R&D MANAGEMENT

Modularity in making: simplifying solution space for user innovation

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An increasingly popular form of open innovation in the digital age is 'making,' where users innovate across multiple disciplines and make products that meet their needs, using mechanical, electronic, and digital components. These users have at their disposal, a wide solution space for innovation through various modular toolkits enabled by digital-age technologies. This study explores and outlines how these users simplify this wide solution space to innovate and make tangible products. Following a modularity theory perspective, it draws on case studies of users and their innovations: (1) Users with initial prototype product designs based on the Internet of things (IoT) from a maker event and (2) users with established product designs from the online community platform Thingiverse. The studies found that users reused the design in the form of existing off-the-shelf products and utilized digital fabrication and low-cost electronics hardware as a 'glue' to create physical and informational interfaces wherever needed, enabling bottom-up modularity. They iteratively refined their innovations, gradually replacing re-used designs with own integrated designs, reducing modularity, and reducing wastage. The study contributes to open innovation and modularity with implications on the design of products and toolkits enabled by the digital age.

1. Introduction

The digital age has brought capabilities to distribute and share knowledge with the World Wide Web (Chesbrough and Bogers, 2014) and extended them to production. Digital fabrication technologies like 3D printing and design platforms have encouraged open development of tangible products, where users can share their designs or contribute to existing designs. It has taken the form of open design projects with large established online communities (Balka et al., 2014), as well as online open design platforms, for making tangible products (Honey and Kanter, 2013), which have been relatively unexplored. Users in these open design platforms collaborate digitally on various small hardware projects, often unconnected to each other. They innovate with a variety of modular toolkits, which expand the solution space for design and innovation (von Hippel and Katz, 2002). In particular, designing with 3D printing toolkits gives users a wide solution space despite minor limitations in shapes (Snyder, 2014) and materials (Sitthi-Amorn et al., 2015). The solution space for users to innovate further increases, when they combine 3D printing with electronic toolkits (Cvijikj and Michahelles, 2011).

Innovation toolkits by their modular design (von Hippel and Katz, 2002) and mechanisms to share and generate designs (Naik and Fritzsche, 2017; Naik et al., 2016) reduce complexity during innovation and design for users. However, users making tangible products uncover the unanswered research question of how users simplify the *combined solution space* from various toolkits available to them to innovate and design. We explore cases where users design innovative, tangible products from the perspective of connectivity and collaboration that modularity brings into the design process and the product design (Sanchez and Mahoney, 1996). Related principles of modularity-in-design and modularity-in-production (Baldwin and Clark, 2006) are also applied. While the impact of modularity on new product development in an organization has often been studied, this paper investigates modularity in the interactions between users. In the context of making tangible products, users make choices regarding modularity by separation, bundling, and coordination of effort to cope with the complexity at hand. Users reduce design decision making and thereby simplify their solution space, through patterns of modularity while they are innovating. Our study aims to gain a better understanding of these patterns, which can be expected to play a highly significant role in user innovation but have so far hardly received attention. The research follows a case study research design (Yin, 2009) and consists of two sub-studies. The first sub-study gives an in-depth look at users beginning the design process with initial designs, while the second sub-study gives an in-depth look at the users with established designs. Together, the two sub-studies aim to draw accurate and reliable conclusions from both the early as well as later stages of users innovating new tangible products.

The findings are valuable additions to understanding the nature of collaboration among users in open design platforms. They identify key factors that enable collaborative innovation between these users and the underlying digital fabrication ecosystem. In these cases, users shared knowledge in the form of design and innovation workload through various forms of modularity-in-design, by working with other users or reusing design from existing products. Furthermore, the study shows that such collaboration is possible because these digital technologies allow embedding of existing products by dynamically integrating them using a combination of modularity operators (Baldwin and Clark, 2000), in a ‘bottom-up’ manner to form new product combinations. The bottom-up approach contrasts with a ‘top-down’ approach of modularizing a complex system. Users develop modular interfaces and combine parts to develop a new system, instead of starting with a system and then defining its components. The insights from the paper can further inform the architecture of design toolkits, which support user innovation regarding the patterns of modularity they offer.

2. Theoretical background

2.1. *Users innovation and making*

Research has long established that users are a valuable source of ideas and defined methods to develop these ideas (von Hippel, 1978). Users often attempt to meet their unfulfilled needs by designing and developing new products and processes and thus provide new concepts and design ideas. They have influenced the development of information systems (Morrison et al., 2000) and security software (Franke and Von Hippel, 2003). They have also designed innovative printed circuit boards (Urban and von Hippel, 1988), construction products and materials (Herstatt and von Hippel, 1992), and developed innovative services in banking (von Hippel and Riggs, 1996; Oliveira and von Hippel, 2011).

User innovation in communities often occurs in products used by hobbyists and enthusiasts (von Hippel, 2005). Users in these communities freely reveal their innovations, so they benefit as a whole without having to independently innovate by themselves (Harhoff et al., 2003). The open-source software movement is an illustrative application case for free revealing in user innovation communities (Harhoff et al., 2003; Lakhani and Von Hippel, 2003). Open source communities are not limited to software, they have spawned around open source projects in hardware as well (Balka et al., 2009; Raasch et al., 2009) with advancing digital technologies.

Users benefit from the availability of modular toolkits (often digital) that enable them to innovate and design through a learning-by-doing process (von Hippel, 2001; von Hippel and Katz, 2002). Toolkits give users the ability to design, which otherwise would only reside in a manufacturing firm. They reduce the interaction and information cost that can arise between the manufacturer and user as users configure solutions or develop new solutions, which meet their specific needs (von Hippel, 2001; von Hippel and Katz, 2002). Well-designed toolkits offer users a *solution space* that does not exceed the manufacturer's production capabilities, and they are user-friendly so that users can learn without additional training (von Hippel and Katz, 2002). Users often develop modules with toolkits which, if proven to be popular and error-free, are later incorporated into standard versions of the products (Franke and Schreier, 2002; Prügl and Schreier, 2006). Furthermore, user communities often accompany toolkits and provide users assistance in problem-solving and diffusion of toolkit related information (Jeppesen, 2005; Prügl and Schreier, 2006).

In the field of making tangible products, which is the focus of this study, users make products with mechanical parts (e.g., 3D printing) or products with electronics (e.g., a microcontroller with sensors). A consumer 3D printer accompanied by 3D design software provides users with feedback that allows them to design with a learning-by-doing process. An increasing number of online 3D printing services and marketplaces supplement consumer printers, so users can print in a diverse set of materials that include metal and ceramic (Anderson and Sherman, 2007; Snyder, 2014). Users have extensively been developing and sharing 3D designs in online user communities over the past years. 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 nature (Kyriakou et al., 2012; West and Kuk, 2014). In the offline world, the idea of a dedicated location to make tangible products, a 'maker space,' has taken hold, where users can get together, learn and develop through complex design and 'making' practices (Sheridan et al., 2014). Along with being dedicated locations, makerspaces contain equipment for rapid prototyping and digital fabrication (Briscoe and Mulligan, 2014; Landwehr Sydow and Jonsson, 2015).

The manifold of possibilities to design in 3D printing creates a very large and diverse solution space for innovation. Solution space for users to design can be defined as the set of available 'design questions' and corresponding 'design options.' Users innovate by going through a series of design decisions, where they choose options for a design question. Reducing the design questions and options they have to answer, reduces complexity for innovating, and thus simplifies the large solution space. (MacLean et al., 1991; Naik et al., 2016).

Moreover, users often face the phenomenon of mass-confusion (Teresko, 1994; Huffman and Kahn, 1998; Piller et al., 2005). It keeps them from finding optimal solutions, because of the overwhelming number of design options that are given to them (see also Matzler et al., 2007). Online platforms offer specialized design toolkits, recommender systems, and communication channels to support users in their activities (Piller et al., 2004; Burke, 2007; Trentin et al., 2013). With technologies like 3D printing, a user's available solution space continues to increase. While behavioral studies have already looked quite extensively into fast and frugal strategies of problem-solving (Kahneman and Tversky, 1984; Gigerenzer and Selten, 2001), fairly little has been said about comparable activities in the context of user innovation in making, where creativity and exploration of new design possibilities play a larger role.

2.2. Modularity

To study how users simplify their solution space for innovation, the theory of modularity is a fitting perspective as it addresses how: (1) to simplify by making complexity manageable, (2) to enable parallel work, and (3) to accommodate future uncertainty (Baldwin and Clark, 2006). Modular systems have distinctive system architectures with a high degree of loose coupling between components in the form of standardized interfaces. Components with standardized interfaces make them almost independent, such that a change in the design of one component has little effect on the design of other components (Sanchez and Mahoney, 1996).

While organizations typically design products, modular product designs can inversely lead to products that design organizations, transforming rigid, centralized organizational structures to flexible, decentralized ones, as a modular product architecture leads to modularization in the development processes (Sanchez and Mahoney, 1996). Product modularity also leads to manufacturing agility and firm growth performance (Jacobs et al., 2011). Standardized component interfaces in modular product architecture enable breaking down the development activities of these components and carrying them out separately, using embedded coordination of development activities. Modularity-in-production occurs when the design process is centralized, but different production sites manufacture the components that are later assembled. In the particular case where the process of design itself is split up across separate modules that are developed separately and connected through interfaces, it results in modularity-in-design (Baldwin and Clark, 2006).

Organizational modularity allows firms to specialize in the competencies they need to perform their development processes. As users and firms often innovate with each other, this perspective explains processes implemented through decentralized coordination between users (also seen in user innovation communities) and firms. Heterogeneity of user needs, an essential aspect of user innovation, is a driver of modularity (Schilling, 2000). User designed products display modularity-in-design as both firms and users design separate modules of the product. The toolkit solution space specifies the design rules that coordinate the development of these modules, without the need for ongoing consultations between the firm and users.

Modularity has been shown to have a positive effect on the launch speed of new products through the mediating effects of product platforms and manufacturing flexibility (Lau Antonio et al., 2007; Vickery et al., 2015). It can improve product performance mediated through supplier involvement (Danese and Filippini, 2013). However, extreme modularity can reduce product innovativeness (Lau et al., 2011) and the positive effect of product modularity on new product introduction performance is reduced with high complexity (Vickery et al., 2016). Modularity along with organizational flatness and coordination can also improve mass customization capability development (Zhang et al., 2014) and benefit organizations through internal quality integration which brings about both supplier and customer quality integration (Zhang et al., 2019).

Modular systems can be decomposed into modules that interconnect using interfaces, through which they interact with each other and exchange resources or data (Sahaym et al., 2007). Modular interfaces can be of two types. First, they can be three-dimensional, such as physical interfaces between two mechanical objects. Second, they can be one or two-dimensional, as seen in computer systems where these interfaces could be informational or used to transmit electrical power (Whitney, 2003). Both types of interfaces can be seen in open-source hardware platforms using modular electronics like the Arduino along with open source 3D designs, which poised to impact specialized equipment manufacturing (Pearce, 2012). However, interfaces are designed within a system (such as a product or an organization) with a modular design. With the advent of user communities and digital fabrication, the organizational and product boundaries have become permeable, thus calling for further development on theory on how systems interface with external systems.

3. Research design

Case study research is a suitable method to explore nascent theory on a current phenomenon within its real-life context, with vague boundaries between the observed phenomenon and its context (Yin, 2009). For a thorough investigation of the above-mentioned propositions derived from theory, we conducted two sub-studies in 2015 and 2016 that Table 1 summarizes. The first sub-study aims for an in-depth concurrent look at users at the beginning of the design process. The second sub-study focusses instead on user activities with established innovations. The two sub-studies together give an in-depth and balanced look at the innovation process followed at both the early and later stages. The following sub-sections explain in further detail the case sampling, and data collection followed, and the analysis conducted.

3.1. Case sampling and data collection for sub-study 1

The first sub-study followed a single-case design and it was on an event called the ‘Internet of Things (IoT) Start-up Summer School’ that lasted for 2 weeks. It was chosen as a critical case on an upcoming phenomenon of maker events or hackathons. The summer school followed an approach taken by other maker events or hackathons conducted in the past, where users collaborate intensively over a short period on innovative projects involving both software and hardware (Briscoe and Mulligan, 2014). IoT refers to connected machines that can perceive, think, and do (through the use of sensors, processing power, and actuators) (Santucci, 2010). The event allowed the participants to work dedicatedly on innovations and exchange with others as well as external experts who visited the premises. The case meets the relevant context of the study as participants used software programming, 3D printing, and electronics toolkits to build innovative products. In addition to developing innovative solutions, the participants also developed business needs and business models with an aim to raise funding for start-ups around their innovations. The case had a high likelihood

Table 1. Summarized research designs of the two sub-studies

Research design details	Sub-study 1	Sub-study 2
Research question	How do users simplify their solution space when designing tangible products?	
Unit of analysis	Solution space of users 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 ten innovative products in two weeks	Six existing innovations by users in an online community, each developed over a period longer than 6 months
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	Multiple sources of evidence, case study database, replication, pattern matching	
Data analysis techniques	Coding based on theory and empirical codes within the case	Coding based on theory and empirical codes within and cross-case-analysis cases
Analysis strategy	Identify characteristics of toolkits and solution space used Identify the process followed by users Draw conclusions	

to yield the best data due to the researcher's opportunity to directly observe the event as one of the organizers (Yin, 2009).

Forty users (between ages 18 and 29, 13 females) were selected from across Europe based on an open call to participate in the event based on their previous entrepreneurial interests and experiences. Current IoT entrepreneurs tend to be young, although the age of innovators and entrepreneurs, in general, is older. IoT development can be expected to be driven by younger people, as experience plays a lesser role than in more mature industries/ technologies (Roberts, 1991; Jones, 2010). They organized themselves into teams and then developed IoT products for two weeks with prototyping toolkits and materials. Thirteen of the participants had a business background; seventeen had a technology background, and 10 participants had a combination of both. The participants were selected out of a larger pool of over 200 applicants based on their background and motivation to develop innovative products in this field. Data collection occurred through five sources. First, the 10 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 so that the participants could freely articulate their answers. Second, the participants individually filled in two surveys during the event. Third, the progress of the products they developed was tracked, and toolkits used in designing their products were recorded. Fourth, the teams pitched their business ideas along with demonstrations of their working prototypes twice during the event, which was recorded and coded. Fifth, the teams also submitted a short report on their planned business idea and description of their prototype. All the data were collected in a case database consisting of notes, case study documents, tabular materials, and narratives in line with the case protocol.

3.2. *Case sampling and data collection for sub-study 2*

The second sub-study follows a multiple case design on user innovations and consists of six cases on innovations by users of 3D printing technologies to allow cross-case analysis between cases thus integrating different and potentially alternative viewpoints of different users for the phenomena (Yin, 2009) and to building theory (Eisenhardt, 1991). The study was limited to open source products as they have rich data available in the form of design source, code, documentation, and discussion communities that can be better exploited using a case study approach. The cases were sampled from significant projects (developed for at least 6 months) in Thingiverse, the design platform mentioned earlier as it was used for discovering, making, and sharing 3D printable as well as designs for electronic gadgets. Two significant innovations were first selected that required considerable time and resources to design, aimed at user needs, and were better than comparable offerings in the market. They also had received inputs from community members, and others often replicated them (hence substantially significant). One case had electronic components, while the other had only mechanical components. These two cases were then extended by four additional cases to bring in more variety in the different pathways taken by the users. The additional cases also allow replication of the findings or to extend any emergent theory for greater generalizability of findings (Yin, 2009) and to reduce selection bias, while drawing generalizable implications from the findings (Eisenhardt, 1989). Hence, two of the additional cases are purely mechanical, while two also include electronic components.

Data sources included user innovator interviews, their web pages, published articles about them, and the innovation artifact itself. The multiple sources of data add richness to the cases, enable in-depth analysis, and give the possibility of data source triangulation (Yin, 2009). Data on the artifact were collected from the design of the artifact, related documentation, and artifact demonstrations. The design history of the innovations and associated discussions also allow us to investigate causes and relationships in detail and over a period (Runeson and Höst, 2008). The 16 interviews with the user-innovators lasted between 30 and 60 min. The interviews were semi-structured with open questions (Appendices A and B) so that the interviewees could freely express their opinions and detailed experiences. On receiving explicit consent from the interviewee, the interview was recorded, transcribed, commented, and analyzed. Else, the crucial 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. The data collected from published documents, release histories, community discussions, websites, online videos, and other published material were saved in a local database.

3.3. Data analysis

The multiple data sources in both sub-studies provided in-depth data to study the issue at hand and lead to the triangulation of data sources that improve the case studies. Data analysis followed an explanation building approach by analyzing data and establishing ‘how’ users simplified their solution space and iteratively revising the emerging patterns or propositions. The theoretical underpinning of modularity formed the basis for a priori codes for examining the data. However, empirical codes were also generated when available (Glaser, 1965). Emergent codes were documented to identify essential sub-categories or unforeseen concepts (Yin, 2009) with a second independent coder to improve accuracy in the coding procedure. It gave the possibility of generating new theory (Eisenhardt, 1989), within the limits of the theoretical perspective of modularity theory. The coders followed a template coding procedure following Lombard et al. (2002) and the Holsti index (Holsti, 1969), resulting in the inter-coder reliability of 0.85. The data analysis established a classification of product characteristics regarding interfaces and operations allowed as well as how user innovators used solution space to develop their novel products.

4. Findings

The qualitative findings from the two sub-studies present how users simplify their solution space when innovating tangible products. The findings for each sub-study are grouped under the two types of modularity observed, which make user innovation more manageable, namely modular process, and modular product design. Furthermore, cross findings from the two sub-studies that identified the emergence of a new type of interfaces and modularity operation follow in the subsequent section.

4.1. Findings from sub-study 1

The participants of the event were introduced to technologies, design thinking, ideation, and prototyping, and they regularly interacted with potential customers and external industry experts. Hence, they followed a rigorous cycle of design and evaluation during the period to develop innovative products with justifiable market needs. Table 2 summarizes key details about the ten user teams and their innovative products. The findings are presented in the form of the modularity they adopted in the innovation process and the product design.

4.1.1. Modular process

The participants benefited from interacting in teams with complementary backgrounds and from guidance and resources available online or at the event. Talking to experts and looking at sample products helped the participants grow in confidence and

Table 2. Products developed in the maker event

Team name	Product	Target users
SensePro	Automatically control GoPro action cameras	Outdoor sports users
Fashionder	Fashion app for smartphones that manages user's wardrobe	Young women
Heartbeats	Wearable bracelets for communication by transmitting heartbeats	Jewelry purchasing end users
Drone In	Drones with projectors and social media for advertising	B2B service to event organizers
Ham	Device for controlling and managing the power usage of household appliances	B2B sales to SMEs
HTH	Sensor-based surgical implants that automatically warn users in case of failure	Selling through hospitals to customers
iVend	Pluggable networked device to automatically manage and maintain vending machines	Current vending machine companies
Columbus	Device to give tourists information on nearby monuments	Cities and tourism companies
Jams	A modular wearable device that can adapt to user needs	Early tech adopting end user
Elevator 4.0	Pluggable networked device to manage and maintain elevators	Elevator maintainers

knowledge in using 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 to work effectively.' (S1-1)

Working at the same location also allowed the parallel distribution of solution development between the participants. They followed a modular process also by benchmarking and linking their solution modules with others as each team demonstrated their prototypes and interacted with the other teams every 2 or 3 days. Working with open source technologies was essential for modularization, as it aided rapid prototyping and artifact development seen among the teams. The ease of finding and reusing solutions in the form of learning resources and already developed software libraries online shortened development times.

'(…) 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 interfaceable. Especially it is helpful that many libraries are downloadable for all the different sensors.' (S1-2)

The participants initially chose a hardware toolkit whose solution space was familiar, and an established online community supported. It allowed them to have a standard reference around which to distribute solution development into process modules and hence manage complexity.

4.1.2. 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 event was the internet of things, the products contained electronic components. The participants built these products by combining different electronic sensors, actuators, and microcontrollers that could connect to the internet. They connected different modules of the platform as well as 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 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 to make a decision on the choice of hardware.' (S1-4)

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 made it 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. They also assembled 3D printed or laser cut enclosures to house the electronics.

4.2. Findings from sub-study 2

In three of the six cases, users combined 3D printing with open-source electronics to add utility to their innovations. The hardware consisted of a low-cost processor or micro-controller that users can easily program and standard interfaces that connected to many modular sensors and actuators. With these parts, users constructed innovative electronic prototypes such as home automation devices, simple robots, and even other 3D printers. The six cases that form the second sub-study are shown in Table 3.

4.2.1. Modular process

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 study looked at the designs that went farthest and emerged as dominant designs. The innovators 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 branching out their versions of them or specialized in specific parts.

As others began to perceive the captured needs of society, the innovations caught their interest, and they slowly became part of the community and contributed by communicating with the user in discussions. Discussions were in the form of comments on the platforms as well as websites and blogs of the user innovators. One of the creators from Robohand explained 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.' (S2-3)

3D printing technologies were used initially to cut costs in designing custom components. 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. In the case of Robohand, a user aptly put across this point:

'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 (…) 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.' (S2-3)

Table 3. User-developed products based on digital fabrication and electronics

Cases	Description	Simplification
Robohand	Low-cost prosthetic hand for amputees and children with congenital disabilities	Components designed for users with diverse expertise
Koruza	A laser-based wireless communication system for multi-user peer-to-peer wireless network	Reused design knowledge by incorporating existing off-the-shelf products
Smartphone loudspeaker	Entirely 3D printed mechanical device that acts as a stand and amplifies smartphone speakers	Designed as an add-on to an existing product
Wii wheel	3D printed add-on to the popular Wii motion-control gaming console for playing racing video games	Designed as an add-on to an existing product
Canedolly	Add-on to a digital camera to record slow-moving time-lapse videos	Reused design knowledge by incorporating existing off-the-shelf products
4Track	A remote-controlled land-based vehicle with tracks and controllable claws.	Shared design knowledge from many users and reused design knowledge

The users in these cases worked on 3D printers for home use (e.g., MakerBot) that were relatively inexpensive. Users chose toolkits with a wide enough 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 their printers.

4.2.2. Modular product design

The innovative products consisted of 3D printed parts, off-the-shelf products from hardware stores, and in the case of electronic products, low-cost electronic components such as sensors, actuators, and microcontrollers. Users relied on standard hardware components whenever 3D printed parts did not meet the material and functional requirements of the artifact. They used 3D printing for parts that physically connected other parts, for example, a casing for electronics. The solution space of low-cost microcontrollers like Arduino enabled the processing of information and interfacing between other electronic components. One interviewee 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.' (S2-2)

4.3. Cross study findings

Comparing the results from the two studies has led to the development of propositions listed in the following sub-sections. They are organized into sub-sections around the themes of modularity and related emergent themes.

4.3.1. Modular process and product design

Both sub-studies saw users collaborating by focussing their efforts toward contributing to a part of the system rather than the whole. A modular process enabled collaboration by dividing the work effort among each other and a modular product design enabled collaboration through reuse of existing design work. Limiting their work to a specific design module that connected to other users' work, such as designing and 3D printing just one component that connected to other users' 3D printed parts, allowed them to reduce the complexity of the process to just the part of the process they were involved in. Thus, following modularization in development processes seen within organizations (Sanchez and Mahoney, 1996) in a user community context resulted in design simplification. The positive effect of process modularity on manufacturing agility, that is, the ability to innovate and respond to customer needs in a timely effective manner (Narasimhan et al., 2006) has been previously studied, but not supported (Jacobs et al., 2011). However, in the context of user innovators in making communities who already possess sticky need information, the locus of design lies within the users who are solving their design problem (von Hippel, 1994). In this context, modular processes could, indeed, have a positive effect on innovation. Thus, leading to the following proposition:

> **Proposition 1** Modularization of the design process in user communities reduces the number of design questions and options, thereby enables simplification of solution space for innovation.

Users reused existing product designs into their work, leading to overall modularized product design. Reusing readily available software libraries or hardware modules through unique configurations of existing parts allowed users to reduce their design effort. Product modularity accelerates innovation through mixing and matching modules and through innovation within a module (Ethiraj and Levinthal, 2004; Ulrich and Eppinger, 2012). Users in both sub-studies similarly reused a variety of existing product designs, thus restricting their design work to their components thereby simplified their solution space for innovation.

4.3.2. Dynamic interfaces to simplify solution space

Modular process and product design in both the sub-studies emerged due to various technologies that allowed modularization and parallel work, either by splitting up the making process or the design work. This is in contrast to designing a modular system (Croarken, 2000), where a system is broken down into modules or deriving future products from a set of common modules of a product platform (a modular toolkit) (von Hippel, 2001; Vickery et al., 2015). In contrast to the firm's perspective of modularizing a complex system to promote innovation, the users' perspective is to integrate a solution that addresses their sticky needs. 3D printing along with web technologies and social media enabled process modularity. These collaboration technologies enabled users to distribute the making process across each other by giving them similar design capabilities and linking them with other innovative users and other community members. Users chose from the variety of collaboration technologies available to them,

Table 4. Characteristics of dynamic product interfaces for users to simplify making

Dynamic soft interfaces	Dynamic hard interfaces
• Programmable interfaces • Information flow between existing electronics • Using modular electronics	• Digitally designed mechanical interfaces • Physically fit existing products • Using digital fabrication

the means to interface with each other, thereby building on-demand 'dynamic process interfaces' between themselves.

Similarly, user innovated products ranged from modifications to new products built out of existing off-the-shelf items. These items included components as well as standalone products, not originally designed to connect to other products. In the latter case, standalone products did not have the necessary interfaces to treat them as components and connect them to other products. User innovators instead built on-demand 'dynamic product interfaces' to connect these products (Table 4). Users could create either hard interfaces, mechanical in nature, or soft interfaces that were informational. Digital fabrication (e.g., 3D printing) toolkits allowed users to digitally create hard interfaces between products, such as slots, gears, clips, and tracks. Users could dynamically design the right shapes and connections and straight away produce them. Low-cost computing in the form of microcontrollers allowed the creation of programmable soft interfaces for information flow between electronic components, by connecting different input–output pins, transferring, and translating information. Thus, the dynamic product interfaces form a key finding across the sub-studies.

Furthermore, 3D printing with its flexibility (regarding object shape and material), as well as the variability of its connections to other forms of design, is readily available. It offers a wide range of users similar solution spaces and the potential to extend each other's work, leading them to digitally develop process and product interfaces. The digital age in the making context means user innovation is not restricted to firm specified modular structures. Users benefit from bottom-up modularity across systems in addition to existing modularity within systems Thus, leading to the third proposition:

> **Proposition 2** Dynamic (process and product) interfaces enable bottom-up modularity, thus enabling higher levels of innovation.

4.3.3. Modular innovation in making

Overall, the two sub-studies provided valuable insights into the process followed by users in developing innovative, tangible products. The findings can be summarized into a 4-step process that gives further insights on how they manage the complexity a large solution space gives them a high number of design questions and options:

The first step was to build a product that implemented the core solution needed; they often restricted themselves to a toolkit with just enough solution space to implement the first working prototype, instead of using the entire solution space available to them. For mechanical parts, this could be in the form of crude 3D prints or fashioned in a workshop. These parts had the necessary spatial dimensions to make the prototype work. Electronic parts were developed often from prototyping electronics platforms like Arduino. Similarly, in software, they implemented only the necessary functions. Thus, users could start small, familiarize themselves with a reduced solution space and if the solution space was still not enough, they reduced the scope of their needs to a set of sufficing needs that could be met using the reduced solution space. User innovators begin making by identifying the minimal solution and the minimal required solution space (with the least number of design questions and options (MacLean et al., 1991) needed for a functional prototype). Thus, while modularization increases the pace of innovation (Croarken, 2000), modularity a toolkit or a product platform with lesser modularity is preferred at the beginning. The finding is summarized by the following proposition:

> **Proposition 3** Toolkits with reduced solution space (lesser modules) enable user innovators to innovate early in the process.

The second step was to include other functionalities into the solution, needed for operating in a real or simulated environment. Such functionalities can 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. For example, Robohand used breathable Orthoplastic material at the points where the prosthetic hand was in contact with human skin and replaced plastic parts with more reliable metal screws and bolts. Suggestions for new materials, designs, and components can come from the user community and network. Incorporating additional components, either stand-alone or modules from product platforms increased functionalities required to meet additional user needs. Additional It leads to the next proposition:

> **Proposition 4** Increasing solution space (additional modules) enable user innovators to innovate later in the process.

The third step involved optimizing the design for performance, as the product gets bulky from the functionalities in the previous step. Users reduce the number of modules and streamlining 3D designs with reduced material to make the product more efficient. Along with efficiency, optimized design can make the product more aesthetic. While the users 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 users increase solution information and start using more advanced toolkits, they reduce reliance on standard parts. In this step, modular design is disadvantageous, and integrated design (Croarken, 2000) performs better and is preferred (Ethiraj and Levinthal, 2004).

Most of the cases of users iterate between steps two and three as they keep improving their products, by either adding newer functionalities or optimizing their design The fourth and final step is an optimized design aimed for production, as was seen in in the case of Koruza after 3 years of developing the product. It marked a departure from the earlier design approach where the product consisted of modular parts that users could easily purchase or 3D print. Koruza plans to branch its 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 reduce modularity to lower costs and make it available in the market.

5. Discussion and conclusion

User innovators in the context of digital fabrication and IoT face a manifold of different options to proceed. The study shows various patterns of simplification by modularity in the treatment of this manifold. Modular structures appear both in the products made and in their design process. While product modularity improving mass customization capability for the organization was previously discussed (Zhang et al., 2014), we find that it can also impact users by simplifying their solution space for innovation, in the context of user innovation in open design or maker communities. It is a new and upcoming area of open innovation in the digital age (Gassmann, 2006; Gassmann et al., 2010) as more users have access to flexible production technologies. The outcomes of this paper add to research on open and user innovation by exploring user innovation in making tangible products. The empirical context of the two sub-studies on user innovators involved in making adds to previous work on users in large open sources projects (Harhoff et al., 2003; Lakhani and Von Hippel, 2003) or open hardware (Balka et al., 2009; Raasch et al., 2009). Users in these two sub-studies were part of smaller projects (one to five members), some of which attracted external contributions only after around 6 months. The users can be considered lead users who went beyond describing problems, stating needs or even suggesting solutions to each other and developing the solutions (Mahr and Lievens, 2012).

The role of modularity in user-designed tangible products was a core component of the theoretical contributions. It allowed reuse of innovation (Kyriakou et al., 2017), decentralization of the design process among users, and its management (Sanchez and Mahoney, 1996), dynamic interfaces for bottom-up modularity and the gradual increase of solution space for the benefit of non-expert users. The findings show that users shared the design workload through various forms of modularity-in-design, by working with other users or reusing existing design work by reusing existing products. Existing products are dynamically integrated by an interfacing operator which is a combination of splitting, augmentation, and linking operators (Croarken, 2000). Hence, the concept of dynamic (process and product) interfaces identified in this study arises bottom-up and ad-hoc, which make them different from related concepts such as top-down 'systems integrators' (Brusoni and Prencipe, 2001). The creation of product interfaces 'on-demand' to integrate different modular systems hence is a novel outcome of these technologies that reflect the digitization of hardware design, where mechanical components are synonymous with software design files and software applications in an embedded system. While these methods would traditionally be expensive or inaccessible, reducing the cost of both 3D printing and computing allows user innovators to use an inexpensive embedded computer or a 3D printed part as links between systems rather than the central system itself.

The results of this paper also have implications for product managers and innovation managers offering toolkits to users in communities (Wendelken et al., 2014) and making events (Landwehr Sydow and Jonsson, 2015). Managers can exploit innovations in communities by encouraging process modularity. Providing access to digital fabrication toolkits can result in additional bottom-up modularity in addition to any top-down platforms they provide, which can lead to additional innovation. Providing a variety of solution spaces (or modular systems) that can be used early or later in the innovation process can promote innovation in user communities.

The user innovations in this context are not entirely open and can include both open source and proprietary components. Therefore, product firms can drive user innovation by opening their product design (Soeldner et al., 2013, 2015), allowing dynamic interfaces with other products. Firms can then identify successful user innovations and further integrate them into their portfolio. In the first substudy, the innovators aimed to build startups around their innovations, implying that manufacturing firms can collaborate with these user innovators turned entrepreneurs and focus on providing the components. The aspects of modularity in both process and product design identified in this paper can guide innovation managers on selecting among various types of toolkits (Naik et al., 2016) and activities around toolkits they can organize for users to effectively reuse knowledge for innovation (Kyriakou et al., 2017). Toolkit makers can benefit from the user innovation process by offering a gradual increase in toolkit solution space as users go through various stages of learning by doing (von Hippel and Katz, 2002). Even when such toolkits with gradually increasing solution spaces do not exist, community managers can manually offer different toolkits with different solution spaces to users and encourage interactions needed between users to enable non-expert users.

The open design platforms and their usage described in the paper highlight the current state of the art in this area and functionalities that can provide further value to users by supporting their characteristic procedural patterns. The limited sample size and research design constrain the significance of our results. Both the single case study and multiple case studies are limited regarding their generalizability to the specific empirical context. The findings in this paper are also limited to making by users and communities in the empirical context of digital fabrication and IoT.

User communities have a large base and user participation, but tapping into it is a challenge to firms, and it needs to be further researched. Future design science studies (Hevner et al., 2004; Peffers et al., 2007) can explore how users' needs and solution information can be identified at prototype stages in user innovation contests (Wendelken et al., 2014). As the variety of user needs and individualization of users increase with the availability of large solution spaces (Naik et al., 2016; Naik and Fritzsche, 2017), managing it also becomes a problem that design of unique artifacts can solve. Hence, future research can address the problem of designing innovative information systems that manage the complexity of individualized needs and their matching solution spaces. Furthermore, designing a system that can generate dynamic interfaces depending on users' needs would further develop the understanding of the bottom-up emergence of modular products when making tangible products, in contrast to purposeful top-down design, a manifestation of open innovation based modularity in the digital age.

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Appendix A

Survey questions for maker event participants

During the event

- How do you rate your technical expertise on a scale of 1-5 (very bad to very good)?
- How do you rate your business expertise on a scale of 1-5 (very bad to very good)?
- Do you have previous ICT experience? If yes, please state.
- Do you have previous startup experience? If yes, please describe it in 2-3 lines.
- Did you have IoT or startup ideas before the academy start? If yes, please list up to three best ideas.
- What ideation tools or methods did you find useful during the workshop sessions?
- What idea do you currently find the most interesting and what do you like about your current idea?
- Describe (in three to four lines) how your idea reached its current state. Who and what inspired you, what decisions you made and why.
- What do you think of the pitch of your team? What are the positives and negatives?

After the event

- Describe (in three to four lines) how your idea reached its current state. Who and what inspired you, what decisions you made and why.
- What helped you understand (and work with) so many innovative technologies during the time at the academy?
- How did you decide on which tool to use (hardware/software) from the choices you had (e.g., Edison, raspberry pi, Arduino, etc.)?
- Were the tools you used for hardware and software flexible enough for you to prototype innovatively and why?
- What other tools and gadgets would you have liked to work with during the IoT academy and why?
- What would be your ideal time-period and schedule to make something you feel is innovative and why?

Appendix B
Questionnaire for user innovators

- Shortly describe your intended product
    - What was the motivation behind it?
- How did you go about designing the product?
    - Specifically hardware
    - Specifically software
    - What is your contribution to the product?
- What were the factors and constraints?
    - Cost
    - Availability of components
    - Openness
    - What tools (if any) did you use for the design process and why?
- Was it developed individually or the result of contributions from a community?
    - Did this decision affect the design choices in developing the product?
- How did he involve others in the development of the product?
- Creativity process:
    - Did you precisely know what you wanted to develop?
    - Did the idea of the product change during the design process?
    - Did the design of the product change during the design process?
    - How did you generate different options at each step of the design process?
- What is 3D printed and why? Why not use traditional manufacturing or standard components?
- Can an end-user or the community further build upon your product?
    - What can they change?
    - What can they build on?
- Business thoughts
    - Why is your product better than others?
    - What is the current state and what are your plans for the product?
    - Who is your target customer/user/community?
    - How does the product get adopted by the community?
    - What support does it get from the community?
    - How do you maintain quality standards?
- Manufacturing
    - How do you plan to manufacture this product in scale?
    - Technology monitoring: How do you do that?
    - Cost control: How do you do that?