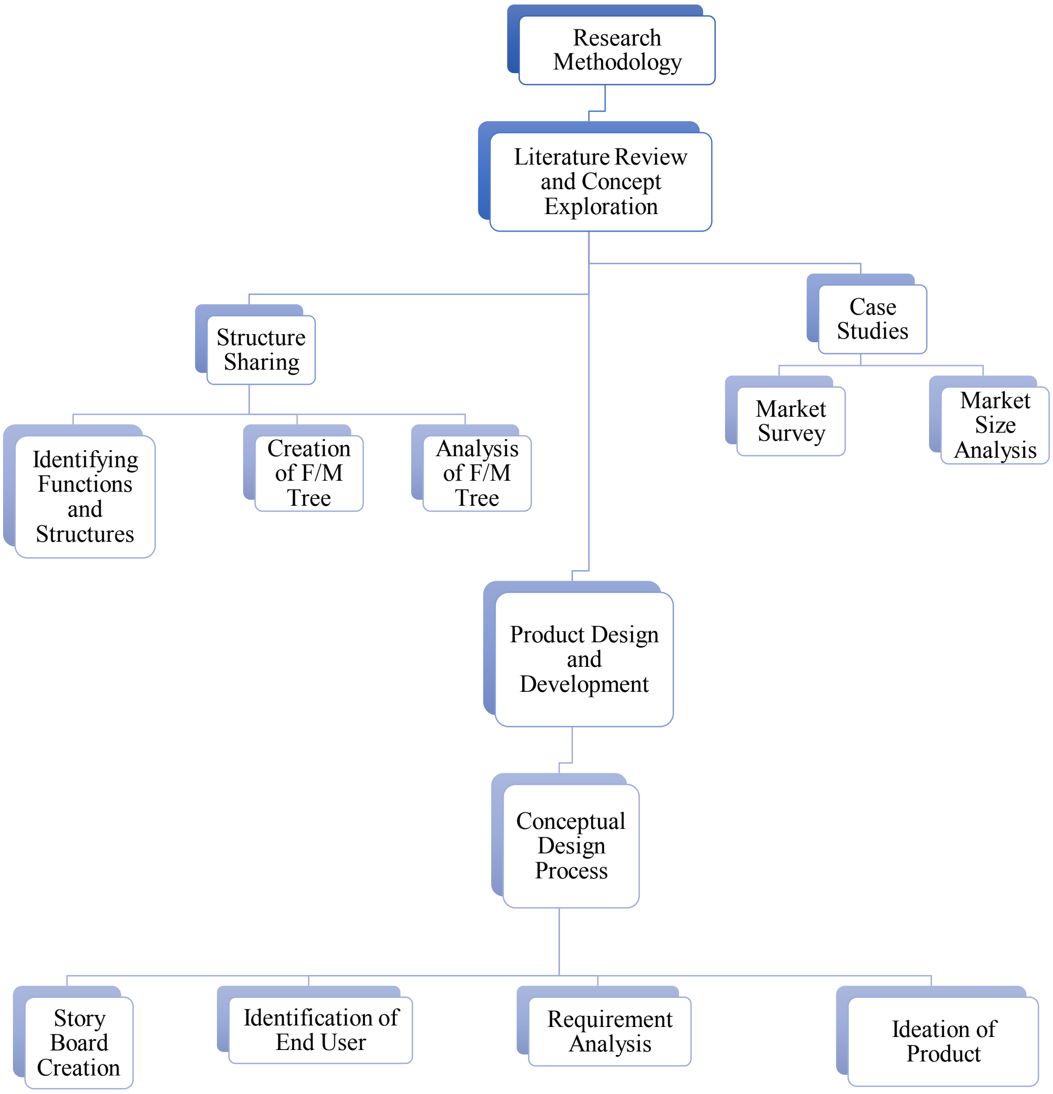

Figure 1 Research Methodology

In the early stages of the thesis, I started with understanding modular design by going through relevant research papers and journals. Assimilating the product design principles in my design thinking was a huge part of my literature review. I read about Don Norman's design principles in The Design of Everyday Things and used Ulrich and Eppinger's Product Design and Development as further reference.

After an extensive literature review, I moved on to evaluating the market. I studied the open offices using various case studies in different European countries and read expert articles about their success and failure in the contemporary scenario. I also explored the existing products and evaluated their strengths and weaknesses in the current market, to understand

and evaluate the present competition. Since similar products already existed in the market, this process gave me an insight into their existing customer base and helped discern the good and bad aspects in their design. I then evaluated the European market size for a product like SPACYPHY, with the characteristics of an automated and mobile workstation.

In the initial stages of the conceptual design, I gathered the product requirements to carry out the QFD analysis. These included the customer requirements and the technical requirements. While it is easier to ascertain technical requirements as a designer, it was more difficult to collect all possible customer requirements before narrowing down the customer. At this point, I divided the user base in various categories to identify the most dynamic combination. The identification of these categories of users and their work environments has been discussed in the following chapters. Once the customer was clearly identified, the requirements were narrowed down. I have tried to keep these requirements as flexible and dynamic in this case, to accommodate future design decisions.

In the next part of the thesis, I explored the concept of structural sharing. I spent three months in the CPDM Lab of the Indian Institute of Science, Bangalore, under the supervision of Professor Amaresh Chakrabarty, where we tried to evaluate sharing in a structure of a service. I took AirBnB and Uber to explore this possibility and the results for AirBnB have been discussed in the latter part of the thesis. This process involved gathering the organisational information of both use-cases and creating F/M trees to assess sharing at different levels.

In the limited period of my thesis, I've tried to provide a theoretical framework for further research on two aspects. First, the conceptual design and use of an automated workstation, and second, structure sharing in services. There hasn't been a lot of relevant research around structure sharing and I hope that the ideas discussed in the thesis instigate further research to provide better and more resource effective services.

Theoretical framework

Introducing Product Design and Development in Structural Engineering

Designers in the new technological age are using a variety of tools and techniques to aid their process of design and development. These new ideas and approaches, over the course of time and intense prototyping, are often directly proportional to the quality of the product. In the development of a product, the major concerns revolve around manufacturing costs and time. During this thesis, as I explored these design processes, I have also aspired to understand the decision-making process involved in the development of a product. If one draws parallels between the small-scale products and the larger construction built-environment, we can observe that these tools and techniques can also be applied in the latter scenario.

I have explored some important tools and techniques in this thesis, like making a product storyboard, customer requirements analysis, QFD, inclusive design principles and structure sharing. However, to establish greater connections and to better understand how this design decision making can be facilitated in the field of structural engineering, one needs to explore different design scenarios and magnify the scale to better suit a life-size built environment.

Exploring potential applications of Structure Sharing in Structural Design

Structure sharing has been defined as the fulfilment of several functions or functional properties by the same structure. It has been an important concept in product design with an aim to design more resource efficient products. In this thesis, I have explored how a structure can mean more than a physical product, and extend the meaning to the services provided by the physical product. For this reason, I have explored the organisational structure of a service landscape that incorporates sharing in various functionalities.

If this knowledge of structure sharing can be applied to physical spaces, we would be able to reduce the construction and maintenance costs by a considerable amount. That aspect remains to be explored, starting with small physical spaces of the workstations. Further studies can produce essential results about how we can upscale this concept to incorporate it with larger building and infrastructural environments.

Chapter 2: Background

Literature review

Open work spaces v/s Private workspaces

A traditional working space, Figure 2, is often perceived as a cubicle farm with rows and rows of semi-partitioned spaces. The concept of open offices has existed since the 1950s and can still be seen in most financial and governmental institutions across the globe. The idea originated in Hamburg, Germany, in an attempt "to facilitate communication and idea flow." The idea around re-introducing office spaces with few physical barriers was that this would increase collaboration, creativity and productivity. Open layouts were meant to encourage a sense of group togetherness and make employees feel like a part of a more relaxed and creative enterprise. Today, it is estimated that 70% of all offices are open-plan. While in some ways, it has improved collaboration and communication in the workplace, it has also done little to enhance creativity and in some cases, has negatively impacted productivity. In several surveys conducted by various organisations, it has been observed that physical barriers have been closely linked to psychological privacy, and a sense of privacy is linked to boosts in job performance. While open office layouts allow more people to work per square inch, is it viable to do that at the cost of productivity? This has been further discussed while analysing different case-studies in the second half of this section.

Figure 2 A traditional working space, or Cubicle Farm

It is, therefore, important to incorporate the end-user while designing a new office building. Design requirements analyse the needs and requirements of the customers, and incorporates their voice into product design and improvement. The office building itself does not add value to the company, rather the impact of the whole work environment enhances the end value for the corporations and their employees. Thus, the challenge for the office building developers is how to engage the end-users in the design stage, to determine their needs and to supply office premises that meet the targets of the corporate vision and the human resources. Due to the continuum of change, developing the building infrastructure to support agility and flexibility is an essential challenge which the office building developers and owners will face in future. (Jiang Yirui, 2016)

In this thesis, we introduce a product which could be a potential solution to this problem. We are talking about creating an office space without barriers that can also be private. With the SPACYPHY units, we aim to design a space that creates a feeling of psychological privacy, but is also flexible enough that people can easily move around and collaborate. The space adapts itself to the user requirements and is designed to be portable, distributed, automated and collapsible. Some of the existing products have been evaluated in the latter part of the thesis to gain more perspective on the importance of introducing this change in the open office regime.

A Paradigm Change in Design Approach

Traditional design processes or methods have often failed due to the inherent complexity of large-scale product design. The push to exclude the human in design through automation has left a void. Many optimization codes, expert systems, and synthesis loops cannot capture the depth or intent of a human designer. Designing large complex systems requires human involvement but the increased complexity also requires a new approach to design (Singer et al, 2008).

Don Norman's Design Principles

Norman outlines six key principles: visibility, feedback, constraints, mapping, consistency and affordances. These principles have been briefly discussed below.

Visibility

The more visible functions are, the more likely users will be able to know what to do next. In contrast, when functions are "out of sight," it makes them more difficult to find and know how to use.

Feedback

Feedback is about sending back information about what action has been done and what has been accomplished, allowing the person to continue with the activity. Various kinds of feedback are available for interaction design - audio, tactile, verbal, and combinations of these.

Constraints

The design concept of constraining refers to determining ways of restricting the kind of user interaction that can take place at a given moment. There are various ways this can be achieved.

Mapping

This refers to the relationship between controls and their effects in the world. Nearly all artefacts need mapping between controls and effects, whether it is a flashlight, car, power plant, or cockpit. An example of a good mapping between control and effect is the up and down arrows used to represent the up and down movement of the cursor, respectively, on a computer keyboard.

Consistency

This refers to designing interfaces to have similar operations and use similar elements for achieving similar tasks. A consistent interface is one that follows rules, such as using the same operation to select all objects. For example, a consistent operation is using the same input action to highlight any graphical object at the interface, such as always clicking the left mouse button. Inconsistent interfaces, on the other hand, allow exceptions to a rule.

Affordance

This is a term used to refer to an attribute of an object that allows people to know how to use it. For example, a mouse button invites pushing (in so doing acting clicking) by the way it is physically constrained in its plastic shell. At a very simple level, to afford means "to give a clue" (Norman, 1988). When the affordances of a physical object are perceptually obvious it is easy to know how to interact with it.

With these principles, I developed the initial interest in design. Designers have long used basic principles of design to create attractive work that clearly communicates. In contrast, this set of principles challenges the designer to also craft systems that are easy to use.

Set Based Design

Originally developed by Toyota within the Toyota Production System, Set-based Design builds on concurrent engineering principles (multifunctional, co-located team design) by establishing a design space for design optimization to meet a challenging set of requirements.

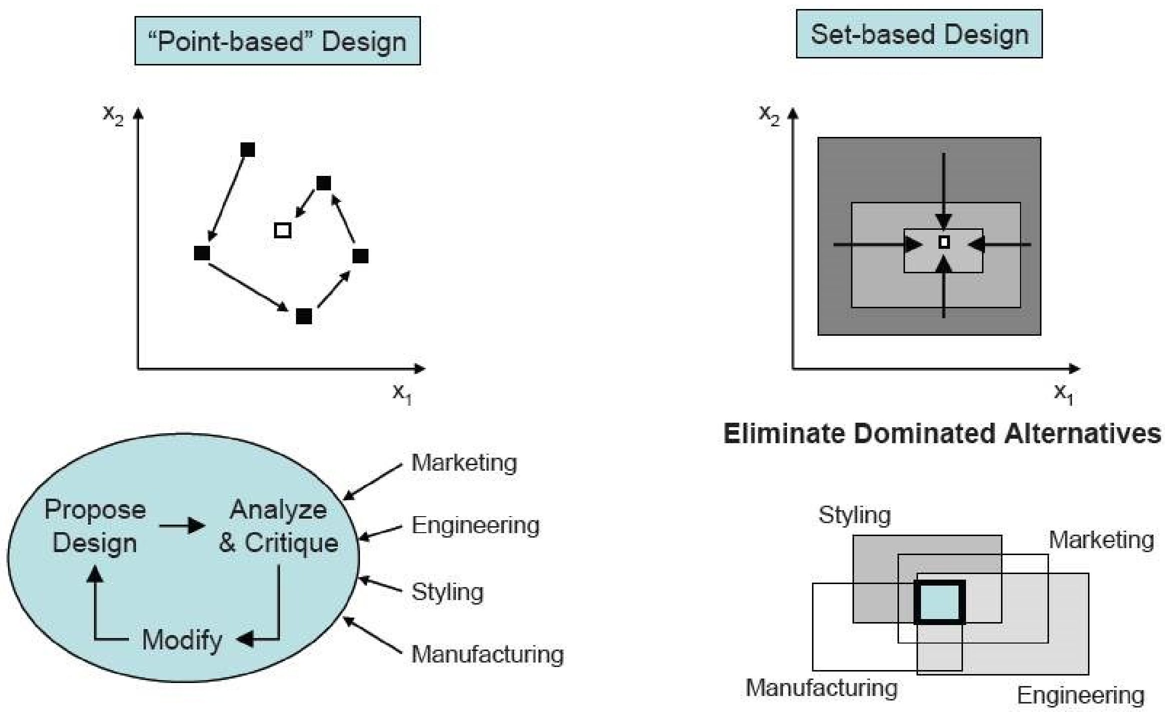

Figure 3 Set-based Design Process

Set based design involves exploring many design alternatives up-front to allow for trade-offs particularly important for integrated systems with competing requirements. It improves on 'point design' with its' many shortfalls – fixation on first design selected, time delay before feedback, and locked in cost too early in the design process. The differences between point design and set based design can be best understood visually in Figure 3.

A key principle underlying set based design involves delaying design decision later in the design process to achieve optimal trade-offs by eliminating inferior or sub-optimal design alternatives. Although counter intuitive while the design decisions are delayed set based design involves front end loading the design stages of the project to develop the design alternatives. The front-end loading facilitates early learning, early identification of risks, and early mitigation of risks. A key success factor is the discipline to identify all possible design alternatives up-front without allowing the design to move on with a favourite alternative – creativity, innovation, and practicality under pin this step.

It is important to understand this new approach to design in our case, since we aspire to build a lean system supporting concurrent engineering which eliminates wastage of resources. Since SPACYPHY is a function-based product, it is important to be able to change design decisions at a later stage after important design learning happens in the due course of several design iterations. Incorporating this approach in our design thinking enables us to maintain design flexibility particularly with respect to modularization and reuse.

Design for Variety

Design for variety methodologies help the design team in coming up with solutions that changes in them and will have less effect on the costs in the life-cycle of a product (Martin and Ishii, 2002).

Ulrich (1995) referred to product architecture as the "scheme by which the function of a product is allocated to physical components." A design must have an arrangement of functional elements, a mapping between function and structure, and specified interactions among components. Thus, any design for a single product has an architecture.

A product family can also have an architecture. A family architecture implies that the different products have a common arrangement of elements, common mapping between function and structure, and common interactions among components. A product family architecture only exists if this commonality is present. Our method seeks a structured approach that aids in developing the arrangement of functional elements, the function–structure mapping, and the interface specifications for a product family. The DFV method gives operational detail to Ulrich's architecture concept. Since SPACYPHY is an approach to develop an array of automated and distributed units, we need to understand the concept of a product family and how interactions are going to happen between two individual units.

As suggested by Ulrich (1995), it is a good practice to identify the coupled components. Two components are coupled if changes made on one of them requires a change in the other one. In fact, while some changes might bring benefits to the design, some other changes that result from these necessary changes may not be as beneficial. As a single unit, it works to our advantage to be able to identify these couple components to study and understand their effects.

An architecture is developed for a product line to maximize the profit potential for the company (Martin and Ishii, 2002). In time, the needs of the customer change, the reliability expectations from the product increases, and so does the demand to reduce the costs of the design and production. Design for Variety is a structured methodology to aid in developing a product platform architecture that incorporates standardization and modularization to reduce future design costs and efforts, and hence will serve as an important tool in the conceptual design of this product.

Inclusive/ Universal Design

It is known that many products are not accessible to large sections of the population. Designers instinctively design for able-bodied users and are either unaware of the needs of users with different capabilities, or do not know how to accommodate their needs into the design cycle (Keates et al, 2000).

Universal or Inclusive design is a design concept that recognizes, respects, values and attempts to accommodate the broadest possible spectrum of human ability in the design of all products, environments and information systems. It requires sensitivity to and knowledge about people of all ages and abilities. Sometimes referred to as "lifespan design" or "transgenerational design," universal design encompasses and goes beyond the accessible, adaptable and barrier free design concepts of the past. It helps eliminate the need for special features and spaces, which for some people are often stigmatizing, embarrassing, different looking and usually more expensive. Figure 4 is a pictorial representation of the Inclusive Design Cube, which demonstrates the process of inclusive design based on motion, sensory and cognitive capabilities.

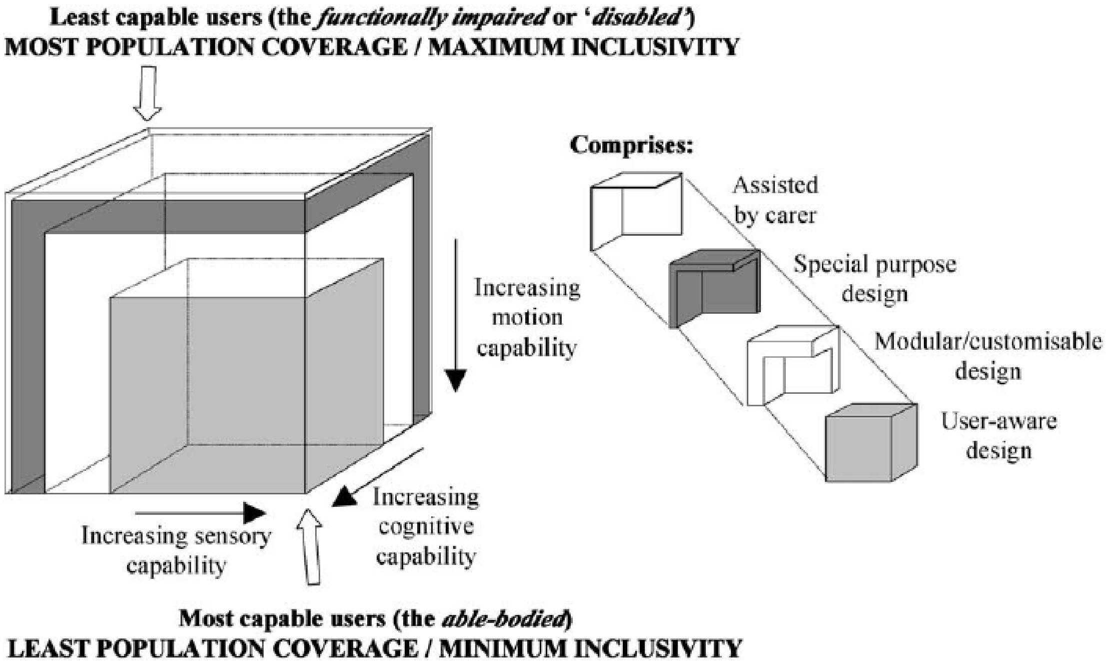

Figure 4 The Inclusive Design Cube (Keates et al, 2002)

One of the use cases of the SPACYPHY units was explored in the health care environment where these units can be used as single patient rooms to serve patients in hospitals. These units can be installed inside the hospital building (in the dorms, in corridors, or any other unused space) to serve as a fully functional single room for one patient (Ghazanfari, 2016). This is where the importance of a universal design comes into picture. To produce a usable and accessible product or service, it is necessary to adopt strongly user-centred design practices. It is important to be able to modify and refine the interface iteratively, combining both design steps and usability evaluations, which typically involve measurement against known performance criteria. (Keates et al, 2000)

Developing a usable product or service interface for a wider range of user capabilities involves understanding the fundamental nature of the interaction. Typical interaction with an interface consists of the user perceiving an output from the product, deciding a course of action and the implementing the response. The Inclusive Design Cube is a very potent visualization tool and communicates the needs of different sections of the population.

Modular systems and Modularity in Design

In the last decade, the concept of modularity has caught the attention of engineers, management researchers and corporate strategists in several industries. When a product or process is “modularized,” the elements of its design are split up and assigned to modules per a formal architecture or plan. From an engineering perspective, a modularization generally has three purposes: to make complexity manageable; to enable parallel work; and to accommodate future uncertainty. Modularity accommodates uncertainty because the elements of a modular design may be changed if the design rules are obeyed. Thus, within a modular architecture, new module designs may be substituted for older ones easily and at low cost (Baldwin and Clark, 2004). The main motives for modularization are lowering the level of complexity, increasing routine and repetition, while maintaining customizability (Martin and Ishii, 2002).

History of Modularity: The Bauhaus

During the Bauhaus era (1919-1933) the German architect Walter Gropius for the first time combined the idea of standardization with functional thinking and industrial production in building construction. The module was linked to a building block concept (*Baukasten*), where the building blocks were functional units in buildings, e.g. kitchen, living room, sleeping room, etc. Under Bauhaus, the module kept the original meaning as a standard measurement, allowing combinations of many building blocks, inspired by children’s toys. The purpose of the Bauhaus building blocks was to create buildings in a more rational way by standardization and prefabricated materials and to be able to make a more thorough and efficient planning. (Droste, 1990)

The functionality of the building block was not directly connected to the module at that time, as the module was only related to the geometry of the interface. The module as a standard measure of length is today still used in architecture and construction. A new difference has occurred between the module and the building block. A module must possess a certain considerable amount of functionality compared to the final product. In an industrial context, it is important that this functionality must be sufficient for independent testing. The meaning of building block is on the other hand reduced to a more limited functionality compared to the final product. (Miller, 2005)

Modules and Functionality

A module must have a certain distinct function that is identifiable and significant in the overall function of the product. Definition of modularity depends on functionality while a module is a unit mostly physical but in some cases (like software, etc.) non-physical. (Pahl and Beitz, 1996)

There are two important attributes necessary to define modularity, one is that designer must be able to create a variety of combinations within a modular system, and another is that each module must provide independent functionality. It is essential to look at the module and the system in which the module is used and then see if they both meet these requirements. Modules must have compatible mechanical and functional interfaces and interactions so that they can be easily exchanged. (Pahl and Beitz, 1996; Ulrich and Eppinger, 1995)

Pahl & Beitz, 1996, directly link the definition of modules to functionality and define different types of modules based upon a range of functions (basic, auxiliary, special, adaptive), Figure 5. A module is in this way the physical realization of a function. If an element does not relate to any of these functions, it is defined as a non-module. In this way Pahl & Beitz avoid that everything becomes a module. (Miller 2005)

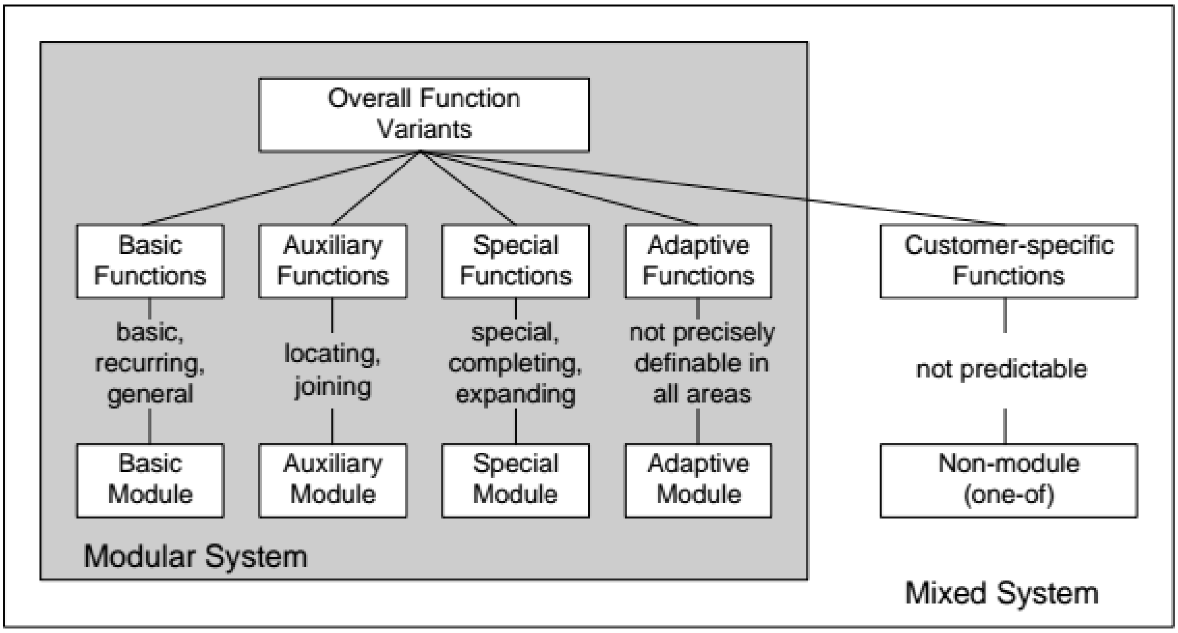

Figure 5 Function and module types in modular and mixed product systems (Miller 2005)

Modularity and Design

Humans interact with artefacts in three basic ways: they design them; produce them; and use them. There are, thus, three basic types of modularity: modularity-in-design, modularity-in-production, and modularity-in-use (Baldwin and Clark, 2004).

Design Patterns are the typical solutions that have been proven to be working fine for a problem over time and have evolved in a Darwinist approach. In fact, modules are structures that contain previous engineering knowledge and by using them all the previous knowledge is gained back again (Anderson & Pine, 1997). Creating hierarchies and breaking down the structures help in identifying each separate component and the designer can then focus on only one solution at a time. It also helps for classifying of tasks and doing them simultaneously and separately and leads to saving time (Alexander, 1964). In Figure 6, it is demonstrated how the system changes after modularisation has happened.

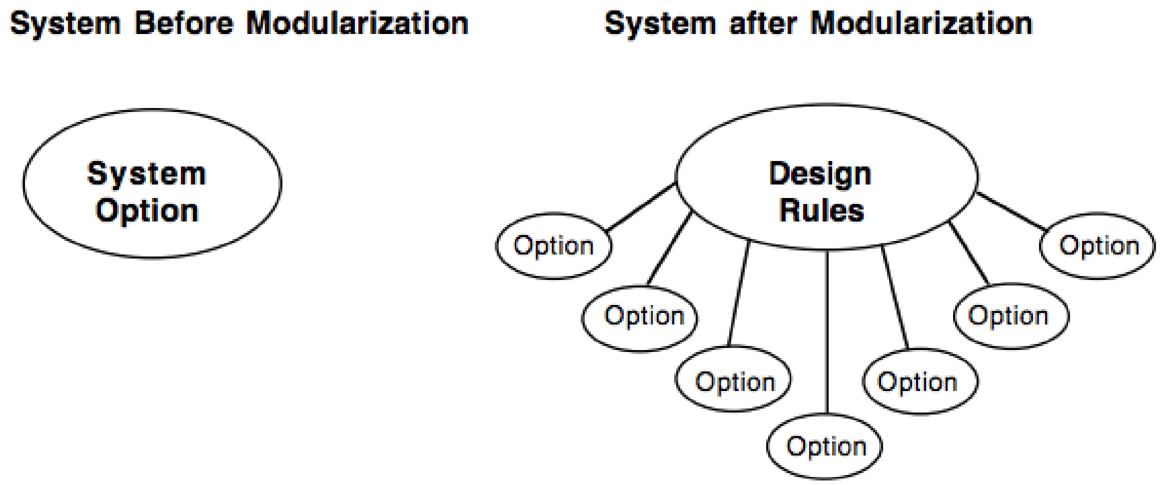

Figure 6 Modularity creates design options (Baldwin and Clark, 2004)

Generally, in the trade-off between standardization and modularization, the target is to maximize the amount of standardization in the product platform and in cases that standardization is no more possible, modularization is applied. If a component doesn't require any change or requires small changes, standardization is possible. Drastic changes will require modularization based on the interactions with other elements and if the changes will result in the changes in the other elements or not. (Martin, 1999)

Modularity in the conceptual design of workstations

Modularity in the design of a complex engineering system with high technical potential is likely to be highly disruptive to the pre-existing industry structure. Modularity-in-design allows users or system integrators to mix and match the best designs within each module category and to incorporate new and improved module designs as they become available. Thus, a modular system design requires that a company operate all aspects of its business more efficiently than its competitors. If it is not "the best" in each module, then competitors will flock to that point of vulnerability. (Baldwin and Clark, 2004)

Since our product already has several competitors in the market, the requirement of modular design has been emphasized. The varying functionalities of the SPACYPHY units also call for modularity-in-design and production, to reduce complexities and ensure that any intersections in design have been eliminated in the final solution.

Moreover, customers prefer variety in the products. Cutting the costs and increasing quality are the benefits of modularization as it imposes less changes in the whole environment of the manufacturing process (Miller, 2005).

Product Development Tools and Techniques

Storyboards

The storyboard is a tool derived from the cinematographic tradition; it is the representation of use cases through a series of drawings or pictures, put together in a narrative sequence.

Storyboards are a great way to visually depict an experience or an interaction among people or people and objects. By creating a storyboard, one can break down the experience or interaction into all its more specific components over time, which allows one to analyse the problem more closely. In the research stage, analysing the problem to fully understand what we are trying to solve and why it needs a solution can be achieved by creating a storyboard.

Draw the problem as it occurs over time. Break down the experience that the user has—whether it be with other people, with an environment, with a website, or with a specific product. The user is the main character in the story and the story is their experience when facing the problem that is being solved. By creating this storyboard, one can see the component parts of the problem and gain a greater understanding of the problem itself.

The storyboard proved to be an important tool in analysing the pros and cons of existing products in the market and filter out the most popular and credible specifications from a variety of products. It also helped in identifying the users and their work environments to create the dynamic use-case.

Quality Function Deployment; QFD

QFD is a system for designing a product or service based on customer demands that involves all members of the producer or supplier organisation. QFD stands for Quality Function Deployment which describes the needs of the customer, as quality; how to achieve those, as function; and who to do it and when, as deployment. The theory was first developed in 1972 at Mitsubishi's Kobe Shipyard and currently it is being used by Nissan, Toyota, Komatsu, Nippondenso and Honda in Japan and Ford, GM, Chrysler, DEC, TI, 3M, HP, AT&T Bell Labs, Xerox, NovAtel, Exxon and Dow in the United States. (Akao, 1997)

QFD brings the possibility to achieve higher quality products, in a faster and cheaper manner. It gives a central role for the customer to drive the design and it makes it clear how to develop the design further. QFD brings better understanding of customer needs, reduces organizational errors, reduces the need for changes in the design, improves the quality of the product, and helps to initiate the manufacturing process faster (Warwick Manufacturing Group, 2013).

In the problem context of the thesis, it was of utmost importance to use QFD because most of the specifications of the product are dependent solely on the needs and requirements of the customers. Every design decision must cater to the varying needs of the customers of the SPACYPHY units. For a specific use-case, like in the case of workstations, it is important to study the basic attributes that a customer asks for, and build on those needs as the environment changes. When we follow this approach, the design decisions are solely dependent on the customer, and hence it was important to thoroughly understand these requirements for all the possible user-environments as discussed in the latter part of the thesis.

Steps in a QFD Analysis

The first step in the QFD analysis is to collect the customer requirements. It is important to identify **every** potential user of the product. The users are not simply one group or type of people; rather enough attention must be paid to the chain of different customers for the product. When identifying customers, it is a must to consider all the people who are potential buyers in the market, whether they are buying the product or they are buying alternative products and whether they are satisfied with the product or not.

Customer requirements are collected in the next phase. Once the end users have been identified, it is important to look at the needs of customers in their own words. Questionnaires can be compiled and telephone interviews, face-to-face interviews, clinics, and focus groups could be executed, and processed data like statistics, company accounts, product reports, news, etc. can be reviewed. Subsequently, the technical requirements also known as engineering requirements need to be listed. These requirements come from technical specifications and regulations.

The next step in constructing a QFD chart is to determine the weightage of each requirement for the customers and how they would position our proposed solution in comparison to other alternatives. This can be achieved by means of a numerical rating of importance to each requirement, and another for how well these requirements are achieved with this product and alternative products. One way to get these numbers is through surveys and then one can make a weighted average of the opinions of customers and experts and input the results in a QFD chart.

The engineering characteristics are then derived based on customer requirements. These are the specifications that should be met so that the customer requirements are fulfilled. Engineering requirements define a set of measurable parameters that need to be optimized so that the product can have different functions and can help in achieving one or multiple customer requirements. Engineering requirements convert the customer requirements into measurable items that can be optimized and then facilitate quality control.

The relationship matrix to correlate the customer requirements and engineering requirements is then filled to determine and mark the relative strength in each relationship. Also, the relationships between two engineering characteristics should be defined which can be a negative or positive interrelation. This means that in some cases maximizing a certain engineering characteristic can lead to minimizing another and they might be conflicting with each other.

The negative effects of changing parameters in the designs can now be perceived. A minimum value, a maximum value or a target value can be determined for each of the engineering requirements to be achieved. The relationship matrix can determine automatically the importance of each of the engineering characteristics because they are directly linked to customer requirements and their importance.

After the QFD chart has been filled in completely, the critical spots are identified; where this design perfectly suits the customer demands, where the product is offering a better solution than others, and where the design lacks competence and must be improved. The analysis helps in further developing the design. (Warwick Manufacturing Group, 2013)

The above-mentioned steps are illustrated clearly in Figure 7.

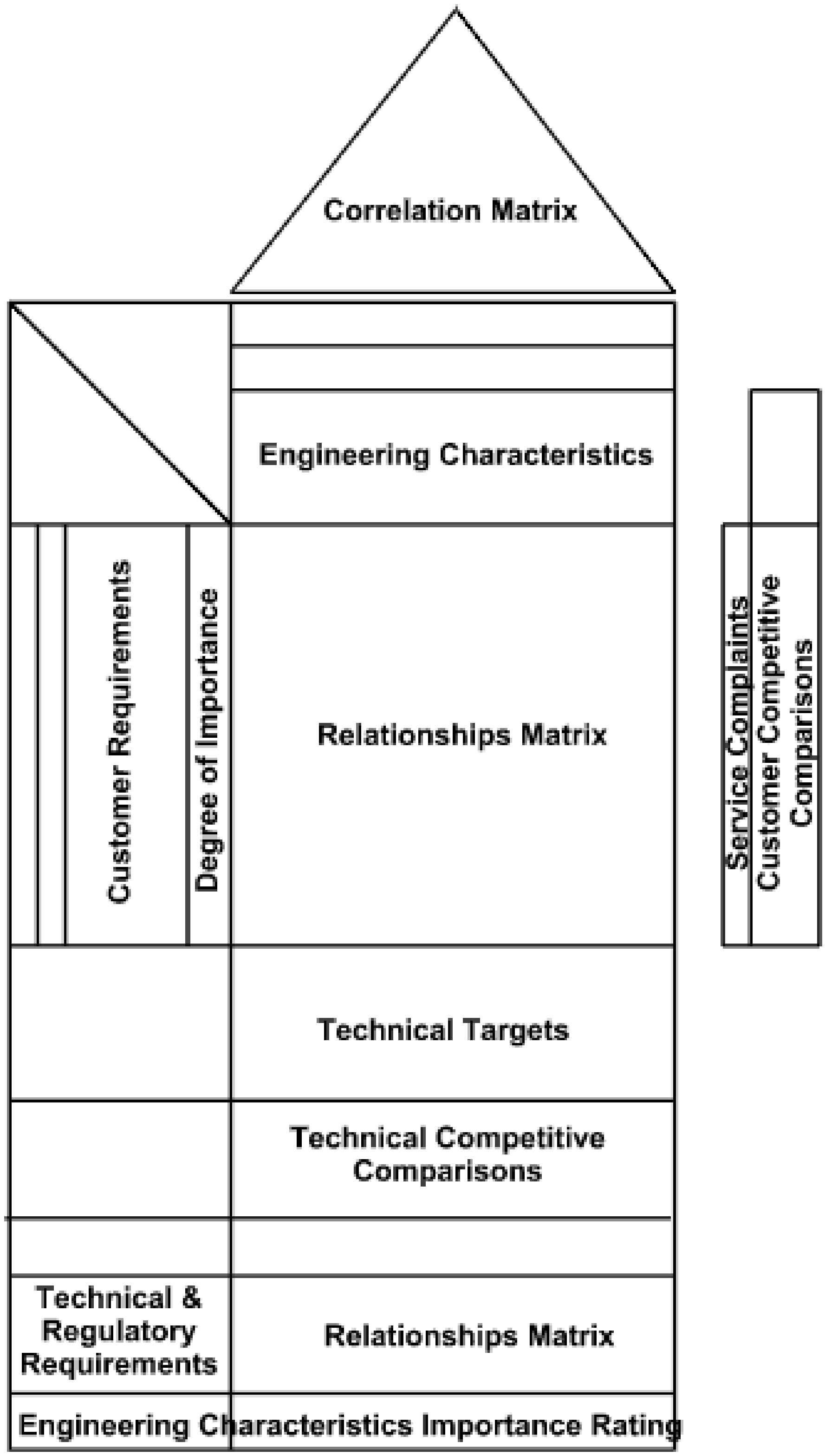

Figure 7 The QFD chart

In the context of built environments, which deal with variety of users and are multi-disciplinary in nature, QFD can serve as an important tool for analysis in the early stages of design. In the construction of buildings, identifying the needs of the end users and linking them to the design specifications can yield leaner and more efficient designs. It would also help in identifying the conflicting engineering requirements and removing them.

In her thesis involving office spaces, Jiang Yirui urges more involvement of the end user in the design process of a building as a finished product; "the office space is not only the building itself; but the maintenance service, restaurant service and other supporting services as well, which significantly influence the satisfaction of the tenants. Future office space developers should take these aspects into consideration in earlier stages of development."

In his thesis about modular and automated healthcare units, Ehsan Ghazanfari also suggests a methodology to inculcate the process of QFD in the design stages of large-scale infra projects; "the methodology that is suggested here to be used in the design of buildings or infrastructure is to breakdown the project into multiple parts and sections and conduct the QFD analysis for each separate section. A generalized QFD analysis can then be done for the whole project to link and analyse the relations between these sections and specific tasks."

In this thesis, however, I have explored the theoretical aspects of these product design tools. A basic QFD analysis was done by collecting the requirements as collected from the point of view of a designer, who is also a potential customer in this case.

This also leaves a window to further explore the engineering characteristics of this product, and carry out a thorough requirement analysis with a broader set of users and competitive products, to attain better results.

Theory of Conceptual Design

Design is claimed to be a mysterious activity by the designers in a way that it has not been recognized to be suitable for scientific experiments for centuries. However, recent research in artificial intelligence and its information processing models have considered design process to be an activity. Thus, design is purposeful and the activity of designing is goal-oriented. The meta-goal of design is to transform requirements, more generally termed '*functions*' which embody the expectations of the purposes of the resulting artefact, into design descriptions. (Gero, 2006)

In this section, I have tried to understand the process of creating a conceptual design. Design can be defined as producing physical artefacts that suit the world around us for better conditions of life for humans. In a design activity, requirements are transformed into artefacts that can obviate the expected need by performing a function and are demonstrated by the design descriptions in the forms of graphics, comments, and formulas to facilitate the manufacturing process. During the design process, perception of the designer, on the context of the design, changes and so the context changes making the design process a learning activity. (Gero, 2006)

Design as a process involves formulation, synthesis, analysis, evaluation, reformulation and design-description making. Design can be categorized in the three classes of routine design, innovative design, and creative design. A *routine design* is conducted in a well-known solution space that contains standard sets of answers for each problem. All the requirements and needed information in this type of design can be derived from previous design works. The constraint that exist in routine design is that it limits the choices of the designer such that the solution space is far smaller than the potential design space. *Innovative design* also takes place in a well-known solution space but it differs from the routine design in that the designer might change the normal values allocated to different variables and the result is a new solution that has not existed before. In *creative design*, however, a new set of problems rises and new variables are created that can expand the space of the potential designs and it shifts the paradigm. (Gero, 2006).

It is suggested that human designers form their individual design experiences into generalised concepts or groups of concepts at many different levels of abstraction - that is, they schematize their knowledge, Figure 8. Such schemas consist of knowledge generalized from a set of similar design cases and form a class from which individual designs may be inferred. In design, any schema must at least be able to incorporate function, structure, behaviour and design description and be accessed by elements within those components. (Gero, 2006)

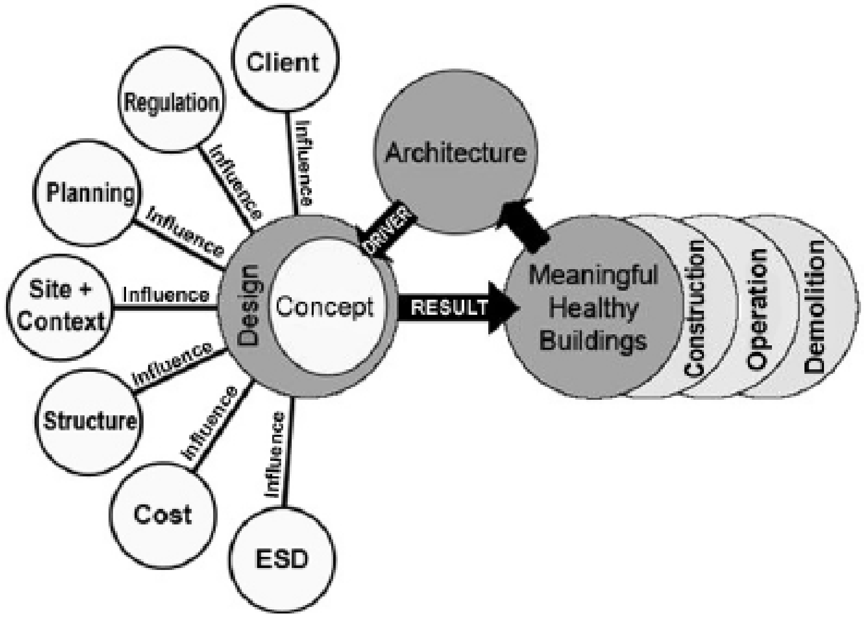

Figure 8 Example schematically showing a current conceptual model describing factors that might be prominent in a building design (Lamborn et al, 2006)

A design prototype (Gero, 1987) is a conceptual schema for representing a class of a generalized grouping of elements, derived from similar design cases, which provides the basis for the commencement and continuation of a design. Design prototypes do this by bringing together in one schema all the requisite knowledge appropriate to that design situation. A design prototype separates function, structure, expected behaviour and actual behaviour. Designing using design prototypes may be thought of as matching a cognitive view of a process model of design (Gero, 2006).

Design requires a representation framework which has sufficient expressive power to capture the nature of the concepts which support design processes. The use of a knowledge representation schema such as design prototypes allows for this. It separates the knowledge from the computational processes which operate on it. The use of this representation effectively provides a translator between structures, which is the syntax of a design, and functions, which may be treated as the semantics of a design. Such an articulation is useful not only in the production of designs but also in their analysis and evaluation. (Gero, 2006)

In this thesis, we follow the initial steps of this process for the conceptual design of an automated and distributed workstation. The results from the analysis done in this thesis hope to provide a platform for further research in this field.

Structure Sharing in Design

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. The concepts of function sharing, structure sharing, function combinations and integrated structures have long been used by designers either consciously or in some cases unconsciously to design more resource effective and more creative products. However, it was not until recently that the works of researchers strived to create fundamental methodologies to help better understand the process of the design of such products. There has been ongoing research for developing some methodologies to apply structure sharing in the design and assess the resource effectiveness to come up with cheaper and more innovative products. Structure sharing is one of the methods of sharing in product design. There exist other types of sharing such as function sharing, structure redundancy, and multi-modal integration. In function sharing, several structures are contributing in achieving one function. Structural redundancy has been used when the designer provides multiple structures that each is enough to fulfil the same function. Lastly, the cases in which one structure can have multiple functions is called as multi-mode integration. (Chakrabarti, 2001)

Structure sharing in principle creates a trade-off between resource effectiveness and changeability of the product parts. The more the sharing in the design, the more cost and resource effective will be the solution, and the less easy to change will be the assembly parts where there's a need for change in cases of damage, reuse, disassembly, etc. Nevertheless, in the design of many products, resource effectiveness is extremely crucial as are its effects on the overall cost, which can be huge and save of materials. (Chakrabarti, 2004)

In this section, we define functions and structures, explore the present methodologies for sharing, and estimate the resource effectiveness of a design alternative.

Function is defined as the intended effect, given the input conditions, while *structures* are any physical entity or feature capable of being identified independently. The input conditions include the typical environment in which the product is expected to work. 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). A product is formed by a collection of various items. (Pahl and Beitz, 1996; Otto and Wood, 2001; Ulrich and Eppinger, 1995; Lindbeck and Wygant, 1995)

A product can be looked at in a function related perspective or in a structure related perspective (Andreasen 1980; Andreasen, 1992; Hubker and Eder, 1988).

To identify all the functions and structures that are taking part in shaping a product, a systematic approach known as constructing the Function-Means (F/M) tree is used. In this method, the main functions expected from the product are identified by the designer and are broken down into the components that provide the means to achieve that function. In the assessment of resource effectiveness and the degree of structure sharing, identifying the structures and functions play a critical role and directly affect the results of these estimations. One of the most important concerns related to identification of these functions and structures is the level of detail that a design solution is being investigated at (Hubker and Eder, 2001). As the aim is to develop methodologies that are universal and do not have subject dependent results, the expected level of detail in design that the designer is looking for in the product must be made clear.

Degree of Structure Sharing is one of the measures developed to help designers in determining how innovative and resource effective their design solution is. It can be calculated by the following equation (Eq. 1):

$$Degree\ of\ SS = \frac{number\ of\ functions\ at\ the\ lowest\ level\ of\ abstraction}{number\ of\ structures} \quad (1)$$

Per this formula, the higher the number of all the different functions, and the lower the number of structures that are used in the design, the higher will be the degree of structure sharing (Chakrabarti and Singh, 2007).

Process of building an F/M Tree

The steps for generating an FM tree are the following (Figure 9):

- Identify the Main Functions. For the cases where there is more than one MFs, each will have a separate FM tree. Each FM tree starts with a MF.
- Identify the immediate next link, which can be a sub-function, means, an organ or a process. Asking the question 'HOW' leads to the next level.
- At each stage look for further branching until a structure is reached.

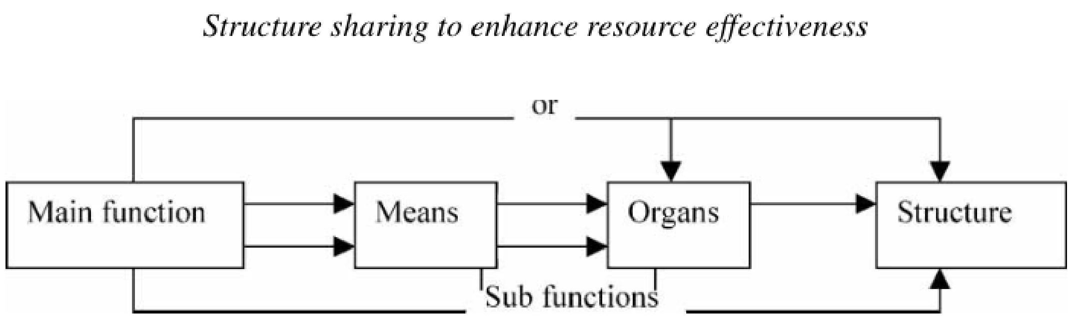

Figure 9 The process for generating an F/M tree (Chakrabarti and Singh, 2007)

- The total number of end points in an F/M tree gives the total number of structures for 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 sub-functions (SFs) (Chakrabarti and Singh, 2007).

Resource Effectiveness, RE

RE is defined as the ratio of number of structures to the number of functions these structures fulfil (Eq. 2; Chakrabarti 2001). Literature review shows that resource effectiveness always increases by increasing the degree of structure sharing (Chakrabarti and Regno, 2001).

$$RE = \frac{number\ of\ main\ functions}{number\ of\ structures} \qquad (2)$$

It has been observed that by reducing the number of structures involved in providing one functionality, the cost effectiveness and efficiency can be improved. It suggests that simpler designs that have less sub-functions and structures will be more resource effective. So, by drawing an F/M tree one can easily derive the values of RE and SS and get measurable and comparable values for analysing different design options.

By looking at other methods of performing a function, the designer might be able to reduce the number of structures and consequently reduce the amount of materials and resources. If there are features that are common between different structures in one F/M tree, there might be the possibility to use the same feature to generate multiple functions. Also, overlapping features in different F/M trees of a single product can be found. The manufacturing processes should also be considered and the variety of techniques that are utilized should be minimized.

However, there are certain limitations to the application of the process of calculating the resource effectiveness. Accounting for the quality of function (QOF) is still dubious. 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 been in the scope of this thesis, but I have mentioned a brief overview of a research by Ehsan Ghazanfari, that tried to solve the concern about QOF. This area needs to be explored further. The negative functions have not been considered in these calculations either. 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 to obtain a more integrated assessment.

Admissibility of Sharing

Quality of function determines how well the function is being performed, and has direct impact in the end user's satisfaction of the product. A new methodology was recently proposed that aims at improving these measures by accounting for the quality of the function. In this developed measure the negative effects have also been considered. The methodology also utilises the additional sub-functions that are created in the design but are not used for design. In the presented methodology, the beginning step is identifying all the structures and main functions and sub-functions and behaviours of a product.

First, an F/M-tree is drawn for all the separate main functions of the product. Then, all the customer requirements and engineering requirements are gathered and a QFD matrix is formed with them. And, now that a proper understanding of the structures that are involved in the design alternative is reached and the requirements of the customer are clarified, the designer can calculate the value of a term that is called as "*Admissibility of Sharing*" and is calculated using the following equation, (Eq. 3); (Ghazanfari, 2016)

$$Adm = \frac{\left(\sum RI \cdot RQOF \cdot \frac{1}{S} \cdot \frac{1}{1+NNE}\right)}{\left(\sum RI \cdot \frac{1}{S} \cdot \frac{1}{1+NNE}\right)} \tag{3}$$

where,

RI:	Relative Importance of Main Function
RQOF:	Relative Quality of Function
S (In the nominator):	total number of structures in the structure shared solution
S (In the denominator):	total number of structures in the unshared solutions
NNE (In the nominator):	total number of negative effects for the structure shared case
NNE (In the denominator):	total number of negative effects for the unshared case

Due to time constraints, this newly developed methodology could not be tested in this thesis, but it opens doors for further investigations in future research endeavours.

Applications of Structure Sharing in Design

Aerospace is one of the areas in which structure sharing has been widely used, as minimum use of resources is of prime concern. Also, today there's a trend in the design of products to add as many features as possible to one single product, making it portable, handy, light, and multi-purpose. In the design of multi-purpose products structure sharing has had a widespread use. (Chakrabarti, 2004)

In the design of built environment and architectural design, space is the main concern. With the growing space constraint, sharing of space can be a major boon. Using one space for multiple functions can be categorized under structure sharing, where the structures are the physical components of the built environment that is being designed and constructed (walls, columns, beams, concrete, reinforcements, façade, glass, etc.) and the functions are how these spaces will interact with the end users and the qualities they must have to fulfil the main purposes they are being constructed for. By introducing the concept of sharing in mainstream architectural design, an innovative approach can be sought in design of buildings and infrastructure, where more functionalities are achieved with the same amount of construction materials and labour requirement. This also helps in reducing redundant spaces.

In this thesis, the concept of structure sharing is being explored for a product service system. I have created the F/M tree for the organisational framework of a service-providing commodity, and identified the levels where sharing occurs. I have also tried to discuss how resource efficiency differs when we consider the product as a structure and the service system as a structure. The results and observations have been discussed in the latter chapters and the conceptual analysis is aimed at providing sufficient background for further research in this area.

Case studies

Seeking productivity in a noisy world: A case study by American Express

With this example, we try to explore what aspects of open offices are causing an impact on productivity by following the journey of Sarah Kauss of S'well Bottle. While setting up the office in an apartment, Kauss and her team reflect on the major issue of working in an open office: noise. But a no barrier zone is bound to be prone to noise, so what drove people to adapt to this new style of professional working environment?

With the onset of the open office tradition, we have seen some exceptionally designed offices by Google and Facebook. Another reason behind the onset of open offices was to create an egalitarian space and bring some parity in the workplace to dismantle the hierarchical structures.

It was noted in various surveys that today's mobile workers spend less than 60% of their time in their offices, and the companies have realised that they don't want to pay for the real estate taken up by the empty spaces, corridors and hard walls that reduce the amount of usable space. The economics of space are why open offices are probably here to stay, at least for the foreseeable future. From 2010 to 2012, the average square metre per person dropped from 21 to 16, and the process of densification in these offices continues.

While, there's a time when you need to share information and collaborate, there's also a time when you need to do some heads-down focused work. Research from the University of Sydney found that "the loss of productivity due to noise distraction was doubled in open-plan offices compared to private offices." With 70 percent of American employees now working in an open-office environment, that's a lot of stressed out workers with poor posture and reduced effectiveness.

These spaces are now an open market for a product like SPACYPHY. People feel more connected to a workplace where they can shape their work environment and decide when and where they're going to work. It is important to create different user experiences so someone can pick and choose what kind of environment they want to have throughout their day. Creating a workplace where everyone feels comfortable talking about their needs also goes a long way until you're able to set up that refuge space or acoustic panelling. SPACYPHY units, when designed as a modular and automated workstation aim at solving this problem. Their dynamic design and flexible use would make them a popular choice for offices that seek to keep the open space but provide the option of privacy to its employees.

Vodafone Amsterdam: Orchestrating the transition to a new organizational culture and work environment

In this case study, we explore how Vodafone is creatively using space to nurture a new work culture. Vodafone partnered with Steelcase Applied Research & Consulting (ARC), the global work and workplace consultancy, to assist them in this major transition in their work culture and in embracing alternative work strategies (AWS).

Working with Vodafone management and staff, the ARC team used a series of proprietary diagnostic and user engagement tools to measure the company's readiness and willingness to embrace change in work processes, technology, human resources, and work space. A key part of the planning process was gathering employee input through a series of interviews, surveys, and workshops.

Both Vodafone leadership and staff desired more emphasis on innovation, placed a greater value on effectiveness than efficiency, wanted to encourage more teamwork, and placed less emphasis on a market-driven culture. At the work environment level, this translated into space that would encourage more communication and collaboration while upholding a healthy lifestyle.

With no assigned workspaces, an open, collaborative layout, and everyone —from leadership to the newest workers— working from the same workspace layouts; the employees were subjected to this new style of working. Presently, 900 people use the building, and up to 1,200 can be accommodated in this facility, which includes open plan workspaces that allow for quick reconfiguration, workstations, offices, and training rooms with raised accessed floors, ergonomic seating that adjusts to users of any size and shape, acoustics controlled via a perforated metal roof liner, acoustic balcony balustrades, and workstation screens, a variety of small to large meeting spaces, communal kitchen areas and a restaurant.

This office space reflects as a perfect example for smart office spaces which were designed keeping the end-user in mind to gain maximum productivity and increased collaboration. The use of ARC products to create spaces for various use-cases reflects on an articulate design process.

Regus Pods

Thinkpods are cubicles-cum-mini-offices with curvy walls designed by Regus in 2007 to encourage the influx of flexible working spaces. The idea is to provide a semi-private space within a busy open-plan office. It comes with a desk, an attached lamp and a chair. Regus recently introduced the Workpod, a self-contained private workspace, and the Meetpod, for groups.

Regus pods are a popular choice in the contemporary markets, typically in places where space is not a constraint, like airports and lounges. But the major drawback of this product is that it requires additional space to be installed. Although the design is sleek and does not require a lot of space, it leads to the creation of redundant space when the pod is not in use.

With the SPACYPHY workstations, redundant space is also a problem that we are trying to tackle. By not assigning a permanent space to these workstations, we create an opportunity for the space to be utilised for other purposes.

Figure 10 The Regus Workpod installed in a shopping mall; inside a Regus Workpod; The Regus MeetingPod

Dorma Wall partitions

Another way of creating a secure and sound-proof space is with wall partitions. Dorma is a leading company that provides a range of movable wall partitions that can be used to divide an open space effectively. With their systems, a space can harmoniously combine lighting and sound insulated room concepts.

Figure 11 An example of a movable wall system by Dorma

The major disadvantage in installing a wall system is that it requires starting and ending points on the walls and the ceiling. In a cramped open office, it can often be a challenge to find end-to-end points for their installation. However, their affordability makes them more popular over the Regus Pods. These wall partitions are a great solution when incorporated in the initial stages of design, but their installation can prove to be a challenge in an existing office space.

These drawbacks can be addressed by the SPACYPHY units, which aim at modifying only the specified space and do not require conformed spatial supports.

Chapter 3: Study of Structure Sharing

Structure sharing and its use in design

Function sharing is a word popularised by Ulrich who uses this word to describe the phenomenon of using a single physical structure to achieve several functions. For instance, the electrical cable holding a light bulb from the ceiling both supports and supplies current to the bulb. In this context, the word 'function sharing' is a misnomer in that what is shared here is the structure and not function. Therefore, it should be called, more appropriately, *structure sharing*. Both function and structure sharing are important concepts in product design, and have often been used, consciously or unconsciously, to promote success-bearing factors in products. While integration has been viewed as promoting resource effectiveness and the resulting efficiency, modularisation is often seen as promoting ease of adjustment, reuse, repair and recycling. However, while the importance of these has been emphasised often in literature, a systematic, in-depth investigation into the possible categories of these broad concepts, their relative importance, and how to use them in design is currently missing. (Chakrabarty, 2001)

The aim of this chapter is to establish the importance of sharing in design by taking a different aspect into consideration, the product-service system. The main issues that need resolving to support maximising sharing in designs have also been discussed in this chapter. The main categories of sharing have been identified and the importance of each of these categories, and how to choose between them in a design process have also been reflected upon.

Recognising Structural Sharing

Structure sharing means simultaneous use of the same structure by several functions (Figure 12). For instance, in some mechanical accelerometers, a cantilever beam provides the inertia necessary for developing a force in response to the acceleration as well as the flexibility needed to develop a displacement in response to the force (serial sharing). Another example is that of the multiple-function cable holder of a light bulb mentioned earlier (parallel sharing), (Chakrabarty, 2001).

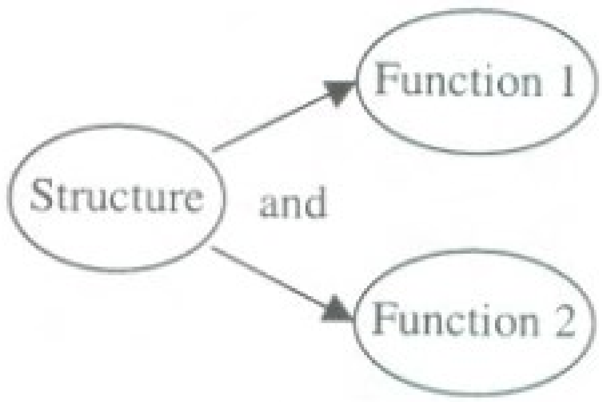

Figure 12 Basic structure sharing (Chakrabarty, 2001)

It is easier to identify sharing in a physical structure. The nodes are easier to identify when one can visualise the functions being executed. In this thesis, I have tried to implement these principles to identify the sharing that goes on in the product-service system of a service providing industry. Resource effectiveness is necessary to keep the product cost in check and reduce the time to market the product, which are both essential in keeping the product competitive. In this thesis, I have explored if a service system can be made more resource effective by inducing sharing in its structure at different levels of execution.

We will now explore an example of a simple product where structure sharing is observed. The product I have chosen is a multi-functional product that combines the functions separately provided by a USB flash drive and a Camcorder (Figure 13).

Figure 13 A portable USB with HD Camcorder

We will now construct an F/M tree for this product. The process was discussed in Chapter 2 of this thesis. In the following diagrams, we can observe how the F/M tree for this product has been developed.

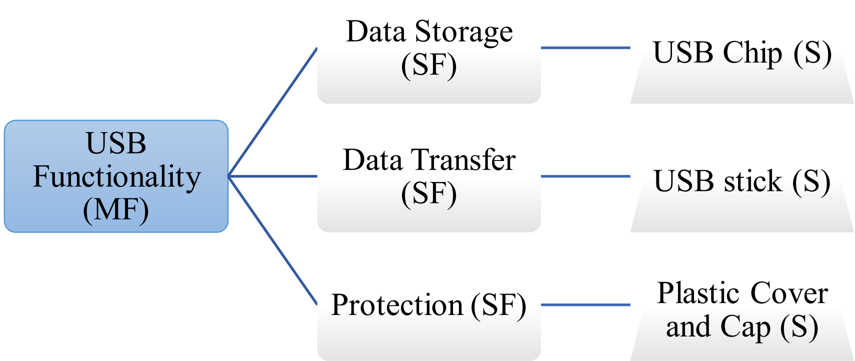

Figure 14 F/M Tree of a typical USB flash drive

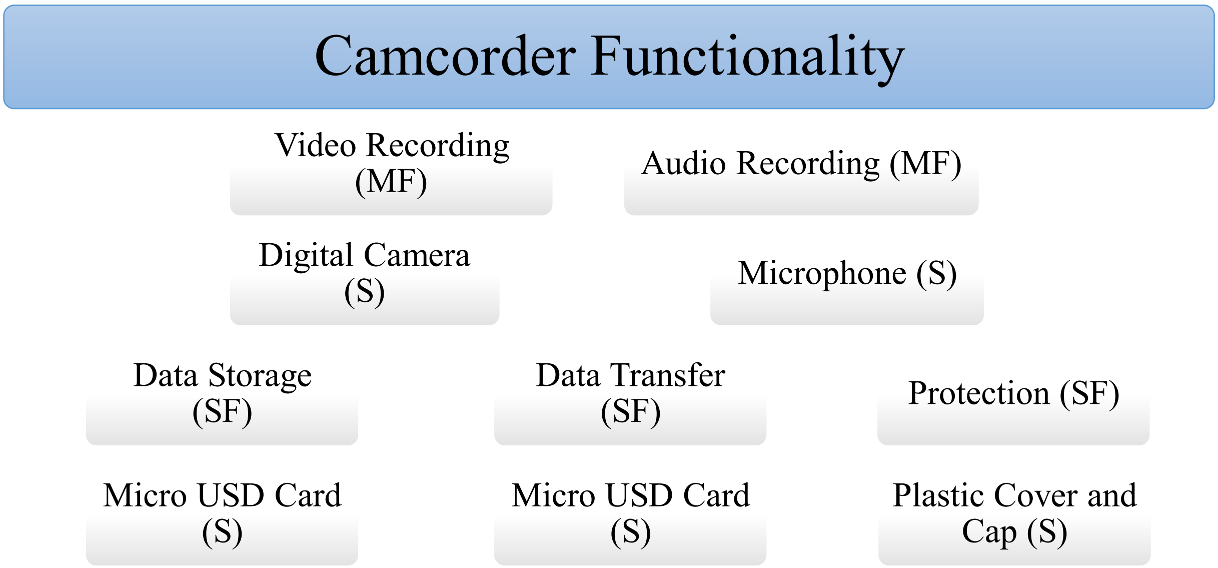

Figure 15 F/M Tree of a Camcorder

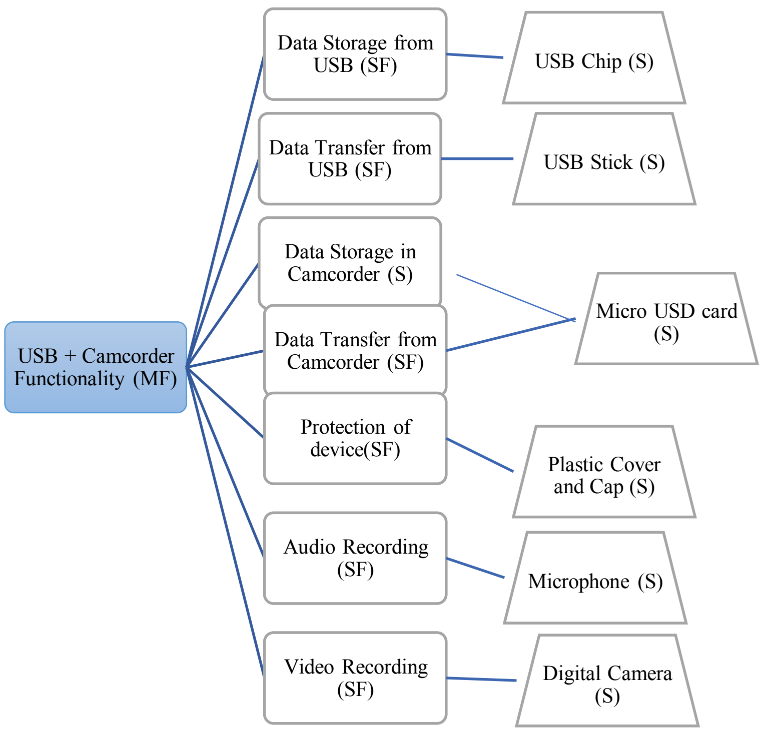

Figure 16 F/M Tree of the Designed Solution (USB + Camcorder)

In these F/M trees, I have identified the main function (MF), sub-functions (SF) and the structures (S) of the product fulfilling those functions. Using the formulae discussed in Chapter 2, we will now calculate the degree of structure sharing and the resource effectiveness of the designed solution, USB + Camcorder.

$$Degree\ of\ SS = \frac{number\ of\ functions\ at\ the\ lowest\ level\ of\ abstraction}{number\ of\ structures} = \frac{7}{6}$$
$$= 1.17$$

$$Resource\ Effectiveness, RE = \frac{number\ of\ main\ functions}{number\ of\ structures} = \frac{1}{6} = 0.167$$

The degree of SS is more even though it has less RE. Therefore, we can infer that RE cannot always be said to be increasing with increase in 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. (Chakrabarty and Singh, 2007)

In the next section, we learn a little about the background of the two most popular service industries of our time. Looking at these industries, we can tell that there is some sort of sharing occurring in their organisational framework. In this thesis, I have tried to identify the type of sharing that goes on in a service system, by looking at one of these two examples.

AirBnB

AirBnB, started in 2008, as an online marketplace for people to list, discover and book unique and affordable accommodations around the world, is one of the fastest growing online industries with their business spread over 191+ countries. It was started as a platform for people to monetize the extra or unused spaces in their homes and for other people to discover a city with a local flavour.

Uber

In 2008, what started as a service to request premium black cars in a few metropolitan areas is now changing the logistical fabric of cities around the world. Whether it’s a ride, a sandwich, or a package, Uber has spread its tentacles in a variety of service industry. For the people who drive with Uber, this service represents a flexible new way to earn money. For cities, this service helps in strengthening local economies, improving access to affordable transportation, and making streets safer. The service has now attained a billion connections in countries across the globe, and continues to grow in the heavy transportation and food delivery service industries.

The availability of shared physical spaces is clearly an important construct in identifying sharing in the above-mentioned service industries. But, what I have also done below is develop a system to understand the function(s) fulfilled by this industry to maintain a steady growth and source of income, and identify the structures performing those functions in the service system.

Developing the F/M tree for AirBnB

In this section, I spent a lot of time trying to understand the main functions and sub-functions of the shared hospitality service structure of AirBnB. After going through the service industry’s literature, I developed the following F/M tree for the service system of AirBnB.

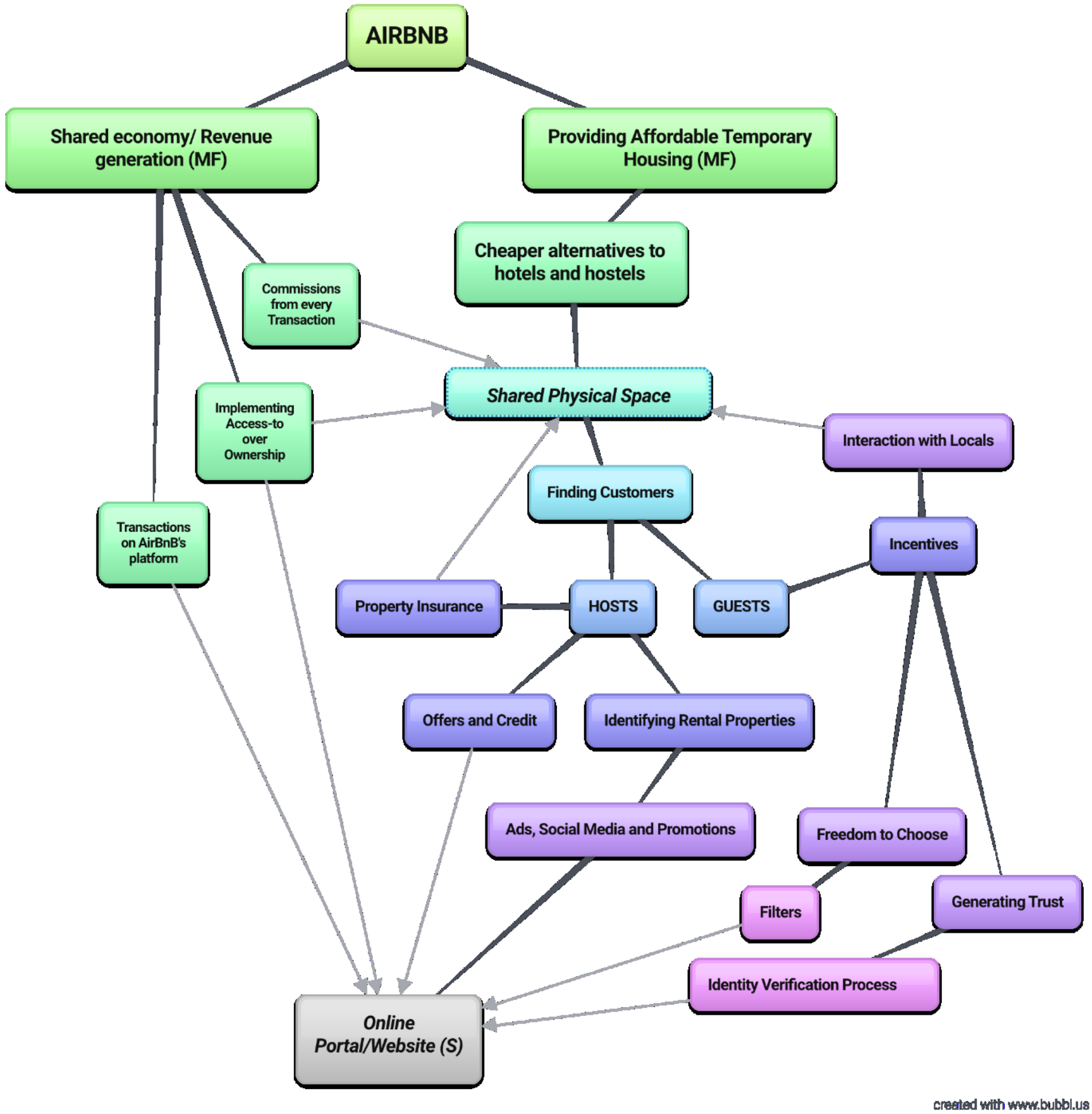

Figure 17 F/M Tree for the service system of AirBnB

Analysing the F/M Tree for AirBnB

As one progresses in making the F/M tree, the underlying question it tries to answer is "how" the functions will be achieved and what means or structures will be used to achieve those functions. In Figure 18 and 19, I have tried to explain the process involved in the creation of the F/M tree by analysing the main functions, means, organs or sub-functions and structures.

MF 1: Shared economy/Revenue generation

Means to achieve MF1:

- managing transactions from AirBnB's platform only;
- following the concept of Access-to rather than Ownership;
- taking Commissions from Hosts (10%) and from Guests (3%);
- minimizing expenditure

***Structure** to attain these means*:

- ➢ creating a portal (website, in this case), to carry out transactions.
- ➢ Shared Physical Space

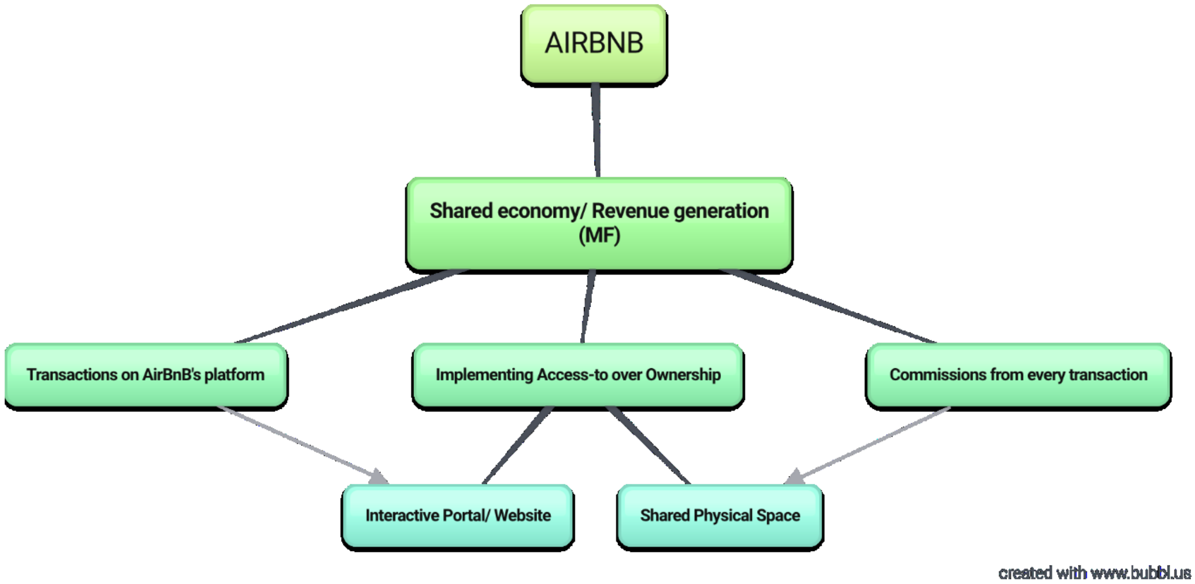

Figure 18 F/M Tree for MF1 of AirBnB

MF 2: Providing Affordable Temporary Housing

Means to achieve MF2:

- Cheaper alternative to hotels and hostels
    - o Shared Physical Space

Organs to achieve Means:

Finding Customers

- ▪ **Hosts** to list their local properties for rent

Means to get Hosts:

- providing insurance policies for the property;
- providing other promotional offers and extra credit;
- looking for people to rent a part or whole of their property for rent;

- providing internet ads, social media interactions, promotional offers, refer and earn offers
    - online portal/ website

- **Guests** to choose AirBnB over competition
  Means to get Guests:
  - interaction with the Locals/ Hosts;
    - Shared space
  - freedom to choose the type of property, amenities provided
    - by providing a filter to choose properties on the website;
  - generating trust;
    - identity verification process for hosts and guests, and insurance policies for the stay duration;
  - providing other promotional offers and extra credit

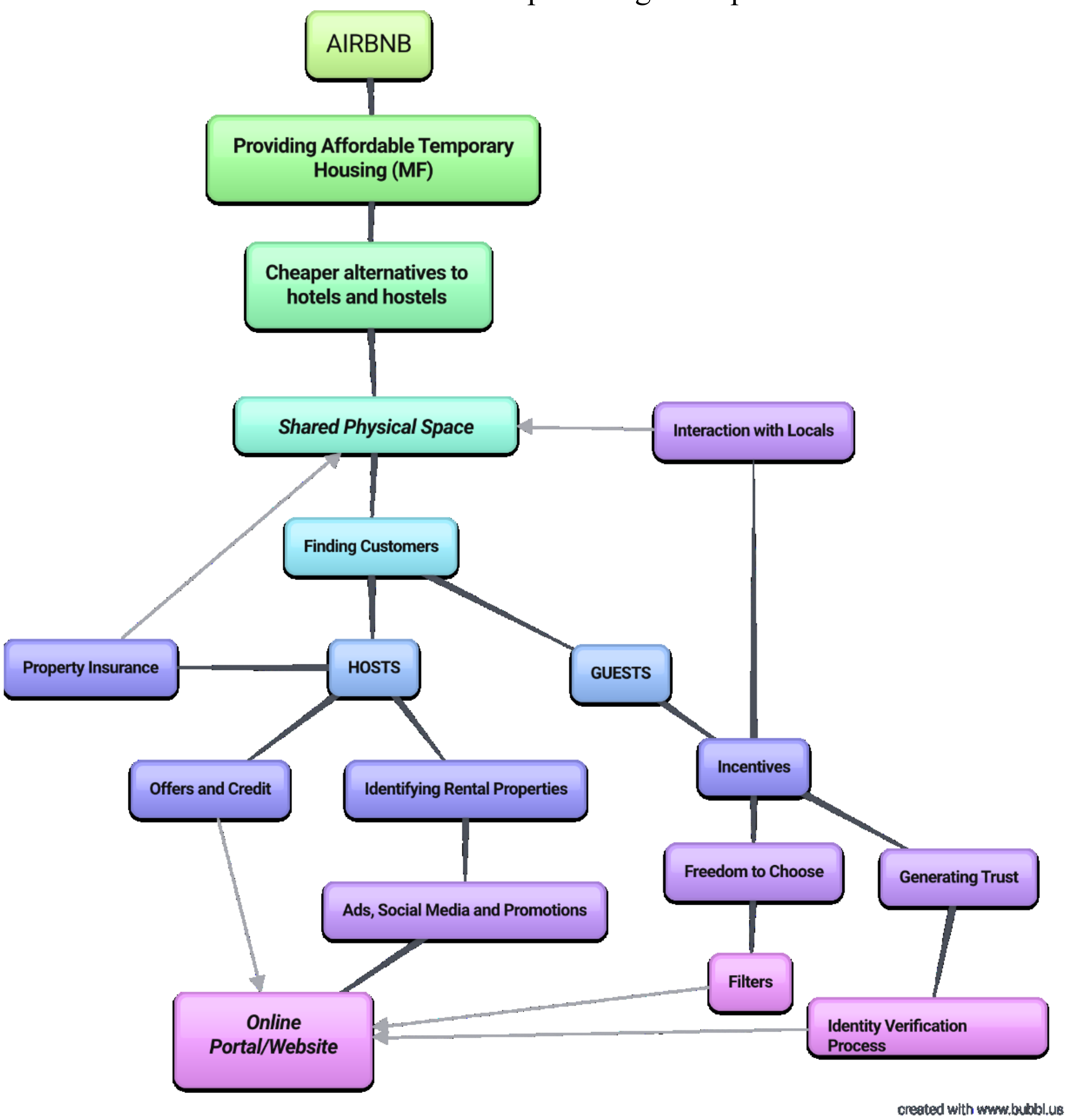

Figure 19 F/M Tree for MF2 of AirBnB

This analysis was carried out in the **CPDM department of the Indian Institute of Science under the supervision of Professor Amaresh Chakrabarty**. This was a tedious process as various versions of the F/M tree had to be constructed to evaluate the functions and finalise the structures. The evaluation of the FBS parameters required thorough understanding of the functioning of AirBnB's service system. I have now calculated the degree of SS and the RE of this model of the service system, by utilising the combined F/M tree in Figure 17.

$$Degree\ of\ SS = \frac{number\ of\ functions\ at\ the\ lowest\ level\ of\ abstraction}{number\ of\ structures} = \frac{9}{2} = 4.5$$

$$Resource\ Effectiveness, RE = \frac{number\ of\ main\ functions}{number\ of\ structures} = \frac{2}{2} = 1.0$$

The high numerical value of the degree of sharing suggests that one structure is clearly performing several functions. The high RE value suggest that AirBnB as a service is fairly resource effective and is a desirable service for the market. However, with respect to the existing solution, an absolute number does not yield clear results. The calculation of Relative Efficiency would provide a clearer picture about the RE in this case. This is because the service industry is a peer-to-peer network, with multiple branches and a lot of sub-functions and organs that have currently not been identified in my case in the limited time of the thesis. A more thorough evaluation is required for several typical solutions with similar functions, to gain clearer perspective regarding the absolute values of resource effectiveness and create a lateral comparison between them.

Comparison between Physical Product and Service System

In this section, I have tried to compare the two separate examples that we have analysed above. The goal behind doing this exercise is to understand how the concepts of product development change when applied to a service system, and how can we make a service system more resource efficient. But, due to lack of sufficient literature in this area, we cannot make concrete conclusions.

In the table below, I have listed the main parameters of comparison between the two examples. This will help us draw any plausible conclusions from the data.

Table 1 Comparison between USB + Camcorder and AirBnB

Parameters	Physical Product: USB + Camcorder	Service System: AirBnB
Main Functions	1	2
Structures	6	2
Degree of SS	1.17	4.5
RE	0.167	1.0

The designed USB + Camcorder solution does not seem like a feasible option, since the values of the degree of SS and RE are remarkably low. As was observed above in case of the USB + Camcorder, RE is independent of the degree of SS. This is because the RE does not depend on the sub-functions. Rather, it entirely depends on the main functions 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 F/M tree should have more RE. A design with lesser number of SFs and structures should be more efficient. (Chakrabarty and Singh, 2007)

To carry out a comparison, further evaluation of typical solutions is necessary. It is also important to assess the relative quality of the functions, RQOF, which has not been considered in the above formulae. The impact of negative effects is also not evident, making the numbers inconclusive. These parameters were considered while evaluating the Admissibility of the Sharing (Ghazanfari, 2016). However, evaluating the admissibility is not within the scope of this thesis, as further surveys and evaluations were required to get a clearer picture of the relative quality of function and its relative importance, which were not possible in the limited time.

In case of a physical product, the structures are relatively clearer, when compared to that of a service. However, without evaluating more typical solutions in both cases, any concrete assumptions and conclusions cannot be made. The more the number of solutions, the better is the assessment. This is because analysing multiple solutions helps us ascertain what works better to make our solution more feasible and unique.

Chapter 4: Conceptual Design of the Product

This chapter provides a systematic framework for the conceptual design of the automated workstation. Various steps of this process have been briefly discussed.

Identifying the customer/user

The initial stages of this thesis dealt with identifying the potential customer for the product. A backbone of the customer identification was provided by evaluating the market for existing products. Various case studies and user group analysis during the literature review revealed that open offices were a potential problem in this context, for the development of the design of this product. But, I wanted to further identify a widespread user base to incorporate more dynamic features in the product.

Individual users

Indoor

For a portable and automated workstation, every individual, ranging from a high school student to a working professional is a potential customer. Everyone requires a private space to work, study, conduct research; in other terms, to focus. Exploiting the needs and requirements of this customer base was of utmost importance to understand how our product could beat the existing competition. Since the problem that we were trying to solve with this product was that of space, I started looking for customers with smaller residential and office spaces; where we could modify the existing space with our extensible design. It was important to study these spaces and understand their basic requirements.

My first case study was that of a professional individual living with their family in a modest-sized apartment, where they do not have a separate and private study. A lot of professionals today are accorded the opportunity to work from home, and in cases such as these it is important to have a private working space at home. I explored different furniture designs for collapsible workspaces in smaller homes (Figure 20).

The problem with collapsible furniture was that it did not provide a sound proof, or even closed, environment for the user. Hence, to tackle these drawbacks, I explored some rough designs (Figure 21), forming the first basic design, Alpha, of the workstation. This is the design that I have worked with in this section.

The idea behind this design was to provide an affordable, comfortable, noise-proof and collapsible workspace that could be attached to any existing space at home that had a table and chair and was preferably closer to a wall. In Figure 21, you can see the basic idea behind the design, where we create a cylindrical or semi-cylindrical environment around the furniture. The material used for this design needed to be sound-proof, and this is where I started to consider collapsible walls. The most favourable building materials were padded wood, glass or plastic. This was the most basic design of the workspace considered for an indoor space for an individual. There were no high costs related to automation associated with this product. I spent a lot of time exploring different products to eliminate their cons and incorporate the pros in this basic design.

Figure 20 Collapsible workspaces

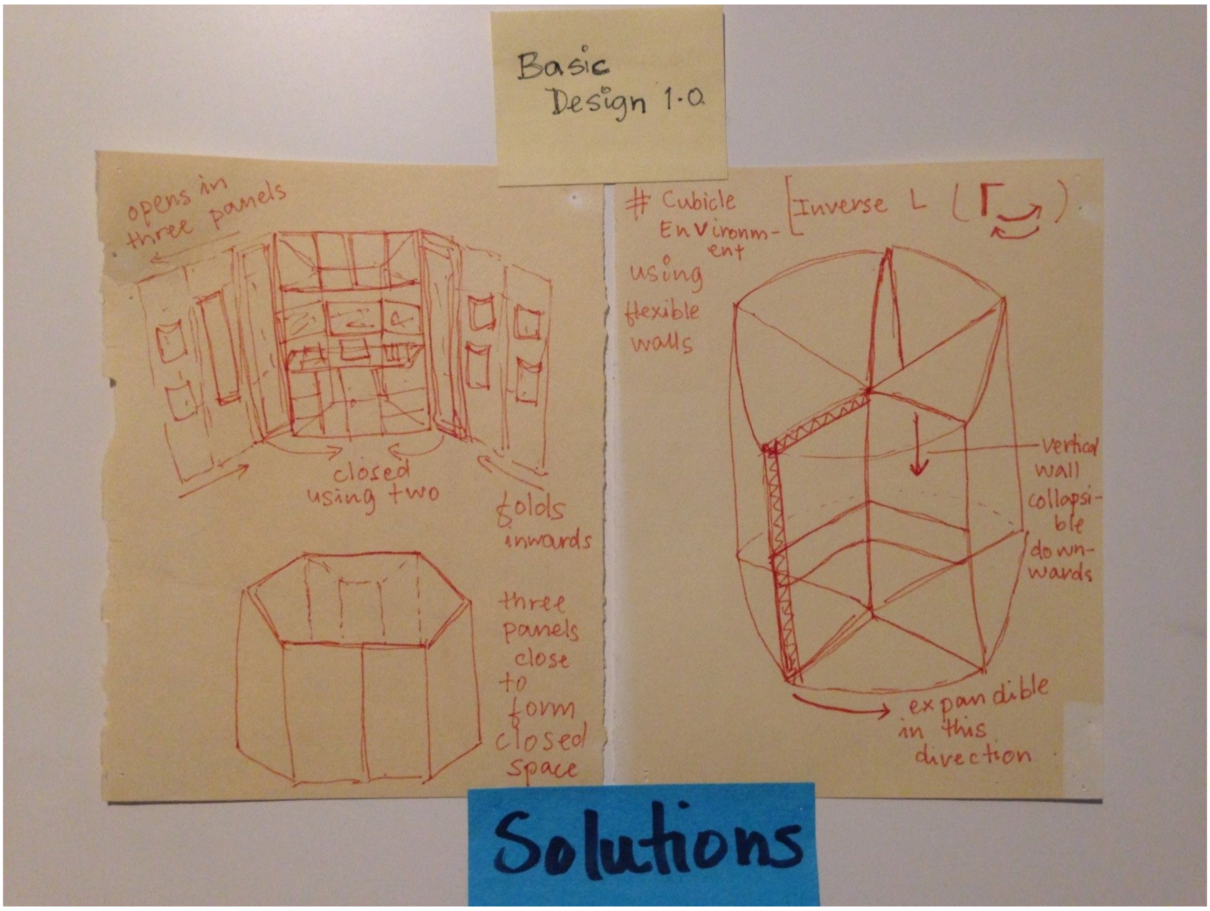

Figure 21 A design example for this problem context; Basic Design, Alpha

Outdoor

The next problem context was an individual user with bigger residential spaces, to accommodate the product in the outdoor environment, like a garage or a garden. For this design, we had to consider a fully-enclosed environment, with the possibility of storage spaces. During this period, I spent some time exploring pop-up and foldable furniture, to enhance the possibility of a modular product that included furniture. In Figure 22, one can see the various possibilities and designs of this kind of furniture.

Figure 22 Pop-up furniture

As I explored different use cases, the design evolved and became more dynamic. I was trying to understand the best possible way to accommodate all customer requirements without making the product unaffordable. Different methods of design helped me adopt this approach of starting from a basic design and evolving as the customer requirements evolved.

Multiuser environments

The next part of customer identification was identifying a group of users as potential customers. This is where open offices were our targeted customers. The idea was to provide a collapsible space for two or more users to be used for meetings, brainstorming sessions or any form of information exchange that required privacy. These workstations will have all the necessary physical and technological aspects of a small functioning office cabin, with the advantage of being collapsed and moved when not being used.

Another use case for this design was distributed units spread across a perimeter to be used as and when required by the user.

The idea is to design a self-operating smart product that modifies itself per the requirements of the user. A multitude of technical requirements surfaced when I started to conceptualise this new design. For complete automation, the workspace was to be provided with a secure locking system. Electrical and cyberspace requirements also grew. Foldable furniture was incorporated in these stations to enable smooth extensibility and collapsibility. Although the complete conceptual design was not in the scope of my thesis, I explored various aspects of the design, like furniture requirements, equipment requirements, cyberspace connectivity requirements and locking mechanisms. However, the collection of these requirements would have required extensive surveys and exploitation of consumer knowledge, which was not possible at this stage.

A design example of a different use-case for SPACYPHY, explored by Ehsan Ghazanfari in his thesis related to modular health pods is shown in Figure 23.

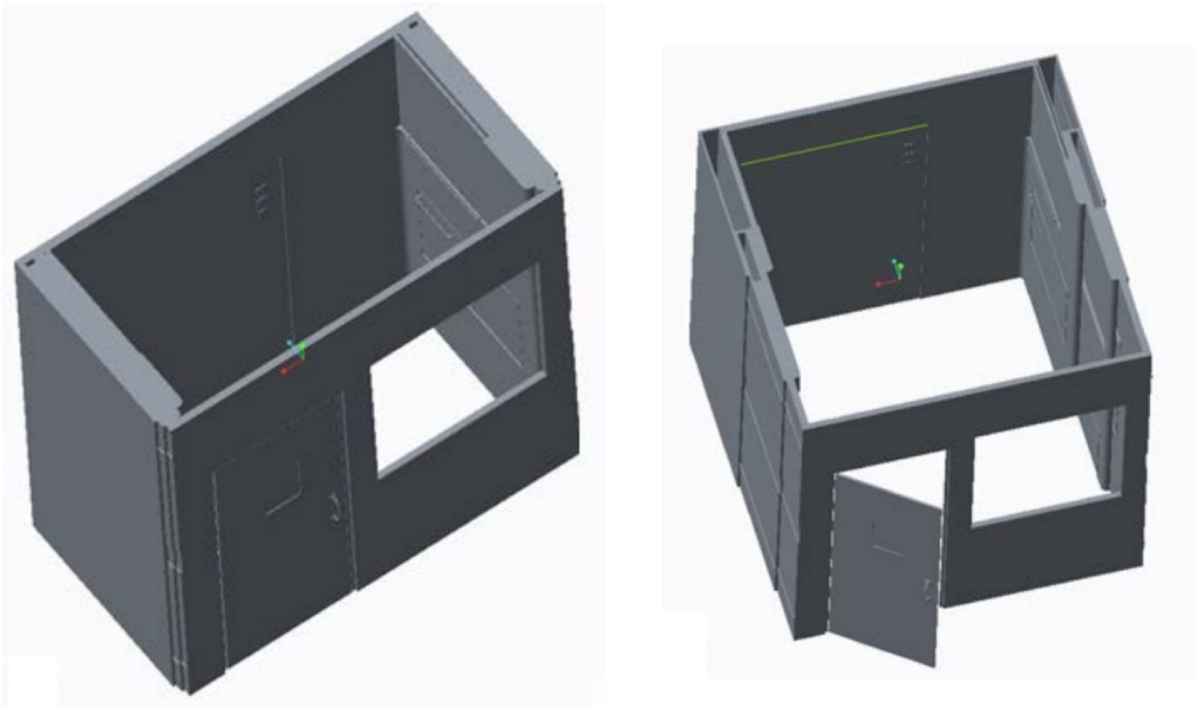

Figure 23 Design example of an extensible system in a health pod (Ghazanfari, 2016)

All the different parts of the assembly were designed as different modules and they were assembled in the software and checks were run for the clashes between different parts. Simulations were run of how the different parts should move and rotate and how the whole solution will expand and contract. The approach in the design is parametric which allows for faster and easier changes in the later phases of the design since all the geometrical properties and dimensions are parameters. Simulations make sure that the mechanisms and the moving parts of the solution are designed properly and will work as intended after manufacturing. (Ghazanfari, 2016)

The requirements explored in this thesis can be combined with the principles of parametric design and we can use CAD for carrying out the design process in future design projects.

Market Size Analysis

A very basic market size analysis was conducted for the European market, to understand the range of potential customers for a modular and automated workstation. This market analysis was done for professional environments, especially one with open offices, and for an estimated average number of individual customers. For this analysis, I considered different scales of businesses and evaluated the need for a workstation for the projected number of employees working in them. I have considered large, medium and small scale businesses, along with personal customers and small, new start-ups. The average data was collected for all the European countries and a market size projection was made. A more intensive analysis was done for Finland. The price per unit was estimated by evaluating the prices of the existing products in the market and by taking into consideration all the additional features incorporated in the product. The projected numbers can be seen in the tables below.

Table 2 Market Size Analysis of Europe

	Offices (Open offices or offices with cubicles)			**Personal customers/ Start-Ups**	
Size of companies	**Large scale business**	**Medium scale business**	**Small scale business**		
Number of employees	>1500	500-1500	100-500	5-50	
Number of companies	Total registered businesses				
		19234500		11356	
% in need for portable workstations		2.00%		1.00%	
Number		384690.00		113.56	
% of prospective customers in that lot		1.50%		80.00%	
Number		5770.35		90.85	
Number of prospective units sold per business		10.00		2.00	
Total number of prospective units sold		57700.00		182.00	57882.00
Price per unit		6500.00		5500.00	
Market size		375050000.00		1001000.00	376051000.00

Target Market	**Europe**
Population of Europe	338 million
Employed persons	151 million
Market Size	**376 million €**

Table 3 Market Size Analysis of Finland

Size of companies	Large scale business	Medium scale business	Small scale business	Personal customers/ Start-Ups	
Number of employees	>1500	500-1500	100-500	5-50	
Number of companies	Total registered businesses				
		122000		1050	www.startup100.net
% in need for portable workstations		2.00%		1.00%	
Number		2440.00		10.50	
% of prospective customers in that lot		1.50%		80.00%	
Number		36.60		8.40	
Number of prospective units sold per business		10.00		2.00	
Total number of prospective units sold		370.00		18.00	388.00
Price per unit		6500.00		5500.00	
Market size		2405000.00		99000.00	2504000.00

Creation of a Story Board

A story board explores the problem context and the journey of design from conceptualisation till production. In my storyboards, I have explored all possible problem scenarios and tried to solve them with existing products. I evaluated the user requirements thoroughly and used colour-coordinated stickers to highlight the advantages, drawbacks and potential design processes. The story board proved to be an important tool in visualising different aspects of the design process. As more customer requirements surfaced, the story board expanded. In the figures below, we can observe the evolution of my story board.

Figure 24 Story Board exploring contemporary products

Figure 25 Story board during the development of the product

Quality function development

The QFD analysis has been discussed in detail in Chapter 2. It was an important tool in exploring the customer requirements and understanding the importance of those requirements. It also helped in assembling technical and functional requirements against the requirements of the customers. In the scope of this thesis, I have demonstrated the QFD analysis for the first basic design, Alpha, for an individual user. The competitive advantage of this basic product over two other traditional products has been detected with the help of this analysis, and a comparison can be drawn based on how well the alternatives can satisfy the customer demands. This was possible by assigning a numerical value to the level of difficulty that is encountered while satisfying each functional requirement. It also helps in establishing connections between functional and customer requirements. Because of this analysis, the level of importance of each requirement in the total performance of the product can be evaluated and understood.

To collect the customer requirements for the basic product, Alpha, I considered myself as a potential customer and tried to evaluate my working space at home. This yielded a primary set of customer requirements to work with. I started thinking as a designer while thinking of the technical requirements for this product. This resulted in a list of primary technical requirements for this design. When all the requirements of the individual customer were accumulated in both indoor and outdoor environments, all the overlapping requirements were eliminated to create a new set of customer requirements. These requirements were for a modular product that could work in both indoor and outdoor settings, with or without furniture. This basic design of the product could be used in residential as well as small office spaces.

In the table below, I have listed out the customer and technical requirements that were used during the QFD analysis.

Table 4 Requirements of the Basic Product, Alpha; Customer and Technical

Customer Requirements	Technical requirements
Accessibility by individuals	Block: internal loads
Accessibility for a closed area	Block: external loads
Accessibility for a quiet space	Block: impact loads
Accessibility for privacy	Block: individuality in working of different modules
Accessibility for workspace	Block: proper adhesion
Design: Quality: easy to store	Block: operability as whole
Design: Quality: sound proof	Requirement of doors and windows
Design: Quality: comfort	Floor: absent: use of floor space for installation
Design: Quality: construction material	Floor: absent: adhesive walls
Design: Quality: robust when open	Floor: absent: connectivity to contained furniture
Design: Quality: self-sustained	Connectivity to the Ethernet
Design: Quality: easy-to-use	Electrical connectivity
Design: Quality: flexibility in operation	Availability of furniture
Design: Quality: transparent	Storage space requirements
Design: Quality: compact when closed	Walls: impact loads
Design: Quality: affordable	Walls: stretchable
Design: Quality. easy to store	Walls: retractable
Design: Quality: movable	Walls: multiple usability
Design: Quality: easily transportable	Ceiling: may not be load bearing
Design: Services: plug points	Ceiling: closed space
Design: Services: electricity	Ceiling: stretchable
Design: Services: air conditioning	Ceiling: retractable
Design: Services: ventilation	Ceiling: easily operable
Design: Services: sound insulation	
Design: Services: wifi/WLAN	

In the following figure, the QFD matrix for the basic design, Alpha, has been demonstrated.

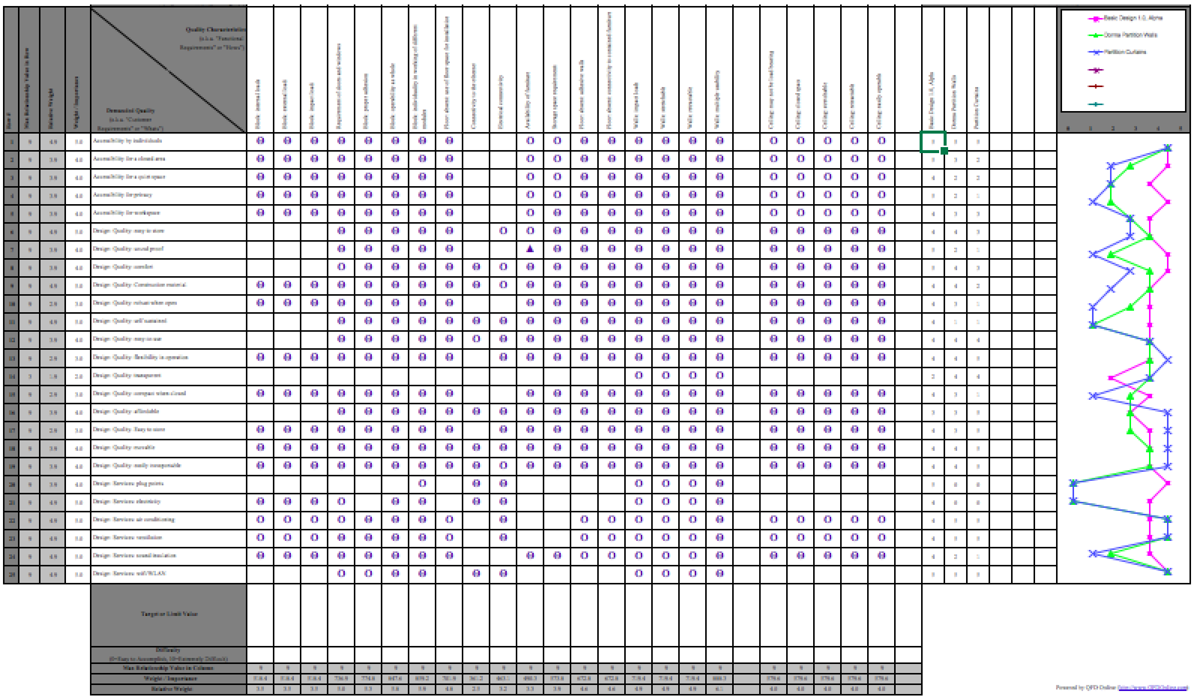

Figure 26 The QFD analysis matrix for the basic design, Alpha (Alpha as shown in Figure 19)

Results of the Analysis

The final output of the QFD matrix is a set of engineering target values to be met by the new product design. The process of building this matrix enables these targets to be set and prioritised based on an understanding of the customer needs, the competitor's performance and the organisation's current performance. After considering all these parameters, the new specifications for the product can be defined. This process goes on for various aspects of the design and development process, and allows the customer to drive the product development process right through to the settings of the manufacturing equipment.

In the example matrix for the basic design of an indoor system of our product, we have assessed it against two competitors in an indoor setting, partition walls and partition curtains. It is no doubt that our product will fare well against either of these competitors, both in terms of space and noise proofing. However, these products are not the best competitors to be used for deciding the design parameters for the product. Another QFD matrix can be computed for more reliable products, such as collapsible workspaces (Figure 20) and/or pop-up furniture (Figure 22).

Chapter 5: Conclusion and Future Work

In this chapter, I have discussed the similarities between a service system and the framework of a distributed modular and automated workstations. I have summarised the various aspects of the thesis and how they are connected. New research opportunities for future work have also been introduced towards the end of this chapter.

Distributed Network of Modular Workstations as a Service System

In Chapter 3, I have analysed a service system as a shared structure and computed the degree of structure sharing and resource effectiveness for the same. The idea behind exploring the concept of structure sharing in service systems is to understand the functions and structures involved in the design and development of a service and help in designing better and more resource efficient services.

The conceptualisation of SPACYPHY units has been so done that we create a system of distributed and automated physical spaces for various use cases, which have a cyber infrastructure and have the capacity to communicate with each other and the control room. In creating this system of distributed units, we are aiming to construct a service system of shared structures. This was the motivation behind studying structure sharing in service systems.

The idea behind developing such connected systems goes beyond energy saving. In case of SPACYPHY, it provides a solution to the rising problem of space. Introducing internet-enhanced automation in these products assures least physical or mechanical involvement. As observed in the F/M tree of the service system of AirBnB, the peer-to-peer network of the service results into a branched set of functions and structures. Similarly, when we design the distributed system for SPACYPHY, the internet-service system would result into a complex mesh of structures and their functions.

However, the aspect that needs more reflection in this case is whether the same parameters can be used for assessing the resource effectiveness of a service system as are used for a physical product. This ambiguity can be eliminated by evaluating the formula against several typical systems for a range of functions, and assessing and comparing those results. Thus, further research is necessary to make any concrete conclusions in this regard. What can be said with certainty is that sharing is observed at different levels of a service system, and structures and functions, although present in a much complex mesh, can be clearly identified.

Let us consider the example of an automated, smart, energy-efficient street-lighting system, to observe the internet-based control system undergoing sharing at various levels of its design. By using a controller on our mobile devices, we can control different parameters of this system. A physical layout for such a system has been presented in Figure 27.

The smart lighting controller serves as the distributed unit in this example. All the controller in different segments are being controlled by the smart lighting segment controller, which is working on the 3G network. The system of distributed SPACYPHY units would work on similar principles as this. However, the system architecture would be more complex.

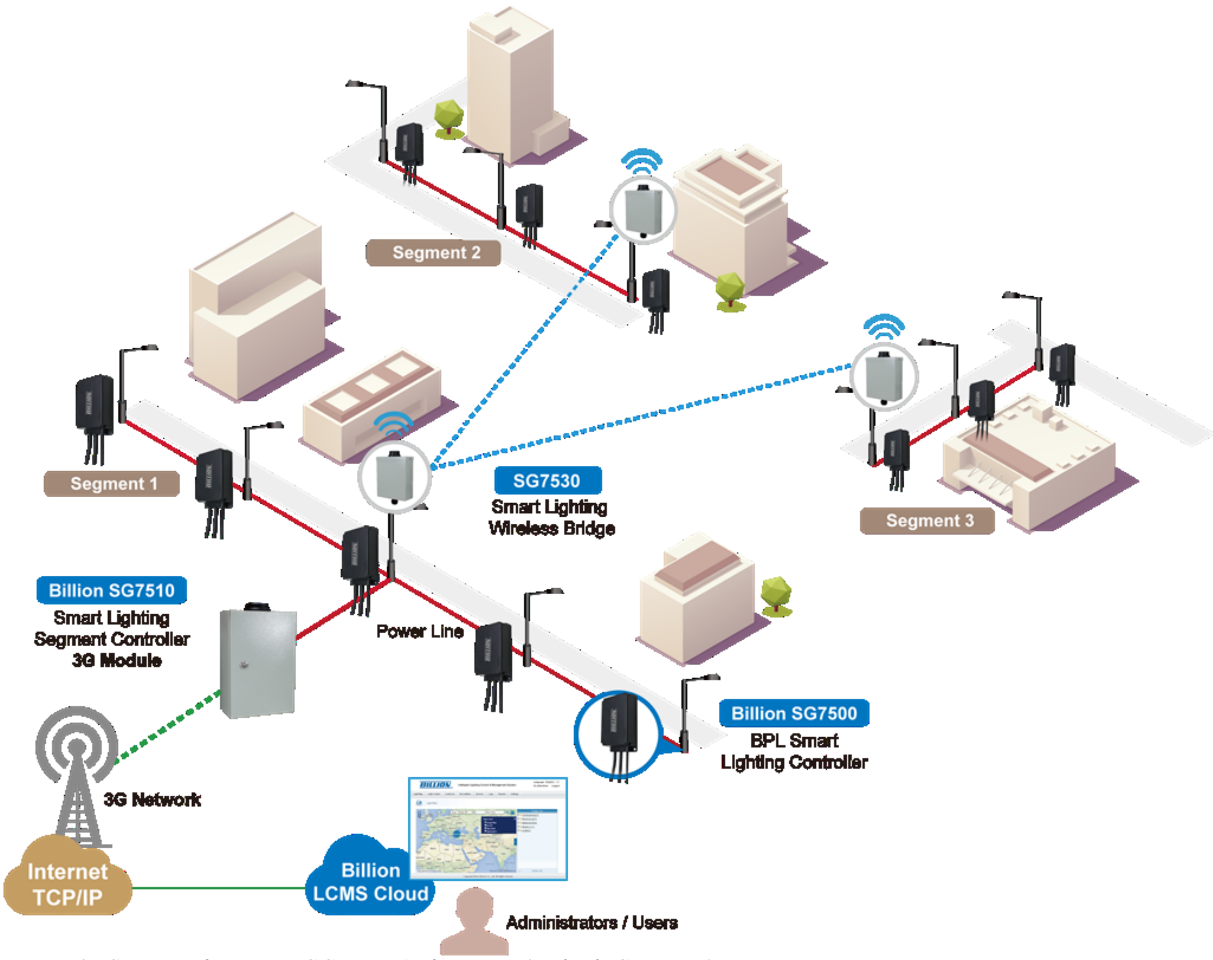

Figure 27 Smart Lighting BPLC System Architecture (Multiple Segments)

Other Use Cases for SPACYPHY units

SPACYPHY units have an increasing number of use cases in the health care environments. It can be used to provide a sterile health pod in a public dormitory or used for out-patient care. The design of the unit can further be customized to be used as a portable health station or blood collection station.

The dynamic design of these units make them eligible to be used as portable classrooms and creates a broad spectrum of demand for such units in developing countries. These units can also be used inside or outside a residential environment to create a make-shift guestroom or temporary storage spaces. If customised further, they could also be used by pharmaceutical companies for temporary sterile laboratories. These units can also be used in the form of hi-tech tents or attached behind cars to create temporary caravans for camping and stargazing. These units can be converted into nurseries with proper customisation to grow season-specific plants. The uses of such a unit are endless, but any customisation would require identification of the potential users and a thorough requirement analysis to make the design feasible.

Research Limitations

During this thesis, it was clear that this conceptual research does not provide any concrete conclusions. Rather, it thoroughly explores a wide spectrum of concepts in the field of product design and development and enlists the different ways of incorporating them in structural design. It also provides a framework or step-by-step process to conduct the conceptual design of a product.

One of the limitations faced during the thesis was imbibing the concepts of product design, which ran on parallel track when compared to traditional design for built-environment. Time was a limiting factor in this case, as learning and understanding these processes took a good amount of time allocated to the thesis. In this thesis, more emphasis was given on the primary research done in the field of structural sharing, such that these concepts were implemented on a service system. Conclusive analysis of the results could not be carried out due to limited time and scope. But the analysis done in this thesis, opens various gateways for future research work, incorporating the new concept of admissibility of design on relative grounds.

Another limitation was availability of relevant literature since structure sharing in services is a newly introduced concept. A lot of time was spent in understanding the service system and constructing drafts of F/M trees to accommodate all the relevant functions. However, I hope that this initiative is further advanced with more extensive research work.

Future Research Opportunities

In the context of product design and development, this research and ongoing contemporary research work opens a portal for instigating multi-disciplinary projects in the field of build environment and large-scale construction. It presents a multitude of research opportunities of structural and civil engineers wherein these concepts of engineering design can be introduced into the traditional practices of construction. With the problem of space ever increasing, one can only hope that construction of smart physical spaces becomes the number one priority and the demands and requirements of the end-users be given utmost priority during the design process.

In the context of structure sharing in services, there is still much to do. This area of research, however briefly explored in this thesis, opens new perspectives to investigate a service system and make it more efficient. Further work in this field can help us develop smart services, specially in the administrative sectors. Developing nations appear to be a potential market for such services. The influx of effective and smart services will eventually lead to a paperless service industry, and provides a panorama of research opportunities in the field of IoT.

As far as further work for SPACYPHY is concerned, the extensive availability of use cases makes it a viable product in the market. Further research can be done in the design and development of some of these use cases, building on the conceptual design principles explored in this thesis. The automation and design of the distributed system for these units holds a lot of potential for further research.

Conclusion

This thesis aims to initiate a change in the design thinking and process of structural engineers. It also addresses the immediate problem of availability of physical space and introduces a new physical product in the form of a modular and automated workstation. Through the course of this thesis, we learn to conceptualise a product by means of product design principles and concepts. The idea of facilitating the design of virtually connected physical units to provide satellite services in the future was put forward. The concept of structure sharing was thoroughly explored and a new aspect of sharing was assessed and evaluated in service systems. Sharing in products and services were briefly compared, and the system of virtually-connected units was explored as a service system. Finally, a conjugation of ideas was put forward to further explore these concepts in future research initiatives.

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