# Part II

## Using Solution Space:

### Exploring Users Simplifying Solution Space


H.S. Naik, *Simplifying Solution Space*, Markt- und Unternehmensentwicklung
Markets and Organisations, DOI 10.1007/978-3-658-18283-0_2

# 1 Needs and Objectives

The first Part of the thesis introduced toolkits for UID and solution space and explained the challenge of simplifying a large solution space for non-expert users. *Part II*[8] of the thesis aims to answer how users simplify their solution space to innovate and design. A growing number of users can construct physical solutions that satisfy their special needs. Toolkits play a significant role in enabling these users to develop solution information (von Hippel & Katz, 2002), but it is important to understand the different steps of this development, the constraints users face, and the support they receive. Exploring how users manage the complexity of creating innovative solutions using multiple toolkits with many solution spaces leads to recommendations for simplifying solution space that enables non-expert users. Hence, this study aims to answer the first sub-research question:

*RQ1: How do users simplify their solution space to create innovative solutions?*

The motivation for this study stems from a lack of research on a user's solution space to innovate with multiple toolkits. Reiterating the first chapter on the challenge of simplifying solution space, both individual users and user firms innovate and develop new products that better solve their problems and fulfill their needs. However, transferring this need information to manufacturers or service providers can be very complex and time-consuming. Toolkits can enable users to perform need-related innovation tasks themselves. Toolkits have been studied as systems specific to a field, for example, integrated circuit design (von Hippel & Katz, 2002), or software game design (Prügl & Schreier, 2006) and are restricted to the solution space of the manufacturer's production system. An emerging trend in user innovation is working with multiple solution spaces from multiple toolkits. The user's perspective on innovation becomes even more complicated as technologies like 3D printing have

[8] An earlier version of this research has been presented at the Open and User Innovation Conference (OUI) 2014 as (Naik & Möslein, 2014)

toolkits for building components but not for complete products. This makes them necessary but not sufficient to create innovative products.

The context of 3D printing further explains the notion of users working with multiple solutions spaces. Despite 3D printing toolkits having a large solution space regarding the broad range of shapes they can design, they have some limitations (Snyder, 2014). Commercially used 3D printing technologies are mostly restricted to printing in a single material. Multi-material 3D printers in use are expensive, often proprietary, and limited to at most three materials (Sitthi-amorn, Lan, & Wang, 2015). Furthermore, the quality of 3D printing technologies varies drastically. Home printers do not always produce parts that meet necessary material characteristics (in terms of strength, reliability, etc.). Printing functional electronic components such as integrated circuits, motors, etc. is still a distant dream. Hence, users often need to assemble their products out of various components that could be either 3D printed or manufactured through other processes.

The objectives of the study are to explore user innovations from the users' perspective as they innovate and design with toolkits that possess multiple solution spaces and to identify how they simplify their solution space in this process. As a solution that meets user needs is the goal of the user innovation process, this study emphasizes user innovators and their associated solutions. The theoretical perspective of modularity as discussed in *Part I* is used as a lens to analyze the organization of the innovation process followed by users and firms and the evolution of the solution. Hence the relevant theoretical concepts here are modular organizations (Sanchez & Mahoney, 1996; Schilling, 2000), as well as modularity-in-design and modularity-in-production (Baldwin & Clark, 2004).

The explorative study follows a case study research approach using the above theoretical perspective (Yin, 2009). The empirical context for the study is user innovations in products involving technologies such as 3D printing and open hardware electronics (as seen *in "maker communities"* and closely related *"maker events"*[9]). The users innovate and develop products that belong to various industry

[9] Chapter 2 further discusses maker communities and maker events.

domains. The study describes user innovations themselves, the characteristics of systems used to design them, and the use of the solution space, and identifies models for simplification of solution space.

This study forms *Part II* of the thesis and consists of five chapters. Following the introduction in chapter 1, chapter 2 and chapter 3 present the literature background and theoretical underpinning of the study. Chapter 4 describes the selected research design, details the processes of data gathering and analysis, and presents the empirical data under study. Chapter 5 presents the main findings of the study. The final chapter 6 consists of discussions on this study and areas of future research.

# 2 Understanding the Context

This chapter describes briefly the necessary literature background needed before going into further details of the study. As the objectives of the study are to explore how users simplify their solution space when creating innovative solutions, it begins with some primary background literature on user innovation, the importance of lead users and communities, and the role of sticky information. This section leads to literature on toolkits and their solution spaces. As the empirical context of the study is user innovation in making tangible products, the next section describes the latest research on users making products using technologies such as 3D printing and open hardware electronics in communities and events. The literature background sets the stage for the next chapter that discusses the research method and data.

## 2.1 User Innovation

Von Hippel conceptualized the term user innovation along with identifying the customer-active paradigm, where the customer actively develops an innovative product idea and takes it to the manufacturer (von Hippel, 1978a). He looked at the industry of scientific instruments and found that users dominated the number of innovations instead of manufacturers, by inventing, prototyping and field testing innovations (von Hippel, 1976). A study on the semiconductor and electronic sub-assembly industry once again reported the significant share of innovations from users and user firms using the equipment rather than the equipment manufacturer (von Hippel, 1977). However, the role of users in the innovation process has been observed even earlier, with cases documented from the 1960s showing significant user contributions (Bogers, Afuah, & Bastian, 2010).

### 2.1.1 User Firms as Innovators

Both individual end users and user firms develop new products and processes in various industries. User firms are credited to innovations in diverse industries such as oil refining (Enos, 1962), chemical industry (Freeman et al., 1968), innovative industrial processes (Foxall & Tierney, 1984), construction industry (Slaughter, 1993),

*Table 1: Compilation (non-exhaustive) of instances of innovation by user firms*

| Industry | Instances of Innovation by User Firms |
|---|---|
| Banking Services | 55% of computerized commercial banking services were first developed and implemented by non-bank firms for their use (Oliveira & von Hippel, 2011) |
| Industrial Robotics | Firms that are both users and producers offer more advanced features (Roy, 2009) |
| Oil refining | Refining firms, users of the technology developed improvements and new processes (Enos, 1962) |
| Chemicals | Major process innovations came from chemical companies running process plants (Freeman et al., 1968) |
| Scientific instruments | 80% of the innovations that offered a significant increment in utility were invented, prototyped and field tested by users (von Hippel, 1976) |
| Semiconductors and electronics | Process machinery user rather than the manufacturer dominates the innovation process (von Hippel, 1977) |
| Clinical equipment | Medical equipment used to determine levels of chemical constituents of blood developed and used by laboratory clinicians (von Hippel & Finkelstein, 1979) |
| Aerospace | Tools used in the aerospace industry were initiated and developed by the aerospace firm (Foxall & Tierney, 1984) |
| Applications Software | User presence in all stages of innovation: need recognition, idea formulation, development and commercialization (Voss, 1985)<br>User firms of Apache web server software modified the software to better meet their specific needs (Franke & von Hippel, 2003) |
| Residential construction | User-builders were exclusive source of innovations that involved integration of components from suppliers (Slaughter, 1991) |
| Automobiles | Japanese suppliers of machine tool for cars got investments, direct development inputs by Japanese car producers (Lee, 1996) |
| Electronics | Japanese electronics firms developed computer controlled tools for their production (Lee, 1996) |
| Convenience stores | Innovation in store inventory management in convenience stores was initiated by the store (Ogawa, 1998) |

development of machine tools (Lee, 1996), convenience stores (Ogawa, 1998) and in the software industry (Voss, 1985). Table 1 compiles a non-exhaustive list of instances of user innovations seen in firms, to highlight the industrial diversity of this phenomenon. User innovation among end users is also very diverse as the next section demonstrates.

### 2.1.2 End Users as Innovators

Users as a valuable source of ideas, and methods to identify them have been discussed in marketing research (von Hippel, 1978b), von Hippel went further and identified "lead users" to a product or process who have strong needs that can become general market needs in the future. They often attempt to meet their unfulfilled needs by designing and developing new products and processes and, thus, can provide new concept and design ideas as well as user need-forecasting (von Hippel, 1986). Lead users are seen influencing the development of information systems as in the library users of OPAC information search systems (Morrison, Roberts, & von Hippel, 2000,) and security software developed by users (Franke & von Hippel, 2003). The lead user concept was further explained along with mechanisms of identifying them with studies in various industries such as computer-aided systems for the design of printed circuit boards (Urban & von Hippel, 1988), construction products and materials (Herstatt & von Hippel, 1992) and in developing innovative services in banking (Oliveira & von Hippel, 2011; von Hippel & Riggs, 1996).

User innovation from end users is also present in user communities especially in products used by hobbyists and enthusiasts (von Hippel, 2005). Users freely reveal their innovations, so they benefit as a whole without having to independently innovate by themselves (Harhoff, Henkel, & von Hippel, 2003). The open source software movement demonstrates typical examples for user innovation communities. Development of open source software has distributed management and has significant contributions from end users. The Linux operating system and Apache server software are well-known examples of open source software that were developed by programmer-users of these software (Harhoff et al., 2003; Lakhani & Von Hippel, 2003). Open source communities are usually not firm hosted and can spawn around open source projects in software as well as hardware (Balka, Raasch, & Herstatt, 2009;

Raasch, Herstatt, & Balka, 2009). These communities can also consist of professional users as seen in Salesforce.com's IdeaExchange or a mix of corporate and individual end users as in Dell IdeaStorm (Li, Kankanhalli, & Kim, 2016). Selective openness by firms in consumer electronics and information technology hardware industries has been shown to have an impact on user involvement and contributions in firm driven user innovation communities (Balka, Raasch, & Herstatt, 2014).

User innovation communities are not limited to software and electronics. Studies have shown that user innovation communities provide value to developing physical products in the field of sporting equipment used in the extreme sports of canyoning, sailplaning, boardercross and cycling (Franke & Shah, 2003). Similar instances of user innovation communities were found in sporting goods and mountain-biking (Baldwin, Hienerth, & von Hippel, 2006; Lüthje, 2004; Lüthje, Herstatt, & von Hippel, 2005; Raasch, Herstatt, & Lock, 2008; Tietz, R., Morrison, P. D., Luthje, C., & Herstatt, 2005).

Communities of lead users bring additional value when compared to regular user innovation communities as their contributions stem from their ability to develop solution information instead of simply describing problems or stating customer needs (Mahr & Lievens, 2012). The capability of an innovation community to go beyond just ideation to implementation is critical to creating business value. That is, the capability to select user-generated ideas from the community for innovation development and then introduce the developed innovation to the desired users via the community (Dong & Wu, 2015).

### 2.1.3 Sticky Information

While users are a valuable source for innovations and lead users can identify upcoming innovations, there can be problems with shifting this need information from the user to the manufacturer when the information is "sticky." Stickiness is the incremental expenditure required in transferring the information from one place to another in a form that is accessible by the information seeker. This problem limits the realization of innovations based on user needs. Stickiness can depend on the type of information, the information provider or seeker, or the mode of interaction in between them (von Hippel, 1994). The concept of information stickiness is similar to tacit knowledge (Brodbeck & Polanyi, 1960). This inherent stickiness of information has been observed in the user innovation communities in sporting equipment mentioned above (Franke & Shah, 2003). Because of this nature of sticky information, many users are not aware of their needs and are not able to formulate these needs explicitly. However, users who engage in learning-by-doing processes can develop new products (Slaughter, 1993), thus suggesting the use of toolkits for user innovation as a means of solving the problem of sticky information. The next section further explains this concept.

## 2.2 Toolkits for User Innovation

Toolkits, as defined by von Hippel and Katz, refer to systems offered to users to innovate through a learning-by-doing process. Toolkits give their users some of the design capability of the firm and thus do the job of transferring the manufacturer's solution information to user-innovators, thereby reducing the stickiness of problem-related knowledge mentioned in the previous section. Integrating user innovation and design ideas requires a connection between problem information found among users and the solution information usually found in firms. The interaction and information cost arising in this process can be handled by information systems which guide users, either through a basic configuration process or even enable them to develop innovative solutions resulting from their specific needs (von Hippel, 2001; von Hippel & Katz, 2002).

Solution space is one of the five main characteristics of toolkits for user innovation as described earlier in *Part I*. Toolkits offer users a 'solution space' of design freedom not exceeding the manufacturer's production capabilities. Users learn to innovate and design solutions by performing learning cycles of trial-and-error in the solution space. Well-designed toolkits are user-friendly enough so users can learn without additional training. Toolkits contain libraries of standard modules or presets that can act as a starting point for users' design changes. Also, properly designed toolkits ensure that the solution space of toolkits is such that the manufacturer can produce user-designed products or services without requiring any further revisions (von Hippel & Katz, 2002). Prügl and Schreier (2006) classify toolkits into expert and basic toolkits based on the solution space they offer to users. The remainder of this section discusses expert toolkits as they deal with user innovation rather than customization, which is relevant for the study. *Part III* discusses basic toolkits further.

Expert toolkits (or high-end toolkits) for user innovation are described as a source of radical innovations, which offer theoretically unlimited solution space to the users within the manufacturer's production capabilities (Franke & Schreier, 2002). Thus, they create radical solutions to both existing and new problems, generate new functions, and even create entirely new products. They tend to be more challenging to use and demand greater user skill and so are appropriate for expert users (Prügl & Schreier, 2006). Lead users who have significantly altered a product or developed new product functionalities for their personal or in-house use can use expert toolkits when there are not satisfied by standard products. Firms have used expert toolkits to "plant" and "grow" innovators among their user base. Lead users using toolkits have been known to develop modules which, if proven to be popular and error free, get later incorporated into the standard versions of the products. This incorporation is seen as in the cases of the statistical analysis software firm Stata and toolkits for the computer game The Sims (Franke & Schreier, 2002; Prügl & Schreier, 2006).

The study on toolkits used in The Sims gives further valuable insights on the usage of toolkits by lead users. Lead-user innovators consider their innovation engagements a long lasting experience that is continuous, evolving, and intense. They are sometimes not content with the official toolkits provided by the manufacturer and resort to using their own toolkits to push further their design possibilities. Furthermore, user created designs and user created toolkits are sometimes not just own creations used only by their creators, but have a high demand among other users as well. It suggests that firms can incorporate user created toolkits along with user created designs into their standard offerings.

Toolkits have also equipped lead users in the form of individuals or groups of individuals to contribute to product design without having all the necessary skills to design a product from scratch. Toolkits achieve this by providing libraries that give users similar capabilities by letting them convert their innovative ideas into novel solutions by combining different modules and not having to work from scratch (von

Hippel & Katz, 2002). Furthermore, user communities often accompany expert toolkits, which assist in problem-solving and diffusion of toolkit related information (L. Jeppesen, 2003). A properly designed toolkit which encourages learning-by-doing and has an active community can train non-expert users to increase their expertise as in the Sims (Prügl & Schreier, 2006). In the context of making tangible products, toolkits can be either software, hardware, or both. The next section further explains toolkits in the context of this study.

## 2.3 Solution Space for Making

This study has a context of user innovation with new production technologies like 3D printing and focusses on the emerging phenomenon of 'making' tangible products. Users making physical product innovations has been driven by technologies like 3D printing and open hardware (Balka et al., 2009) such as Arduino microcontrollers, which have introduced innovation opportunities by faster prototyping and easier availability of parts through direct online distribution. Social interconnectedness due to growing participation of people from different communities, skills, and interests have played a significant role as well (Honey & Kanter, 2013). Maker events extend the approach of online open design communities by offering a localized social gathering for a fixed time that accelerates knowledge sharing among the community members (Chorianopoulos, Jaccheri, & Nossum, 2012).

A consumer 3D printer accompanied with 3D design software provides users design feedback cycles that allow them to design innovative products with a learning-by-doing process. Consumer 3D printers typically print in various plastics. They are computer-controlled machines that successively lay out layers of material to create the desired shape of the object. It follows an additive process, which contrasts with traditional subtractive processes of machining, where the material is removed using methods such as cutting and drilling. An increasing number of online 3D printing services and marketplaces supplement consumer printers as means for users to print their designs. As this technology can print in virtually any shape and a diverse set of materials that include metal and ceramic (Anderson & Sherman, 2007; Snyder, 2014) it provides users with a large solution space.

Using these technologies, users have been developing and sharing 3D designs in online user communities. The online community Thingiverse, which was started by 3D printer manufacturer Makerbot is known as an online community where designs have extensively branched out because of its open source network nature (Kyriakou, Englehardt, & Nickerson, 2012; West & Kuk, 2014).

In the offline world, the idea of a dedicated location to make tangible objects, a "makerspace" has taken hold where users can get together, learn and develop through complex design and making practices (Sheridan et al., 2014). These makerspaces contain equipment for rapid prototyping and digital fabrication. Events called "hackathons" which were initially conducted for developing new software, now are carried out in these makerspaces using these technologies and they include "maker events" that allow rapid prototyping and development (Briscoe & Mulligan, 2014; Sydow, 2015).

With this necessary context for the study, the next chapter delves into the theory for conducting the study. Users as they innovate and design in these communities and events employ principles of modularity theory. The next chapter summarizes aspects of modularity that forms the theoretical lens for conducting this study.

# 3 Theoretical Underpinning

Theory on modularity as described in *Part I* is a useful viewpoint to understand both organizational forms as well as product design. It is a general systems concept that describes the degree to which components can be separated and recombined. This refers to the rules of the system architecture which enable or prohibit the mixing and matching of components (Schilling, 2000). The theory is especially suited for this study because modularity is distributed nature enables simplification. As this study explores how user innovators simplify their solution space, the focus is on exploring and identifying how solution space is simplified through occurrences of modularity, as users organize their innovation activities with others, and as they develop their innovative solutions.

*Modularity in organizations* marks a shift from large hierarchical integrated organizations that have disaggregated into loosely coupled organizations that work together with coupled production arrangements. Through this change, firms can specialize in their respective competencies while offering more heterogeneous products and services. Heterogeneity in inputs and demands drives interfirm modularity and competition acts as a catalyst (Schilling, 2000). In the context of user innovation, organizational modularity is in between users themselves and between users and firms. They work together to establish modularity-in-design and share the design load between them (Baldwin & Clark, 2004). Organizing can range between increasing modularity and growing integration depending strategic goals as is explained in Table 2.

*Modularity in products* makes it easier for lead users to develop focused product functions without having to redesign the whole product. Users can also develop complex products traditionally developed by large teams using pre-designed customizable modules, which would have required much more labor when designed from scratch even by experienced users (Baldwin & Clark, 2004).

An example for such a case of a modular toolkit is the open source Drupal Content Management System. It consists of various modules developed by its open source community, each of which users can easily configure. Every user can then develop a distinct platform using a unique combination of Drupal's modules configured to the user's needs. Lead users with sufficient PHP programming knowledge can develop their innovative modules and offer it to other users in the Drupal community. Thus, the Drupal website hosts and offers to other users established modules developed in a distributed fashion. Hence, it exhibits modularity-in-design, modularity-in-production as well as modularity-in-use (Baldwin & Clark, 2001, 2004).

*Table 2: Factors driving modularity and integration, based on Schilling* (2000)

| **Driving Modularity** | **Driving Integration** |
|---|---|
| Heterogeneity of customer needs | Increasing market power |
| Heterogeneity of components needed | Maintaining architectural control |
| Environmental pressures from<br>• Competition<br>• Technology change<br>• Creation of standards | Specificity in components |

## 3.1 Operations in Modularity

Baldwin and Clark summarize six core design operators of a modular system (Baldwin & Clark, 2001). These operators are relevant in both the context of organizations and product design. In product system design, these operators apply in a more top-down fashion while they evolve bottom-up in organizations. These operators provide flexibility in design as long as new design follows the underlying design rules. The basic operators are the following: 1) Splitting into independent modules, 2) Substituting of modules in a system, 3) Excluding modules to modify the system, 4) Augmenting new modules into the system, 5) Inverting the order of module dependencies, and 6) Porting modules to use in different contexts. These operators have led to other derivations such as linking, recombining, and extending modules, which

Table 3 describes along with the basic six operations.

*Table 3: Operations on modular systems based on Baldwin and Clark* (2004)

| Operations | Description |
|---|---|
| **Splitting** | A combination of different modules can replace a module. It increases the options in the system and can increase economic value |
| **Substituting** | A module can be replaced by another improved module as long as the design rules are followed in the new module |
| **Excluding** | A module of the system can be excluded if the value it brings in is not needed or introduces new problems |
| **Augmenting** | A new module can be introduced to the system that provides additional value to the system |
| **Inverting** | The hierarchy of modules can be changed by creating a new grouping of design rules that is separated from the architectural module |
| **Porting** | A module can be ported to another system by creating a "shell" so that it works for systems other than that for which it was designed |
| **Linking** | Pre-existing modules can be linked differently to create new functionalities |
| **Recombining** | Linked modules can be integrated to create efficiencies at the cost of losing the option generated. It is the opposite of the splitting operator |
| **Extending** | Modules can be extended by modifying them to provide additional value |

## 3.2 Interfaces in Modularity

Modular systems connect to each other, and with their connection, they interact with each other and exchange resources or data (Sahaym, Steensma, & Schilling, 2007). Modular interfaces in products can be of two types. Firstly, they can be three dimensional as in the case of physical interfaces between two mechanical objects. Secondly, they can be one or two-dimensional, as in computer systems where these interfaces then could be informational or used to transmit electrical power (Whitney, 2004). Table 4 explains these types of interfaces using examples.

*Table 4: Types of interfaces in modular product systems*

| Types of Interfaces | Examples |
| --- | --- |
| ***Physical Interfaces*** | Plugs and sockets so that two modules that follow standards in dimensions so that they can physically fit together (Whitney, 2004) |
| ***Information Interfaces*** | Two modules that follow the same communication protocol, so they can transfer information to each other (Whitney, 2004) |
| ***Resource Interfaces*** | Power wiring through plugs and sockets to transfer electrical power between the modules (Sahaym et al., 2007) |

Modularity in design has well-known benefits such as cost reduction, lesser learning time, design flexibility, and customization. It certainly has impacted the computer industry both regarding software and hardware (Baldwin & Clark, 2001, 2004). Open source hardware platforms using modular electronics like the Arduino along with open source 3D designs are poised to impact specialized equipment manufacturing as well (Pearce, 2012).

# 4 Method and Data

This chapter presents the method and data used to identify how users simplify solution space when creating innovative products. The chapter divides into three sections. The first section places the research approach followed in *Part II* within the overall research approach of the thesis. The second section describes the research design in detail which includes the method used, data collection processes followed, and data analysis in the two sub-studies. The third section describes the empirical data samples, which consists of cases of user innovations.

## 4.1 Research Approach

The objective of this Part is to study how users simplify their solution space when creating innovative solutions. The context for this study is user innovation in creating tangible products, where users innovate using new digital fabrication technologies like 3D printing, electronics, and related software. As this is rather a new phenomenon, explorative qualitative research approach is appropriate for its study. The case study research method is, particularly suited for this study as it can investigate a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not evident. Case study research is preferred to address “How” or “Why” questions that deal with contemporary events where no control of behavioral events is required. Furthermore, it relies on multiple sources of evidence such as documents, archival records, interviews, direct observation, participant observation, and physical artifacts that were available for this study (Yin, 2009).

The overall study in this Part is consists of *two sub-studies* that follow case study research methods to gather data and analyze two aspects of this phenomenon. The first sub-study gives an in depth concurrent look at users early in the design process, while second sub-study gives an in-depth look at the users who have designed established user innovations. The first case study is a single case study on an event users made innovative IoT products, comprising of 40 users divided into groups developing innovative products over a period of around two weeks. It gives a close look at user innovation in this context by direct access to the participants and observing the design process over its duration. The second sub-study consists of six

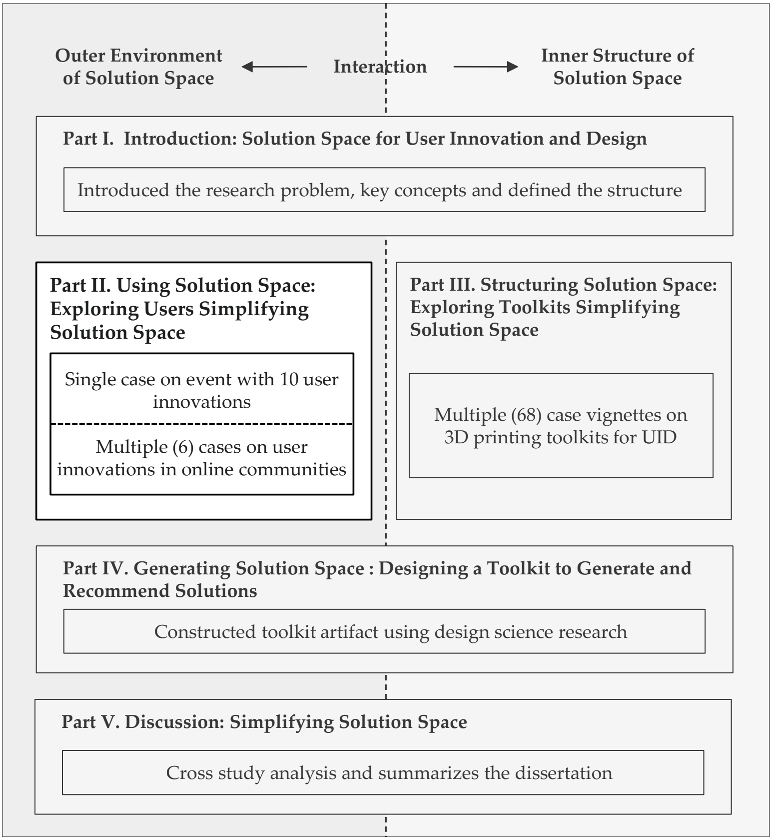


*Figure 6: Part II within the overall dissertation research approach*

multiple cases on user innovations chosen from online open source communities related to 3D Printing. This sub-study gives an in-depth understanding of how users had designed established products over a longer period. Together, the two sub-studies aim to draw accurate and reliable conclusions from data, both from the early stages as well as later stages or after the development process.

The research approach of this study follows the overall research approach and structure of the dissertation. Figure 6 presents the research approach of *Part II* in the overall context of the dissertation. The research design section explains in further detail the selection of cases, case details and data analysis for the study.

## 4.2 Research Design

As described in the previous section, the research question of how users simplify their solution space when creating innovative solutions is answered using two sub-studies that follow the case study research method (Yin, 2009) and are closely related to each other. The first sub-study gave an in depth concurrent look at users early in the design process, over a period of around two weeks. The second sub-study explored users who had already designed established user innovations over a longer period of six to 12 months. The two sub-studies approach the research problem from two consecutive empirical levels. They are placed side-by-side in the overall research design and compared, to look for replications, differences, and extensions to any emerging theory (Yin, 2009). Table 5 summarizes the research designs of the two sub-studies.

In preparation for conducting case study research, I followed the recommendations by Yin on how to prepare case designs (Yin, 2009). Doctoral courses on qualitative research methods and case study research were part of my preparation for this study. To gain a deeper understanding of the empirical context of 3D printing and open hardware electronics, the author's educational background as an electrical engineer and past work experience as a software engineer and an applications developer were supplemented with online courses on the Arduino platform and training sessions on digital fabrication techniques. The next step was the development of a case study protocol that guided the data collection process, based on the recommendations of Yin.

It was followed by screening candidate cases to select cases that yielded the best data and were sufficient in number following a replication design (Yin, 2009).

*Table 5: Summarized research designs of the two sub-studies in Part II*

| Research Design Details | Sub-Study 1 | Sub-Study 2 |
|---|---|---|
| **Research Question** | How do users simplify their solution space to create innovative solutions? | |
| **Unit of Analysis** | Solution space of users<br>Solution space of user team | Solution space of users |
| **Design Type Selection** | Single Case Study | Multiple Case Study |
| **Case Study Protocol** | Developed based on recommendations from Yin (2009) | |
| **Case Sample** | Event with 40 users designing 10 innovative products | Six existing innovations by users in an online community |
| **Theory** | Modularity in organization and design | |
| **Data Sources** | Semi-structured interviews, surveys, direct observations, physical artifacts, presentations and reports | Semi-structured interviews, documentation, release histories, community discussions, websites, and other published material |
| **Data Collection Principles used** | Multiple sources of evidence, case study database, replication, pattern matching | |
| **Data Analysis Techniques** | Coding based on theory and empirical codes within case | Coding based on theory and empirical codes within and cross-case-analysis cases |
| **Analysis Strategy** | Identify characteristics of toolkits and solution space used<br>Identify the process followed by users<br>Draw conclusions | |

In both sub-studies, users work with multiple toolkits and multiple solution spaces each restricted to a specific application area. As this Part addresses simplification of the overall solution space for the user, the two sub-studies emphasize on the following. Firstly, the characteristics of toolkits and solution space used to develop their innovations and secondly, the process followed by users for developing their innovations is studied. The following sections describe the research design followed for each of the two sub-studies in further detail.

### 4.2.1 Research Design for Sub-study 1

The first case study follows a single case design on an event for making innovative IoT products that lasted for around two weeks with 40 participants. The participants divided themselves into teams, which worked together as they developed innovative products using 3D printing, and open source electronics that aimed to solve real world problems. As they were under observation for the duration of the event, it provided valuable data on the process users followed when innovating and designing tangible products. Furthermore, the participants worked together in teams on their innovative products, providing empirical evidence on user innovation done in teams. Hence, the case has two units of analysis. The first unit of analysis is the solution space of each user and the second unit of analysis is the solution space of the team working together.

#### 4.2.1.1 Case Sampling

A single case design on only one such event was chosen as it was a critical case on the upcoming phenomena of maker events or hackathons, which have had limited social science inquiry. The sub-study selected the event IoT Start-up Summer School[10] for the in-depth case as the event program followed the approach user innovators take to build new products. It follows a similar format to other maker events conducted in the past that promoted user innovation in digital fabrication, such as "Think.Make.Start"[11]. The case also met the relevant context of the study as participants used 3D printing and electronics toolkits to build innovative products. Furthermore, this particular event was chosen as a case as it had a high likelihood to yield the best data due to the researcher's access to directly observe the event as one of the organizers (Yin, 2009).

[10] IoT Start-up Summer School was organized by Friedrich Alexander University Erlangen-Nürnberg and UnternehmerTUM in Munich as part of STARTIFY7, a European Union funded project to promote entrepreneurship in ICT technologies.

[11] Think.Make.Start is a recurring prototyping workshop for 14 days where participants can develop and build innovative products with inputs from experts from industry and research. It is conducted by UnternehmerTUM in their high-tech prototyping area called MakerSpace.

The academy targeted young candidates from maker and startup communities, to encourage them to design products around identifiable needs and plan business models around their products. The participants were young adults between the ages 18 and 29, with a gender distribution of 13 females to 27 males. Thirteen of the participants had a business background, 17 with a technology background and ten with a combination of both. The academy selected the participants out of a larger pool of over 200 applicants based on their background in the field of IoT and motivation to develop market ready innovative products in this area.

#### 4.2.1.2 Data Collection and Analysis

Data collection for this study was primarily through multiple sources and guided by the research question and the theoretical perspective of modular organizations, design, operations, and interfaces discussed in the previous chapter. Data collection occurred through five sources. Firstly, the ten teams were each interviewed three times during the period. The average total interview time spent with a team was 101.5 min (all three interviews). The interviews were semi-structured and conducted through open-ended questions to so that the participants could freely articulate their answers[12]. Secondly, the participants individually filled in two surveys during the event[13]. Thirdly, the progress of the products they developed was tracked, and toolkits used in designing their products were recorded. Fourthly, the teams pitched their business ideas along with demonstrations of their working prototypes twice during the event. Fifthly, the teams also submitted a short report on their planned business idea and description of their prototype, which the analysis also uses. All the data was collected in a case database consisting of notes, case study documents, tabular materials, and narratives in line with the case protocol.

These multiple data sources provide in-depth data to explore the issue at hand and lead to the triangulation of data sources that improves the case studies. Furthermore, data points taken from different points of time in these two weeks mean that the entire

[12] The questionnaire for the interviews is in Annex A.

[13] The survey questionnaire is in Annex C.

process of prototyping was tracked with longitudinal observations for the period of the event (Yin, 2009). Data analysis was done by following an explanation building approach by analyzing data and establishing "how" users simplified their solution space and iteratively revising the emerging patterns or propositions. As the event was well documented for the period of two weeks, a time series analysis was also conducted to find any observable empirical trends that seem to replicate among the users and user teams in the case study. The theoretical underpinning of modularity formed the basis for apriori codes for examining the data. However, empirical codes were also generated when available, following the constant comparative method (Glaser, 1965). It gave the possibility of generating new theory (Eisenhardt, 1989), within the limits of the theoretical perspective of modularity theory.

### 4.2.2 Research Design for Sub-study 2

The second sub-study follows a multiple case design on user innovations and consists of six cases. These cases are on innovations by users who used 3D printing technologies with the solution space of the users to design their products as the units of analysis. Using the case study research method on innovative users and the products they designed brings out the user side of user innovation. More importantly, it focuses on the usage of toolkits and other systems over a period, leading to the development of the products. Sub-study 2 follows a multiple case design as it allows cross-case analysis between cases thus integrating different and potentially alternative viewpoints of various users for the phenomena. They also typically build a stronger base for theory building (Yin, 2009).

#### 4.2.2.1 Case Sampling

Selection of an appropriate sample of relevant cases is critical to ensure that the research study is in-depth and can lead to replication of findings or contrary findings. The goal of case sampling here was to select a sample of users with innovations in the field of 3D printing that are substantially significant instances and to find other cases that replicate or extend any emergent theory. Yin recommends the replication design for greater generalizability of findings (Yin, 2009). Guidelines for theoretical sampling from Eisenhardt also emphasize replication, and they helped to reduce selection bias as much as possible while extracting generalizable implications from the findings (Eisenhardt, 1989).

The study was limited to open source user innovations, i.e. products whose designs are open source. Open source products have rich data available in the form of design source, code, documentation, and discussion communities that can be better utilized using a case study approach. To build the sample of open source user innovations connected to 3D printing, popular online maker communities that work with 3D printing were investigated. These were (1) Thingiverse a leading 3D design community for discovering, making, and sharing 3D printable things that also has designs for electronic gadgets and (2) Instructables the maker community.

User innovations in these communities differed between those that had electronic components and those having only mechanical components, so they were treated separately. Two cases were chosen that represent these two groups of user innovations and were significant innovations, i.e., they were innovative solutions that required considerable time and resources to design, aimed at user needs and were better than other similar offerings in the market. They also had a growing influence in their communities, had received inputs from community members, and others often replicated their solutions. The first case of *Robohand* was purely mechanical, but vital as it brought down the cost of developing a customized prosthetic hand, by a factor of a few hundred times to almost only the cost of only the raw materials. The second case of *Koruza* extensively used standard electronics and 3D printed parts once again, to bring down the cost of laser wireless internet device significantly.

These two cases were extended by four supplementary cases to bring in more variety in the different pathways taken by the users in developing their innovations and in exploring replicability of the findings. They were selected following the same sampling process and hence, two of the supplementary cases are purely mechanical while two also include electronic components. Including additional cases reduces bias from individual sources of data and follows the recommendation of Eisenhardt that the optimal case number for building theory is between four and ten cases (Eisenhardt, 1991).

One main case study and two supplementary case studies with electronic components used the Arduino microcontroller and platform (however, Koruza later replaced the Arduino with the Raspberry Pi). The selection is based on a basic exploratory overview study on different hardware based platforms offered to end users. From a variety of modular electronics platforms that allow user innovations along with the Arduino such as *Lego Mindstorms*, *Littlebits*, *Ninja Blocks*, *Raspberry Pi*, *Tessel*, and *Twine*[14] it was seen that users who created innovative products worked with open platforms like Arduino often, where the openness provides design flexibility.

#### 4.2.2.2 Data Collection and Analysis

This multiple case study on user innovations had multiple sources of data such as user innovator interviews, their web pages, published articles on the user innovations, and the innovation artifact itself. The multiple sources of evidence add richness to the cases, enable in-depth analysis and give the possibility of data source triangulation (Yin, 2009). Data on the artifact was collected from the design of the artifact, related documentation, and artifact demonstrations. The design history of the user innovations and associated discussions also allow us to investigate causes and relationships in detail and over a period (Runeson & Höst, 2008).

Although the user innovators were part of online communities, they submitted their creations individually. Therefore, individual users were interviewed. The interviews with the user innovators lasted between 30 to 60 minutes. The case on Robohand includes interviews of the user innovator, Richard and another key member of the community with major contributions. The case on Koruza used interviews conducted in 2013 and 2015 along with communication on updates in between, thus giving a longitudinal dimension to the data collected. The interviews have been carried out with the help of an interview guideline for semi-structured interviews consisting of open questions[15]. This approach was deliberately chosen so that the interviewees could freely express their opinions and full experiences. On receiving explicit consent from

[14] Please have a look at the glossary in Annex E for more information on these terms.

[15] The interview questionnaire can be found in Annex A

the interviewee, the interview was recorded, transcribed, and commented before analysis. Else, key points of the interview were noted down and augmented with other data sources mentioned above. In some of the cases, the user innovators answered open-ended questions over email because they preferred the flexibility to respond to questions asynchronously. Data from the documentation, release histories, community discussions, websites, online videos, and other published material were downloaded and saved in a local database. This data along with the data from the interviews was coded based on apriori concepts from modularity theory and characteristics of toolkits for user innovation described earlier. Emergent codes were also documented to identify important sub-categories or unforeseen concepts (Yin, 2009). Analysis for emergent codes was done following the constant comparative method (Glaser, 1965), where every coded data point was noted and compared against other incidents for similarities and differences and labeled as such and grouped. It established a classification of product characteristics in terms of interfaces and operations allowed as well as how user innovators used solution space to develop their novel products. The classification system was developed based on combined inputs from discussions with two independent researchers. Eventually, the analysis led to a model on how users simplified solution space when designing innovative solutions.

## 4.3 Case details

Following the research design of the two sub-studies in the previous section, the section further describes the details of the cases used in the two sub-studies. The first sub-study explores how users simplify solution space early in the design process, in the event that took place over a period of around two weeks. The second sub-study explored how users who had already designed established user innovations over a longer period of six to 12 months simplified their solution space.

### 4.3.1 Case Details for Sub-study 1

The first sub-study is a single case study on an event themed on Internet of Things, for training and promoting participants to design and develop innovative products based on user needs that can in the future be part of market-ready products or services. The interactive academy provided participants workshop tools, open source electronic hardware and end user 3D printing technologies, which were similar to the tools and technologies used by open source maker communities.

*Program:* The program structure had a strong emphasis on teamwork, hands-on learning, and workshops. The participants spent the first two days of the event familiarizing themselves by attending presentations and interactive workshops with the fields of IoT, design thinking, ideation, user needs, and prototyping. Day 3 onwards the participants formed teams and started prototyping their products. The time spent on prototyping versus attending training sections increased from Day 4 onwards, with more than 85% of the time dedicated to prototyping. The participants also carried their prototyping equipment and work on their products even after working hours. While the participants were mostly independent in how they designed their products and developed their market needs, they received regular feedback from trainers and workshop mentors. Trainers were present for an average of two hours out of which they conducted presentations for 60-90 minutes and used the rest of the time for discussions. At any point of time, 2-4 mentors accompanied the participants and gave them preliminary evaluations of their ideas.

*Team formation:* Interactive workshops on ideation conducted in the first two and a half days with exercises for groups drawn on random. These group exercises allowed the participants to familiarize themselves and have the first set of ideas, which they can further develop. On the third day, they self-organized into teams and start building their products. The participants organized themselves and worked in 10 teams of 3-5 members. They sought to form mixed teams of technical and non-technical participants. Three of the ten teams consisted of all participants with a technical background, while one team comprised of all non-technical participants.

*User Needs:* The participants identified user needs based on their experiences and designed innovative Internet of Things products to solve these needs. They further verified these user needs by evaluating their products with potential users.

*Design Process:* After that, they organized themselves into teams and started brainstorming and evaluating potential ideas as well as prototyping them. The participants worked within their teams, continuously designing and evaluating their prototypes. They also received regular technology tutorials on open source electronics like the Arduino, Raspberry Pi, etc., software related to the field (such as *Thingworx*[16]), and business tutorials such as business modeling and funding. The participants had full control on the tools they chose and design decisions of the prototyping process. Also, they also had the opportunity to get help from experienced mentors during the prototyping sessions. Furthermore, they also had the facility to use a 3D printer and a laser cutter if required. The evaluation of their ideas and prototypes happened at multiple levels. The teams regularly pitched their ideas to potential investors and industry experts, who gave them valuable feedback on what the market required. Furthermore, the teams also interacted heavily with potential customers and industry experts outside the event, by engaging in face-to-face interviews, phone calls and conducting surveys. Hence, they followed a rigorous cycle of design and evaluation during the period to develop an innovative product that has a legitimate market need.

*Innovative Products Created:* Table 6 summarizes Key details about the ten user teams and their innovative products. The teams designed these products for a variety of uses, from add-ons to action cameras to marketing campaigns using drones. The design ideas came from team members who identified these needs for themselves and evaluated these needs by talking to other potential users.

[16] Thingworx offers IoT software platforms.

*Table 6: Products developed by maker teams and their need evaluations*

| Team Name | Artifact | Team Size | Customer Target | Need Evaluations |
|---|---|---|---|---|
| ***SensePro*** | Device that connects to a GoPro action camera for automated controls | 5 | End users connected to outdoor sports | Interviews and two surveys |
| ***Fashionder*** | Fashion app for smartphones that manages user's wardrobe | 3 | End user target group of young women | Interviews with potential users |
| ***Heartbeats*** | Wearable bracelets for communication by transmitting heartbeats | 5 | Jewelry purchasing end users | Interviews with jewelry shops and potential users |
| ***Drone In*** | Drones with projectors and social media for attracting young users | 3 | B2B service to event organizers | Conditional contracts from customers |
| ***Ham*** | Device for controlling and managing power usage of household appliances | 3 | B2B sales to SMEs | Interviewed German home appliances companies |
| ***HTH*** | Sensor based surgical implants that automatically warn users in case of failure | 3 | Selling through hospitals to customers | Contacted clinics and medical equipment manufacturers |
| ***iVend*** | Pluggable networked device to automatically manage and maintain vending machines | 4 | Current vending machine companies | Contacted vending machine companies and users |
| ***Columbus*** | Device to give tourists information on nearby monuments | 5 | Cities and tourism companies | Contacted city tourism offices |
| ***Jams*** | Modular wearable device that can adapt to user needs | 5 | Early tech adopting end user | Interviews with customers |
| ***Elevator 4.0*** | Pluggable networked device to manage and maintain elevators | 4 | Elevator maintainers Building owners | Interviews with elevator maintainers |

### 4.3.2 Case Details for Sub-study 2

The second sub-study was a multiple case study with six cases on user innovations based on 3D printing found in online user communities. Open source communities in 3D design such as Thingiverse, have large collections of open source design files commonly stored in STL format. Each user design project or a "Thing" may consist of multiple designs that are viewable using a browser-based 3D viewer. Instructions, photos, and even videos of the final product often accompany them. A Thing may also contain non-3D printed components. These are often standard products and components available off the shelf and then used in the creation of the thing.

Users often used 3D printing in combination with open-source electronics hardware platforms to add utility to their innovations. The hardware consisted of a low-cost processor or micro-controller that users can easily program and with standard interfaces that connected to a large number of modular sensors and actuators. Users could combine these sensors and actuators with the processor to build innovative electronic prototypes such as home automation devices, simple robots, and even other 3D printers. The six cases are described in the following sections.

#### 4.3.2.1 Case 1: Robohand Prosthetic Hand


*Figure 7: Website screenshot of Robohand the 3D printed prosthetic hand*

Robohand is a low-cost prosthetic hand developed by Richard, an artist, and woodworker from Johannesburg, South Africa with inputs from Ivan Owen, who often created theater props. There have been more than 200 hands developed and offered by him as a service as he moves on to design other innovations beneficial in his regions, such as solar-powered 3D printers, rugged battery backups, and even a Roboleg.

*User Need:* Richard lost fingers on his right hand in an accident and found out that commercial prosthetics were too expensive. He decided to design an alternative.

*Design Process:* Through constant pain that kept him up for days, he used his workshop and maker experience and constructed a prosthetic hand for himself. He soon collaborated with Ivan Owen who had worked on similar designs for building theater props. After a few trial and error cycles, and some exposure to 3D printing technologies, they developed an open source 3D design of Robohand. They first designed it in a workshop environment and then digitized it using general 3D design software and home printers. The first sign that they were reaching the end of their tunnel was when little Liam, a boy with a few missing fingers was fitted with a Robohand and he shouted out "It copies me!"

*Innovative Product Created:* Robohand has an open source design and consists of plastic 3D printed parts, medical Orthoplastic, and inexpensive materials that are available in a typical hardware store. It is a purely mechanical device without any electronics.

#### 4.3.2.2 Case 2: Koruza Wireless Communication System

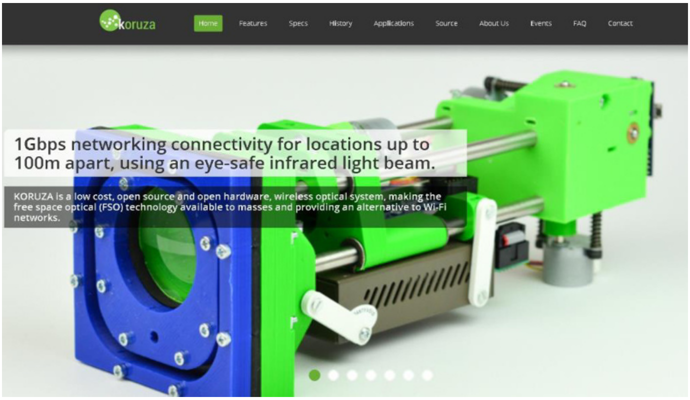


*Figure 8: Website screenshot of Koruza wireless system*

Koruza is an innovative open-source, open-hardware laser-based wireless communication system that can provide speeds of up to 1Gbps wirelessly, significantly faster than the current state of everyday fiber access networks. The capacity is sufficient to offer multi-user peer-to-peer daisy chain wireless connections and is ideal to provide last mile access as well internal area networks.

*User Need:* When Luka Mustafa or Musti for short, an enthusiast of decentralized ad-hoc networks was working on his student thesis, he stumbled upon an idea. He found that transmitting information over laser is significantly cheaper if the range is limited to a hundred meters. It gave him the idea of a point-to-point device that will promote a bottom-up organic network and be an alternative to traditional fiber and Wi-Fi networks.

*Design Process:* Musti used a 3D design tool with no specific solution space, but one that could give him the solution he wanted. The 3D printed parts, other components were refined through many iterations over the last year, and after four generations, it has transitioned from a large indoor system to a robust sleek outdoor system.

*Innovative Product Created:* It uses commoditized electronic components, such as a laser source and detector, lens, Ethernet converter, a microcontroller that formed the basic information interface along with 3D printed parts.

#### 4.3.2.3 Case 3: 3D Printed Smartphone Loudspeaker

The Smartphone Loudspeaker is a completely 3D printed stylized device, purely mechanical, with no electronics. The device fits perfectly with a specified smartphone and acts as both as a smartphone stand as well as amplifying the smartphone speakers.

*User Need:* User needed a stand and a way to amplify the sound of the smartphone to watch and listen to multimedia comfortably.

*Design Process:* User is an experienced designer of CNC designs who migrated to designing for 3D printers. A MakerBot Replicator 2 printed out iterations of the design.


*Figure 9: Screenshot of the 3D printed Smartphone Loudspeaker*

*Artifact Created:* In this case, the product is an add-on by itself to the smartphone and hence has to have the necessary physical interface to integrate with the smartphone despite there being no interface from the smartphone side.

#### 4.3.2.4 Case 4: Wii Wheel Gaming Add-on


*Figure 10: Screenshot of user published picture of the Wii Wheel*

The Wii wheel is 3D printed with no electronics is also an add-on to the popular Wii motion-control gaming console from Nintendo for the special of playing racing video games.

*User Need:* User needed a racing wheel to play the game Mario Kart 8

*Design Process:* Simplify 3D made the design and a Felix 3.0 dual printer it out after a few iterations

*Artifact Created:* It looks and feels like a steering wheel but has a slot that exactly fits a Wii. Once again, the user innovator had to design a physical interface to this product so that it can add on to the Wii. The Wii, on the other hand, is quite sleek and does not have any physical features that promote extensions.

#### 4.3.2.5 Case 5: Canedolly Time Lapse Camera Add-on

The Canedolly is an add-on to a digital camera; users can configure it to move the camera slowly along a guideway over a period so that it can record time-lapse videos.

*User Need:* for a specific user need of taking stylized time-lapse videos with smooth camera movements.

*Design Process:* An FDM printer built the plastic parts of the Canedolly. The metal rail was crafted using a metal saw and handiwork tools. Electronics were soldered in, and Arduino libraries were used to program the micro-controller.

*Artifact Created:* The Canedolly is a device that can be mounted on an uneven terrain and has a metal strip that acts as a track where the camera can be installed and an automated mechanism to guide the camera along the track over an extended period. It consists of standard parts from a hardware store such as screws, bolts, pulleys, belts tracks, and electronic hardware components such as motors, heat sinks, and Arduino microcontrollers. The Arduino and motor system are connected to the internal mechanisms of the camera to access its controls.

*Figure 11: Screenshot of Canedolly for moving time-lapse pictures*

#### 4.3.2.6 Case 6: 4Track Robotic Vehicle

Thingiverse and Instructables have many user designs on remote controlled land and air based vehicles. The 4Track is one such user innovation that emphasizes having tracks and controllable claws.

*User Need:* To build low-cost robotics for hobby enthusiasts

*Design Process:* The user started out with making mechanical parts for a robot that moved with tracks. After five iterations and ten months of work, it resulted in an Arduino based robot with mechanical claws.

*Artifact Created:* Just like the exemplary Rover, in this case, the mechanical components are a combination of 3D printed parts such as the cylindrical wheels and the mechanical claw, along with standard screws and cables. The motors and sensors controlled by an Arduino microcontroller give it functionality. The Arduino platform and 3D design software were used to develop this product.

*Figure 12: Screenshot of 4Track robot with claw*

Having presented the case details for both studies, the next chapter presents the findings for the two sub-studies and findings from the cross-study analysis.

# 5 Findings

After conducting the two sub-studies that form this part, this chapter presents the major findings from the analyzed case data. The chapter consists of two sections. The first section presents the findings from the first sub-study, which is a single case study on a maker event themed around Internet of Things. This section focuses on collaboration activities observed during the event and design of their products. The second section presents findings from the second sub-study on multiple cases of user innovations in open source maker communities. The next chapter discusses these findings.

## 5.1 Findings from Sub-study 1

The first sub-study explored how users simplified their solution spaces when creating innovative solutions in the context of the early stages of building tangible products. It is a single case study on a two-week event to make innovative products using 3D printing and electronics. The goal of its participants was to collaboratively develop new ideas based on user needs, and develop them into functional prototypes while constantly evaluating prototype to meet user needs. As the period of the event was short but intensive, design processes that may have taken months occurred within the short time frame of the event.

The participants at first went through many ideation rounds and lightweight prototyping sessions to understand and to get familiar with the design thinking. They then identified user needs and further evaluated these needs by their interaction with potential users and industry experts. A participant summed up the experience as:

> *"I loved the design thinking talk as I found it detailed and really interesting, it gave me more to think about… I also really enjoyed the group task we did for building a quick prototype as it taught to think fast and try to be creative."* (EP1)

### 5.1.1 Modular Organization

The participants benefited from interacting in teams with mixed backgrounds that shared the large solution space available to them. They benefitted through guidance and resources they could find online as well as at the event. Talking to the mentors at the Academy and looking at their sample products helped the participants and gave the newcomers confidence and knowledge to use various tools and their solution spaces. One of the participants sums the feeling up with the following:

> *"When we started to prototype, we had big problems. However, with the help of my team, we got to a stage where together we are solving our problems and helping each other. We inspired each other to be better, to be motivated, and work effectively."* (EP2)

Working at the same location also allowed distribution of ideas and new solutions. The participants could regularly benchmark their teams against the other teams. It helped them gain solution information on intermediate designs as they heard each other pitch their ideas and demonstrated their prototypes every two or three days.

Working with technology that was open source was essential for the rapid prototyping and artifact development seen among the teams. It was quite evident that the ease of finding and reusing solutions in the form of learning resources and already developed software libraries online made development times very short. Initially, the participants chose a hardware toolkit whose solution space was familiar and an established online community supported:

> *"(…) my experience and technical skills, the teammates and of course forums and communities (…) Also, during my study I got a lot of information from googling and looking into forums … for us they were flexible enough for (prototyping innovatively). The tools we had (sensors, interfaces, Arduinos) were easy and fast connectable and interfacable. Especially it is helpful that many libraries are downloadable for all the different sensors."* (EP3)

### 5.1.2 Modular Product Design

The products developed by the participants after the ideation phase were either working prototypes that showed technical capability or partially working replica devices that simulated the real product and demonstrated a new idea to get valuable user feedback. As the theme of the academy was IoT, the products contained electronic components. The participants built these products by combining different electronic sensors, actuators, and microcontrollers that could connect to the internet. The participants connected various modules of the platform as well other external products and the microcontroller acted as the informational interface between them. Using this modular electronics toolkit meant that design work was mostly substituting and augmenting modules in the system. Participants simplified their solution space by relying on existing hardware modules and creating new software programs and informational interfaces between them.

Modular toolkits with relatively smaller solution spaces like the Arduino platform were a popular choice as it was a modular toolkit for users. The participants could mix and match different modules and then quickly program the logic connecting them to get the necessary functionality. The reasoning behind their choice in the words of the participants is as follows:

*"We had access to a wide range of tools made the prototyping easier and flexible"* and *"the simplicity to use and configure the hardware device was also a parameter in order to take a decision on the choice of hardware."* (EP4)

The most basic Arduino board has an easily programmable microcontroller with input and output pins that easily connect to other electronic modules using wires and a breadboard. It was an ideal starting point for the development of many of the products. Once the electronics of the artifact were connected and functioning, the participants soldered them into place to make them more stable. The also assembled 3D printed or laser cut enclosures to house the electronics. After developing a first functioning prototype, teams either worked on optimizing the design by using smaller and more efficient and special purpose boards or added additional functionalities to make their prototype better suited for the market need. An overview of the ten teams and their products is in Table 7.

*Table 7: Products, their design, and their components*

| Team Name | State of Product | Artifact Components | Tools Used |
|---|---|---|---|
| ***SensePro*** | Working Prototype with basic user evaluation | Interface to GoPro, gesture detection modules, Arduino, 3D printed box, custom software | Arduino based IDE, electronics, Tinkercad |
| ***Fashionder*** | Working Prototype with basic user evaluation | Smartphone with camera, barcode scanner module, mobile app | Barcode scanning libraries<br>PHP |
| ***Heartbeats*** | Demonstration of Idea with functional components | Arduino mini, vibrator module, heart rate sensor, Bluetooth modules,<br>3D printed bracelets | Tinkercad<br>Arduino modules |
| ***Drone In*** | Demonstration of Idea without functional components | Drone, projector | Drone assembler kit |
| ***Ham*** | Working Prototype with basic user evaluation | PCB with microcontroller, Wi-Fi, power electronics, cloud-based app for smartphones | Advanced electronics<br>PCB modeling software |
| ***HTH*** | Demonstration of Idea without functional components | 3D printed bone (to demonstrate implant's location), Ultrasonic sensors (to demonstrate principle) | 3D design downloaded<br>Arduino modules<br>Ultrasonic Sensor |
| ***iVend*** | Demonstration of Idea with functional components | 3D printed case, breadboard, and Arduino, infra-red sensor, display | Tinkercad<br>Arduino modules |
| ***Columbus*** | Demonstration of Idea with functional components | Mobile App, Bluetooth low energy beacons, Arduino | Arduino IDE |
| ***Jams*** | Working Prototype with basic user evaluation | 3D printed clip-on cases, Arduino mini based modules for each Jam, innovative bus system for connecting modules | Arduino, soldering tools, electronics, Tinkercad |
| ***Elevator 4.0*** | Working Prototype with basic user evaluation | Arduino, Distance sensors, laser cut box for casing, display, Wi-Fi | Arduino IDE<br>adobe Photoshop, laser cutter |

## 5.2 Findings from Sub-study 2

The findings of the second sub-study on user innovations based on 3D printing found in online user communities are presented here. In these cases of user innovations in open source communities, users had gained knowledge through either formal studies or their hobbies and work experiences, but they were not particularly trained in this area. Although the products they developed may have been commercially available, they often were too expensive or constraining. As one of the interviewees expressed:

> *"I designed them a few years ago when I was in university (studying electronics and robotics). I wanted to program robots and develop path-planning algorithms, but commercial, educational robots for universities are extremely expensive and hard to come by. Designing my own printable robots allowed me to make custom parts and reduce the cost!"* (UI1)

The users also had very specific needs that existing products did not satisfactorily meet. They were unsatisfied with the existing products in the market and sought to create their own. As a user innovator mentions:

> *"And I started investigating things online, and all the different prosthetics that are available, and none of them are trade friendly, and none of them are functional as in returning functionality to your hand as a tradesman."* (UI3)

### 5.2.1 Modular Organization

The user innovators from the hardware open source communities studied began by working on their innovative ideas independently and shared their designs in online platforms like Thingiverse and Instructables. The user innovation cases sampled in the study are of designs that went farthest and emerged as dominant designs. However, users also received some assistance in this process. Other users contributed, by sharing the design process and hence simplifying solution space by commenting on each other's projects and suggesting ideas. On a much smaller scale, they made derivatives of the designs by forking out published designs and made their own versions of them or specialized on different parts.

Collaboration to simplify solution space was, however, not restricted to the user community platforms as in the case of Robohand. After Richard the founder had first built a few prototypes at his workshop, he then contacted Ivan over email after watching a video of him on the social media site YouTube, showing a large mechanical hand that he used as a movie prop. Ivan, in turn, got the idea of using a consumer 3D printer to lower the cost of designing the components from a colleague.

As others began to perceive that the user innovations captured needs of society, the innovations caught their interest and they slowly became part of the community and contributed by communicating to the user in discussions. Discussions were in the form of comments on the platforms as well as websites and blogs of the user innovators. For example, Ivan Oven who built mechanical hands as theater and cinema props also contributed to Robohand. Users credited the open source development approach to the success of some of their projects. Ivan says that it enabled collaboration between a diverse set of individuals:

> *"As a tool for open source development; this makes it possible for people from a wide range of experiences and backgrounds to collaborate with one another. You can have everyone in the mix from people who have their PhDs in material science to people who are tinkering in the garage."* (UI3)

#### 5.2.1.1 Community Funding

An interesting finding that emerged was that crowdfunding played a major part in the case of Koruza and Robohand. Luka Mustafa from Koruza used a successful crowd funding campaign to present his design at the American Conference on Information Systems (AMCIS) where he received valuable feedback for his design and attracted potential collaborators. He later won a fellowship that allowed active development with a dedicated team. Robohand also started a crowdfunding campaign to purchase some basic tools that helped them get started. They also received further aid from the 3D printing firm Makerbot:

> *"I decided to give it a try and send Makerbot an email. I let them know what we were up to and asked them if they were able to help in any way or even provide us with a machine or two to use. I saw this as a long shot. We have no background in this field, we have no*

*credentials, and will you please send us two of your very high tech machines for free. Much to our surprise and delight, they responded extremely positively. They were supportive and encouraging of what we were trying to accomplish and even provided us with two of their printers to attempt to develop the design."* (UI3)

#### 5.2.1.2 Sharing user innovations

The user innovators publish their innovations in these platforms after they have developed working prototypes rather than share work in progress designs. Publishing the designs on the online platforms often happened at a much later stage when there was a working prototype ready. Users publish their user innovations in the form of editable 3D design files, in an open format such as STL, a list of standard hardware and electronic parts, downloadable software and a manual consisting of steps needed to reproduce the innovation.

#### 5.2.1.3 Modularity-in-production with 3D Printing

Using 3D printing technologies to cut costs in designing custom components was the initial motivation of the users. However, as they started using this technology, additional benefits became clear. Users could print out multiple copies that were exact physical representations of a 3D design. It encouraged users to collaborate when jointly working on a product. Ivan aptly put across this point in the case of Robohand:

*"We were able to print out the same component, get on video chat and when holding the same object, even though we were so far apart, look at it, explore, brainstorm and make those changes, email each other the files, and then reprint and start the process over again."* (UI3)

*"It was an incredible boost to the speed of the design process, much along the lines of stepping out of a horse drawn carriage and immediately hopping into a formula one racer."* (UI3)

The technology reduced time for trial and error cycles of visualizing a new design and printing it. The reduced trial and error cycles enabled users to make many iterations in design, in some cases vastly go further than the initial plan of the design, and achieve much more. A large number of design versions and variations and the following statement from Jon of 4Track emphasize this point:

> *"I started out by making a very simple tracked robot (Caterpillar) and later combined four of these to make a much larger and complex robot (4Track). The whole process took several months (10 months) and many changes, so the end result was very different to what I had imagined in the beginning."* (UI4)

The users worked on commercial 3D printers for home use such as the printers from Makerbot that were relatively inexpensive when compared to professional 3D printers and printed in different types of plastic. OpenSCAD was a favorite design tool as it was easy to build 3D designs based on geometrical shapes for functional purposes. Therefore, users chose toolkits with a sufficiently broad solution space to design functional shapes. There was an emphasis on a 3D printer that had excellent print quality, high reliability and safety, which was plug & play and easy to use. In the case of Koruza and Robohand when the commercial printer needed further feature improvements, they either modified the printer or made printers themselves. Richard, for example, has also developed a 3D printer called Robobeast. It has a design optimized for rugged conditions with features like a backup battery and solar panels that are suitable for outdoor printing.

### 5.2.2 Modular Product Design

The innovative products consisted of 3D printed parts, off-the-shelf products that users can purchase in a hardware store, and as in the case of electronic products, low-cost electronic components such as sensors, actuators, and microcontrollers. They used standard hardware components whenever 3D printed parts did not meet physical and functional requirements of the artifact. They used the solution space of 3D printing to create 3D printed parts that physically connected other parts for e.g. casing for electronics. The solution space of low-cost microcontrollers like Arduino enabled processing of information and interfacing between other electronic components. Table 8 presents the components used in all the six products. The words of one of the interviewees summarized the use of solution space by users very well:

*"The 3D printed parts are often designed around the standard parts, and the low-cost modular electronics platforms such as Arduino were like the **glue** that connected the other parts".* (UI2)

*Table 8: Products designed and their components*

| Case | 3D printed Parts | Standard Parts | Electronics |
|---|---|---|---|
| **Robohand** | Finger and palm area of prosthetic hand with screw holes | Screws, Orthoplastic material in contact with skin, nylon cables | -None- |
| **Koruza** | Frames, stands, casings | Screws, waterproof casings | Micro-controller, laser transmitter, and receiver, Ethernet card |
| **Smart Phone Speaker** | 3D printed speaker with socket | -None- | -None- |
| **Wii wheel** | 3D printed wheel with socket | -None- | -None- |
| **4Track** | Wheels, body, casings, mechanical arm | Screws, rubber bands | Micro-controller, sensors, and motors |
| **Cane Dolly** | Adjustable legs, casing, stand for camera | Screws, metal rail | Micro-controller, motor, and wiring |

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## 5.3 Cross Findings from Sub-studies

### 5.3.1 Stages of User Innovation

The two sub-studies provide valuable insights on the process followed by user innovators making innovative products. The users in the first sub-study on the maker event followed the early stages of this process and outlined a plan for the future. The users in the second sub-study developed their products over a period of 6-12 months. The stages identified in both the sub-studies were consolidated and modeled into a 4-step process that users followed. Figure 13 presents the process model.

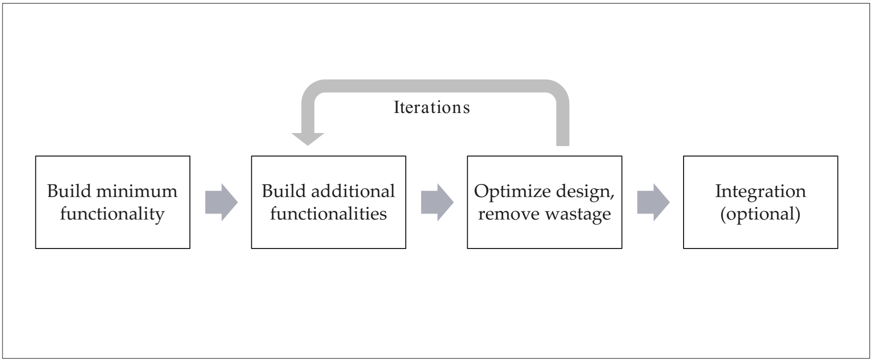


*Figure 13: Stages of the user innovation process for tangible products*

**The first step** was to build an artifact that implemented the core functionality they had identified, which could act as a solution to the needs identified. Their solution information was initially restricted to their educational or professional backgrounds that were often specialized to one discipline and some basic design experiences. Because of this restriction, users often started designing with toolkits that had enough solution space to implement a first working prototype. For mechanical parts, this could be in the form of crude 3D prints or parts that were fashioned in a workshop. These parts needed to have the necessary shape to make the first prototype work. Electronic parts often were prototyping electronics like Arduino modules, plugged to breadboards and connected to each other with jumper wires. This limitation was also in software, with just the basic implementation of necessary functions. When the available solution space was not enough, users reduced their scope of their needs or simply altered them to match what they could design.

Once they created the first working prototype, **the second step** was to include other functionalities into the artifact they needed before the artifact could be operational in a real or simulated environment. Such functionalities may include: the stable connection between various components, casings for electronics, using materials the right strength, etc. Parts from hardware stores may have superior physical properties (strength, weight, shape, etc.) to 3D printed plastic parts, which make them necessary to operationalize the prototype. Robohand, for example, used Orthoplastic material at the points where the prosthetic hand was in contact with skin to let the skin breathe. It used standard metal screws and bolts in these designs, as they were much more stable and reliable than plastic parts. Suggestions for new materials, designs, and components can come from the user community and network.

As the artifact incorporates more functionalities, it gets bulky, and it requires optimization. Users then try to optimize the design in **the third step** by reducing wastage. They decrease the number of parts by integrating some of the modules and streamlining 3D designs with reduced material to make the artifact more efficient. Along with efficiency, they also try to make the artifact more aesthetic. While the user innovators may not always be directly designing to appeal to others, they have a strong sense of how their designs should appear and appreciate positive feedback from others. Over time as the user innovator increases solution information, starts using more advanced toolkits and may reduce reliance on standard parts.

Most of the cases of user innovators iterate between steps two and three as they keep improving their products by either adding newer functionalities or optimizing their design. In the case of Koruza, after three years of developing the artifact, it was preparing to go into production as **the fourth step**. It marked a departure from the earlier design approach where the artifact consisted of modular parts that users could easily purchase or 3D print. Koruza plans to branch their design to have two parallel design versions. One design is for production, and the other will continue as a modular design for makers to develop further. The production version will further integrate the design to lower costs and make it available in the market.

### 5.3.2 Dynamic Interfaces to Simplify Solution Space

As mentioned earlier, many user innovations did not restrict themselves to one solution space for their creations but rather often used multiple solution spaces that best fit their needs. Users used multiple toolkits from different fields that included machining tools, 3D printing tools, as well as modular electronic systems.

User innovated products ranged from modifications to new products built out of existing off-the-shelf items. Some of these were components, while others were standalone products, not designed to be connected to other products. In these cases, the products did not have necessary interfaces to treat them as components and connect them to other products. User innovators instead built their *dynamic interfaces* to connect these products. In some cases, user innovators insisted on developing everything from scratch. However, as the products grew more complex, they were often designed as add-ons to existing products than new products from scratch.

They used toolkits that gave them sufficiently large solution space to create interfaces dynamically. These dynamic interfaces could either be hard interfaces, mechanical in nature or soft interfaces that were informational in nature. 3D printing toolkits allowed users to build hard interfaces between products, such as slots, gears, clips, tracks, etc. Low-cost computing in the form of microcontrollers created programmable soft interfaces for information transfer different electronic components. Thus, these dynamic interfaces may be electronic in nature by connecting different input-output pins, transferring and translating information, or mechanical in nature by having matching right shapes and connections that users could dynamically design using additive manufacturing or 3D printing technology.

Both these types of dynamic interfaces reflect the digitization of hardware, where mechanical components are software design files and software applications in an embedded system. While these methods would traditionally be expensive or inaccessible, the reducing cost of both 3D printing and computing allows user innovators to use a computer or a 3D printed part as links between systems rather than the central system itself.

# 6 Discussion

This chapter discusses the findings from both the sub-studies and the cross-study analysis in the previous chapter. The first sub-study is a single case study on a maker event on Internet of Things, where participants with multiple toolkits and associated solution spaces designed innovative solutions based on their estimated needs over a period of around two weeks. The second sub-study consisted of multiple cases on user innovations in open source maker communities and described how users developed their innovative solutions from the various solution spaces to design they have access to, in the form of open hardware electronics, 3D printing, etc. The second sub-study complemented the findings of the first. Together, they provided the advantage of observing the development process up close and identifying mechanisms for simplifying solution space in both nascent as well as established user innovations. The section below discusses the overall findings from both the sub-studies.

## 6.1 Solution Space for User Innovation

The empirical context of the two sub-studies on user innovators involved in 'making' differs from previous work on user innovators organized in communities. User innovation communities have been discussed around large open source projects such as in Linux operating system or Apache software (Harhoff et al., 2003; Lakhani & Von Hippel, 2003) or in open hardware (Balka et al., 2009; Raasch et al., 2009) mentioned in Chapter 2. Instead, the users in these two sub-studies were part of smaller projects (one to five members), some of which attracted external contributions only after a duration of around six months. These users can be considered lead users who went beyond describing problems, stating needs or even suggesting solutions to organizing among each other and developing the solutions (Mahr & Lievens, 2012).

The two sub-studies applied theory on modular organizations to the separation of design process between firms and users and between users' themselves (Schilling, 2000). Modularity in product design was a core component in the user innovations, and it allowed decentralization of the design process and its management (Sanchez & Mahoney, 1996).

In the studied cases, users shared the design workload through various forms of modularity-in-design, by working with other users or reusing existing products with embedded design. Existing products with embedded design are dynamically integrated with each other by a combination of splitting, augmentation and linking operators (Baldwin & Clark, 2001). Dynamic interfaces in this study are developed in the decentralized and ad-hoc approach which make them different from the concept of 'systems integrators' (Brusoni & Prencipe, 2001). The creation of interfaces "on-demand" to integrate different modular system hence is a new outcome of these technologies.

## 6.2 Conclusion

Part II of the thesis has studied user-innovators in online maker communities and in an offline maker event to understand how users simplify solution space when creating innovative products. It describes two sub-studies and presents their findings. The findings show that user innovators varied in their approaches to developing solution information based on their knowledge and availability of tools and technologies. However, these approaches changed with time as they developed their expertise and further clarified their need information. Non-expert users can learn from this behavior and start with toolkits that offer the minimum necessary solution space to build their first prototypes, while gradually expanding to more advanced toolkits. The advanced toolkits give them the solution space needed to develop specific solutions for their specific needs.

The user innovations in the two sub-studies were often add-ons to larger products or novel combinations of existing products. It was another approach of using embedded design knowledge to simplify users' solution space to design. It was possible by building their dynamic interfaces that adapted to existing products, which were either, or both: 3D printed hard interfaces or soft interfaces programmed on embedded systems.

Springer
http://www.springer.com/978-3-658-18282-3

Simplifying Solution Space
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Toolkits
Naik, H.S.
2017, XX, 207 p. 35 illus., Softcover
ISBN: 978-3-658-18282-3