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Removing barriers to sustainability research on personal fabrication and social manufacturing

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A B S T R A C T

Since the beginning of the New Millennium, increasingly widespread availability of the Internet and digitally enabled tools have made production processes more accessible to private individuals, introducing new opportunities for personal fabrication and social manufacturing. Yet scant sustainability research has been conducted on this important sector. We argue that research barriers, particularly relating to confusing terminology and lack of individual-centric analytical tools, are largely responsible for this void. The objective of this study is to overcome these barriers by (1) providing an integrating framework that can improve transferability, to other conceptual analyses, of the results of sustainability research conducted from a particular conceptual viewpoint, and (2) suggesting how some firm-centric analytical tools can be modified for effective use in studies of individual-level phenomena. We base our framework on the emerging concept of social manufacturing, first eliciting its main aspects and dimensions with a conceptual literature study, and then discovering its central properties with an empirical case study. We conclude by using the new social manufacturing framework to suggest modifications of three common sustainability analysis tools to make them more applicable to research on individual-level production. By making future investigation in this area more accessible our work contributes to both sustainability research and to the emerging field of research on social manufacturing.

1. Introduction

Since the beginning of the New Millennium, the increasingly widespread availability of the Internet and digitally enabled tools have made production processes more accessible to private individuals (Rayna and Striukova, 2016). Major examples are the enhanced affordability of rapid manufacturing technologies, such as 3D printing (Ford and Despeisse, 2016; Rayna et al., 2015) and direct digital manufacturing more generally (Chen et al., 2015; Holmström et al., 2017), as well as new Internet-supported business models such as open innovation (Huizingh, 2011), which make company boundaries more permeable and thus allow individuals outside a company to connect to its innovation processes. These changes have introduced important new opportunities for personal fabrication (Burns and Howison, 2001; Dougherty, 2012; Gershenfeld, 2008) and social manufacturing (Cao and Jiang, 2012; Markillie, 2012). These terms are partially overlapping, but they have a different emphasis. While personal fabrication means making one's own products by improved access to machinery, social manufacturing highlights individuals' cooperation with organizations (Hamalainen and Karjalainen, 2017).

While individual participation in service industries and digital content production have significantly increased (Bruns, 2007; Hamari et al., 2015) and while new manufacturing technologies have proliferated and created new possibilities for similar participation in physical production as well (Fox and Stucker, 2009; Gibson et al., 2010), scant sustainability research has been conducted on this important emerging area (Kohtala, 2015). We believe that the multiplicity of partially overlapping concepts relating to personal fabrication and to distributed production in general (Kohtala, 2015) have been a significant barrier to systematic study of this increasingly important field.

The objective of this study was to provide a conceptual framework that would facilitate future sustainability studies of individual participation in physical production. We perceive two major barriers that may have been restraining sustainability research in this area. The first of these barriers is the multiplicity of terminology relating to production that incorporates private individuals, as described in Kohtala's (2015) study. The second barrier is that

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sustainability research has been till now mainly directed toward traditional firm-centric production; its analytical tools have thus tended to be optimized for this particular purpose and may not be directly applicable to production processes involving private individuals.

We divide our objective into four general research questions, the first two of which tackle the first barrier of terminological multiplicity, while the other two aim at finding ways to overcome the second barrier by offering a way to modify existing sustainability analysis tools:

- What are the commonly used terms pertinent to individual participation in production?
- How could these terms be related to each other systematically in a way that could help the transferability of results of sustainability research conducted from one conceptual viewpoint to other conceptual analyses?
- What are the properties of this conceptual framework that would be particular to individual participation?
- How can this framework be applied to commonly used sustainability analysis frameworks that were originally designed for firm-centric production, to make those frameworks applicable to the analysis of forms of production in which individuals are major participants?

Regarding these research questions, some central definitions should be noted. We define an "individual" as an active private participant who is neither an employee nor an independent full-time professional, but also is not a mere consumer. Our unit of analysis is individual participation in or contribution to physical production, where this participation by one or more individuals can take place in any phase of production – in our categorization, mainly in one of three phases: either during ideation, or design, or actual fabrication. Further, individual participation can take place in cooperation with other individuals or with organizations, or it can occur in a solo project run by the individual alone.

The rest of this paper is structured as follows. To answer the four research questions, we conducted two studies, one conceptual and one empirical.

In the conceptual study, presented in the *second section*, we search the literature for concepts related to individual participation in production. We then analyze these concepts for their similarities and differences, hence eliciting the main aspects and dimensions of a framework that could be used to organize them. We build on the emerging concept of "social manufacturing", from the operations management literature, and adapt it to our particular context. Although manufacturing commonly refers to making products, we use the term in this paper more broadly to mean any physical production, including the processing industry and energy generation. Further, we use "manufacturing" to refer to the whole value chain of physical production– in particular, from ideation, to design, to actual fabrication.

In the *third section* we present the empirical study, introducing the case study approach, presenting the selection criteria for our six cases, and reporting the main characteristics of social manufacturing that we identified from the cases.

In the *fourth section* we discuss the question of how the sustainability of social manufacturing should be studied. We take three commonly used sustainability analysis frameworks and show how they can be informed and modified by the social manufacturing framework to make them more applicable to individual participation in physical production. The *fifth section* clarifies the limitations of this study and suggests future research. The concluding *sixth section* summarizes our arguments for the significance of the social manufacturing phenomenon and states our contributions to this emerging area.

2. Conceptual study: creating a framework for analyzing individual participation in physical production

In this section we tackle the terminological barrier to sustainability research on individual participation in production that was revealed in a recent literature review (Kohtala, 2015). We seek answers to two questions: What are the commonly used concepts relevant to individual participation in production? How could these terms to be related to each other systematically in a way that could help the transferability of results of sustainability research conducted from one conceptual viewpoint to other conceptual analyses?

We attempt to answer the first question by searching the literature to elicit a list of concepts that relate to individual participation in production. Then, based on the emerging notion of social manufacturing, we deal with the second question by creating a framework that can be used to organize these concepts.

2.1. Literature survey method

To assemble a preliminary list of concepts we build on the recent work by Cindy Kohtala (2015), who reviewed sustainability studies on distributed production. "Distributed production" can be seen as an umbrella term that includes not just production shared among firms but also various configurations in which one or more of the participants is an individual. Concentrating on physical production, Kohtala reviewed a wide variety of design, production, consumption, and environmental studies, including both theoretical and empirical articles from peer-reviewed journals and conferences. Although researchers in other fields such as management (Fox, 2012) and future studies (Fox and Li, 2012) also have examined the sustainability of distributed production, Kohtala's coverage is extensive, and her findings can be taken as current and representative.

2.2. Identifying concepts related to individual participation in production

Kohtala (2015) extracted the following concepts commonly used in the context of sustainability of distributed production: *distributed manufacturing*, *mass customization*, *personalization*, *peer production*, *prosumption*, *fabbing*, *personal fabrication*, and *Fab Labs*.[1]

As we analyzed the above concepts, we noticed that the group is dichotomized into (a) firm-centric concepts, where the individual participation is quite limited (distributed manufacturing, mass customization, and personalization), and (b) individual-centric concepts, which focus primarily on individual contributions (peer production, prosumption, fabbing, personal fabrication, and Fab Labs).

Such terminological dichotomization can be problematic, because it is a barrier to capturing the expanded role of individuals who participate in production together with firms and other individuals. In contrast, multiple theoretical frameworks related to service and content production recognize cooperation between firms and individuals (e.g., Kenney and Zysman, 2015; Hamari et al., 2015). There are also multiple frameworks related to R&D or, more generally, knowledge generation, that include firm-individual aspects (e.g., Brabham, 2008; Chesbrough, 2003). Unfortunately, these frameworks are often not directly applicable to similar cooperation in physical production, despite the fact that these

[1] Definitions of and references for these terms are given in Table 1.

forms of cooperation are spreading to physical production, facilitated by the development of new production technologies (Fox and Stucker, 2009; Gibson et al., 2010) and new business models (Vargo et al., 2008).

To form a more complete conceptual picture of individual participation in production, we sought to elucidate concepts that are typically used within service and digital content production, as exemplified by the well-known companies Uber, AirBnB, Wikipedia, and YouTube.[2] This approach did not aim to extensively cover academic research in this context; rather, it served to provide a general picture of the terminology.

We extracted the concepts related to these companies in two steps: searching first with Scopus and then with Google Scholar. Google Scholar gave us access to non-scientific publications, which was useful since academic research on Uber and AirBnB was still scarce.

We searched Scopus for publications in which the company name appeared either in title, abstract, or keywords. We then reviewed the keywords and selected concepts that could be related to individual participation in production. In addition to some of the concepts already mentioned by Kohtala, we were able to extract the following list: *sharing economy, collaborative consumption*, and *crowdsourcing*.

We then used Google Scholar to locate the five most cited non-technical publications[3] for the Uber, AirBnB, Wikipedia, and YouTube platforms, extracting the concepts and frameworks used to describe them. These publications are: Uber (Barro, 2014; Bilton, 2012; Feeney, 2015; Lashinsky, 2014; Rempel, 2014), AirBnB (Edelman and Luca, 2014; Guttentag, 2015; Sperling, 2015; Yannopoulou, 2013; Zervas et al., 2014), Wikipedia (Bruns, 2008; Denning and Horning, 2005; Kittur and Kraut, 2008; Kittur et al., 2007; Voss, 2005), and YouTube (Burgess and Green, 2013; Davidson et al., 2010; Keen, 2008; Lange, 2007; Smith et al., 2012). In addition to previously retrieved concepts, we identified the following concepts: *platform economy*, *produsage*, and *co-creation*. As a final member, we added to our list *open innovation* because it was mentioned in Kohtala's paper, although she did not originally include it in her list that concentrated on physical production.

Having identified this broad group of concepts for individual participation in production, we proceeded to elicit a definition for each concept from the literature. Within each concept, we gave particular emphasis to the roles played by individuals. The list of concepts and their definitions is presented in Table 1.

2.3. Social manufacturing framework

To organize the concepts we retrieved, we created a framework that differentiates the various concepts based on intensity of participation, and on the value chain phase where the individual participation is typically focused. We built our framework on the emerging concept of social manufacturing.

We begin with a short introduction to previous uses of the term "social manufacturing" and then proceed to create a new definition that could serve as a basis for the social manufacturing framework. We conclude this subsection by presenting a classification or map for the terminology of distributed production, based on the new framework.

2.3.1. A short history of the term 'social manufacturing'

The term social manufacturing was first used in Bloomberg web news (2011), which stated, "Kenandy Delivers Social Manufacturing Application on Force.com, Bringing Social, Mobile and Open Cloud Computing Technologies to Global, Distributed Manufacturing." Less than a year later, Paul Markillie used the term in an article in The Economist, writing about new manufacturing technologies: "… a new industry is emerging. It might be called social manufacturing … much of what is coming will empower small and medium-sized firms and individual entrepreneurs" (Markillie, 2012).

By using Kenandy Inc. as one of their example cases, operations management scholars particularly in the Chinese context soon adopted the term (Cao and Jiang, 2012), perceiving it as the latest version of advanced manufacturing systems (Tao et al., 2015). Although they included in their theorizing the possibility of individuals taking active parts in manufacturing, the main role for the individual was still that of a consumer: "… SMEs, workshops, small factories, and even individuals … provide various service-oriented capabilities to satisfy customers' personalized requirements …" (Jiang et al., 2016: 15).

In contrast, the use of the term in the Western context has followed Markillie's ideas of individuals as active agents using new manufacturing technologies such as 3D printing (e.g., Hirscher et al., 2018; Jeffery, 2013). While the concept of the use of social manufacturing in Chinese operations management research resonates with the terms "distributed manufacturing," "mass customization," and "personalization," its use in the West resonates with the terms "peer production," "prosumption," "fabbing," "personal fabrication," and "Fab Labs." Hence, social manufacturing interestingly seems to suffer from the same kind of conceptual dichotomy as does distributed production. A recent article by one of us and a coauthor named these two strands as "institutional" and "diffuse" views of social manufacturing, trying to strike a balance between these two by defining social manufacturing as "significant cooperation between established firms and independently operating individuals" (Hamalainen and Karjalainen, 2017: 796).[4]

Until now the work on social manufacturing has not focused significantly on sustainability issues. (For a recent exception see Hirscher et al., 2018).

2.3.2. Aspects and dimensions of the social manufacturing framework

We now attempt more precisely to bridge the conceptual chasm between uses of the term "social manufacturing" by suggesting a framework with two aspects, and proposing three dimensions along which individual participation may vary. Our earlier analysis of the concepts of distributed production showed that the level of individual participation or contribution varies a great deal: it plays a dominant role in the individual-centric concepts (peer production, prosumption, fabbing, personal fabrication, and Fab Labs), while in firm-centric concepts (distributed manufacturing, mass customization, and personalization), the individual contribution is minimal.

In contrast, by analyzing the second subset of terms that was based on our literature searches with Scopus and Google Scholar, we noticed that individual participation in these terms (sharing economy, collaborative consumption, crowdsourcing, platform economy, produsage, co-creation, and open innovation) was significant but not quite as dominant as it was in the individual-centric

[2] Uber is a transportation network company whose service is provided by private individuals using their own vehicles. AirBnB is a website where private individuals can offer and find lodging. Wikipedia is a free Internet encyclopedia. YouTube is a video-sharing website.

[3] By "non-technical publications", we mean writings that did not concentrate on algorithms or mathematical modeling of website traffic.

[4] Zwass (2010) has noted that the related term co-creation also is used in two distinctive ways, which he names as "sponsored" and "autonomous" co-creation.

Table 1
Summary of concepts for personal fabrication and distributed production.

Distributed manufacturing. From the engineering point of view, the term distributed production is a synonym for distributed manufacturing, which can be given two distinctive meanings. It can refer to one company using geographically dispersed manufacturing locations, or it can refer to intelligent manufacturing systems focusing on internal control (Windt, 2014). In the latter case the system can reside within one single factory (Kühnle, 2009), yet consisting of "a network of autonomous processing elements, with the capability of rapid dynamic reconfiguration" (Lima et al., 2006; referring to Lima, Silva, and Martin, 1999).

Distributed manufacturing is a firm-centric term and refers to the operations of a single company. Cooperation between two or more legally independent enterprises should be termed a "production network" (Windt, 2014).

Mass customization. Mass customization refers to a mode of production that aims to "deliver products and services that best meet individual customers' needs with near mass production efficiency" (Tseng and Jiao as quoted by Tseng et al., 2014). By offering each customer an ideal product, the company can sell more units and get a better price for each unit sold (Jiang et al., 2006).

Customization is facilitated by modularity and product family architecture (Tseng et al., 2014), as well as by flexible processes and integration between supply chain members (Fogliatto, da Silveira and Borenstein, 2012). The recent development of rapid manufacturing technologies has greatly supported mass customization (Fogliatto et al., 2012). But in addition to these flexible manufacturing technologies, the development of modern information technologies is important, because it enables integration of the customer into the process (Piller et al., 2004).

However, in spite of the closer customer integration, it is the company that decides the product variants and specifications. In this sense mass customization is not different from mass production (Jiang et al., 2006). The customers' participation remains "passive and limited," when they are choosing from these predefined selections (Tseng et al., 2014: 9; Fogliatto et al., 2012).

Personalization. Personalization is "a customer co-creation process and can be considered as an extension of mass customization" (Tseng et al., 2014: 10). Whereas mass customization from the customer's point of view consists of the elements "choose and buy," personalization raises the element count to three: "design, choose and buy" (Hu, 2013: 7).

Personalization attempts to increase products' personal relevance to the individuals by making customer participation more proactive and extensive than in mass customization; "customers collaborate closely with designers to develop products which satisfy their requirements" (Tseng et al., 2014: 9). In contrast, with mass customization customers would typically select from a predefined set of offerings. As a result, personalization can efficiently satisfy individual needs, whereas mass customization is aimed toward more defined market segments. Additionally, the increased customer participation is also perceived to increase the total quality of product (Tseng et al., 2010).

However, even though customers play a more significant role in the design process, to a large extent design remains the responsibility of professionals working for the company.

Peer production. Peer production is a model for organizing production in a networked information economy without relying on markets, managerial hierarchy, or contracts. The most well-established example of peer production is open source software (Benkler, 2002, 2006).

Internet popularity of P2P platforms such as Tribler and Bittorrent has grown very rapidly. These platforms started emerging in the late 1990s, and already in 2006 P2P traffic counted for over two-thirds of total Internet traffic (Pouwelse et al., 2008). Many of these platforms concentrate on sharing software and video content, often violating copyright laws. On the other hand, these platforms have also proven their power by quickly organizing large groups of people to support human rights and democracy regardless of geographic location. Pouwelse et al. have called these two manifestations of P2P platforms "pirate side" and "Samaritan side."

Personal fabrication, fabbing. Personal fabrication or fabbing means the ability to design and produce one's own products, at home or in a workshop, and by using machinery. It has been suggested that personal fabrication is able to revolutionize manufacturing as personal computers did to information processing a generation ago, and challenge the conventional model of mass production, which is built upon the advantage of economies of scale (Gershenfeld, 2008).

It should be noted that the term fabbing can also be used for digital rapid manufacturing technologies specifically (e.g. Burns and Howison, 2001).

"Making" is a parallel term for personal fabrication that is increasingly being used (Browder, Aldrich, & Bradley, forthcoming). An emerging research stream about the connections between making and entrepreneurship (Browder et al. forthcoming; Langley et al., 2017; Van Holm, 2015; Wolf and Troxler, 2016) is also highly relevant to social manufacturing research, and vice versa.

Fab Labs. Fab Labs are open access facilities that are equipped with tools for every phase of the technology development process, including design, fabrication, testing and debugging, monitoring and analysis, and documentation. Their aim is to enable personal fabrication.

Fab Labs have also the potential to help bridge the "digital divide" by bringing the digital revolution to developing communities, enabling them to create tools for solving their own problems (Mikhak et al., 2002).

Fab Labs also build on the idea of sharing knowledge and designs with other Fab Labs in different countries. The transferability of both projects and people from one Fab Lab to another is further facilitated by a common set of tools and processes that all the Fab Labs share (FabFoundation, 2015).

Sharing economy, Collaborative consumption. Sharing economy presents an economic model in which individuals are able to borrow or rent assets owned by other individuals, or services provided by them (Hamari et al., 2015). The concept of sharing economy has emerged through the proliferation of enabling social technologies as well as through the growing sense of urgency around resource depletion, pollution, and poverty. Sharing economy activity appears primarily when the price of a particular asset is high and the asset would be underutilized if not shared.

Sharing economy is a term that largely overlaps with peer production, especially as both rely on online technology platforms. However, sharing economy is commonly used to refer to goods and services that are not purely digital, rather have some physical dimension to them. For example, Schor and Fitzmaurice (2015) name re-circulation of goods, exchange of services, optimizing asset use and establishing social connections as the four major categories of sharing economy. Further, with the emergence of platforms such as Uber and AirBnB, the term sharing economy increasingly includes the idea of for-profit operations that challenge and interrupt traditional business models (Cheng, 2016).

Co-creation. Co-creation is a term that in academic literature is primarily used in marketing science. Co-creation means active cooperation between firms and consumers. From consumers' point of view, this cooperation is not as much about modifying physical products, as it is about modifying experiences with those products or services. As Pralahad and Ramaswamy (2004: 8) formulated it in their seminal paper: "product may be the same … but customers can construct different experiences." Later Vargo, Maglio, and Akaka (2008) suggested that value co-creation relies on service-dominant logic, which perceives service (and not product) as the basis of economic exchange.

In his critical paper Grönroos (2011: 279) noted that "Value co-creation easily becomes a concept without substance." One of the central problems with the term is that the meaning of value creation and of the value itself is not clear. Grönroos reviews literature and presents different ideas of value, such as assessing benefits and "hedonic appreciation of the object." What is common in these different definitions of value creation is that they seem to revolve around the value-in-use. Grönroos further notes that literature is often vague about the specific interactions (between the company and the consumer, and between the consumer and the product) that actually create the value.

Co-creation is clearly a firm-centric term. It essentially deals with optimal strategic responses that corporations should employ when dealing with the new and creative class of consumers termed "prosumers" (Zwick et al., 2008).

Prosumption. Prosumption is a term that was first coined by the futurologist Alvin Toffler in 1980. Prosumption means that people produce the goods and services that they (or their families) consume. This can include a large variety of activity, such as health services, peer support groups, and food production. By becoming prosumers, people bridge the chasm between production and consumption that resulted from the industrial revolution, which according to Toffler "violently split apart two aspects of our social lives that had always, until then, been one " (Toffler, 1980: 53). The change to prosumption can be triggered by private individuals' need to take more control over their lives, but it can also be the outcome of corporations' need to cut costs by introducing self-service.

For over two decades, the idea of prosumption had little impact on research; few academic articles discussed it prior to 2000. However, the development of the Internet and the ubiquity of online sites with user-generated content, on one hand, coupled with the rise of the "maker movement" (Dougherty, 2012) on the other hand, have altered the landscape in this regard. Today, Toffler's ideas of the prosumer and prosumption are frequently discussed in both academic (Ritzer, 2015; Ritzer et al., 2012; Ritzer and Jurgenson, 2010) and non-academic publications (e.g., Rifkin, 2014).

(*continued on next page*)

Table 1 (*continued*)

Open innovation. Open innovation is a new paradigm in innovation management. It is based on the insight that "valuable ideas can come from inside or outside the company and can go to market from inside or outside the company as well" (Chesbrough, 2003: 43). An organization cannot innovate in isolation, and the purpose of R&D laboratories expands from creating knowledge internally to absorbing external ideas.	
Professionals working in portfolio careers can be simultaneously serving multiple organizations (Dahlander and Gann, 2010). Open innovation can also rely on user innovation and crowd-sourcing for new ideas and input to enhance the quality and variety of existing products (Huizingh, 2011). The open innovation paradigm thus incorporates cooperation with individuals both as paid professionals and as unpaid volunteers.	
Crowdsourcing. Crowdsourcing means outsourcing a specific task to a "crowd" by making a public call. Instead of by designated subcontractors, the task is to be performed by self-selected agents, who are typically private individuals. The term was originally coined by Jeff Howe, who suggested it as a new model for problem solving and content creation (Howe, 2006, 2008). The term was first used in an academic article in 2008 by Daren Brabham, who defined it as "an online, distributed problem-solving and production model" (Brabham, 2008: 75).	
The proper definition of crowdsourcing remains the subject of debate. Although some researchers (Buecheler et al., 2010; Huberman et al., 2009) consider it to include platforms such as Wikipedia and YouTube, other researchers argue that these are not crowdsourcing ventures (Kleemann et al., 2008). Nonetheless, other scholars have suggested that the concept closely relates to – and even overlaps with – open innovation. In an attempt to solve these conflicts, Estellés-Arolas and González-Ladrón-de-Guevara (2012: 197) have suggested an integrated (although somewhat lengthy) definition of crowdsourcing: "Crowdsourcing is a type of participative online activity in which an individual, an institution, a non-profit organization, or company proposes to a group of individuals of varying knowledge, heterogeneity, and number, via a flexible open call, the voluntary undertaking of a task. The undertaking of the task, of variable complexity and modularity, and in which the crowd should participate bringing their work, money, knowledge and/or experience, always entails mutual benefit. The user will receive the satisfaction of a given type of need, be it economic, social recognition, self-esteem, or the development of individual skills, while the crowd-sourcer will obtain and utilize to their advantage what the user has brought to the venture, whose form will depend on the type of activity undertaken."	
Produsage. Produsage means user-led content creation. It is a term coined by Axel Bruns (2008) to explain the production of digital content and knowledge. The central idea is that the usage and development of this content happens simultaneously, with people functioning in the hybrid role of produser (Bruns and Schmidt, 2011). Participation in produsage is voluntary and unpaid, but may result in professional employment in the field.	
Bruns contrasts produsage with the physical fabrication as described Toffler's (1980) prosumption model, which he perceives to follow the different logic of scalability: "As von Hippel points out, clearly 'production and diffusion of physical products involves activities with significant economies of scale,' and a direct translation of produsage to the physical realm is therefore unlikely …" (Bruns, 2008: 390). Bruns further critiques that prosumption "describes merely the perfection of the feedback loop from consumer to producer; it sketches a capitalist paradise in which 'the willing seduction of the consumer into production' is complete, but where production and distribution remain driven very much by corporate interests" (Bruns, 2008: 12). Two short comments might be appropriate here. First, it appears that Bruns is misinterpreting Toffler's ideas, where prosumers are explicitly presented as active "do-it-yourselfers" (Toffler, 1980: 12), who may not be independent from the markets, but who nevertheless actively decide which services and fabrication they prefer to do by themselves. It appears that the critique that Axel Bruns directed towards Toffler's prosumption model regarding the relatively passive role given to individuals, would be more accurately directed to Pralahad and Ramaswamy's (2004) ideas of co-creation. Second, with new manufacturing technologies such as 3D printing, it appears that the economies of scale for physical production that Bruns and von Hippel have emphasized are quickly diminishing.	
Platform economy. Platform economy is a term used to describe new collaborative modes of business. Kenney and Zysman (2015) defined platforms as "frameworks that permit collaborators – users, peers, providers – to undertake a range of activities, often creating de facto standards, forming entire ecosystems for value creation and capture" (Kenney and Zysman (2015): 2), perceiving that they are "likely to effectively define the digital era, with the algorithm and Internet and cloud as the building blocks" (Kenney and Zysman (2015): 3). Kenney and Zysman maintain that platform economy can go two different ways, it could produce a few monopolist corporations, who "[squeeze] the platform community" (Kenney and Zysman (2015): 15), but it could also create a new generation of thriving entrepreneurs. There is some overlap with other concepts that also include the use of technology platforms, e.g. crowdsourcing (Kittur et al., 2013) and sharing economy (Cheng, 2016), for which platform economy might offer terminologically a more neutral alternative (Kenney and Zysman, 2016). What is specific in platform economy is that it emphasizes for-profit activities and the centrality of the platform. The term is still quite new and is not (yet) being widely used in academic contexts.	

concepts; rather, they included more strongly the idea of cooperation, with individuals making their underused resources available to companies and other individuals. Further, although all these terms implied significant participation by individuals, the tasks performed by these individuals nevertheless varied considerably. For example, within the sharing economy, individual participation usually relates to the actual production or fabrication phase, whereas with crowdsourcing, participation can occur either in fabrication or in the much earlier phase of idea-generation. With open innovation, participation is explicitly related to generating ideas or knowledge.

Hence, we argue that the *intensity of individual participation* is one aspect of the social manufacturing framework, and we further suggest that this participation can usefully be quantified as "minor, partial, and main", with "minor" referring to minimal contributions (particularly in firm-centric concepts), "partial" referring to significant but not dominant contributions (often in collaboration with firms), and "main" referring to dominant contributions (particularly in individual-centric concepts).

Observing that individual participation can take place at various times, between the phases of ideation and fabrication, we identify in many of the concepts, e.g., in crowdsourcing and in produsage (i.e. user-led content creation) an intermediary phase of design. These observations led us to choose the *position of individual participation in the value chain* as an appropriate second aspect in our proposed conceptual framework for studying social manufacturing, with ideation, design, and fabrication defining a three-dimensional space in which the individual participation may vary. In a way, this part of our social manufacturing framework could also be seen as an expansion to co-creation typology that includes the phases of ideation and design, but not fabrication (Piller et al., 2010). [5]

2.3.3. Classifying distributed production terminology within our social manufacturing framework

We then used the social manufacturing framework to analyze the concepts that we had retrieved earlier. For each concept, we elicited the level of individual contribution in each of the phases of ideation, design, and fabrication based on descriptions in Table 1. We map these dimensions visually in Fig. 1: an individual's participation in ideation is on the x-axis, participation in design on the y-axis, and participation in fabrication is expressed by the boundary thickness (a thin boundary line meaning a minor, a medium line meaning a partial, and a thick line meaning a main contribution). Furthermore, the sharing economy and produsage concepts have thick dashed lines, since in them, although individuals are the main contributors in production, this production is commonly about services or content, and not about actual physical fabrication.

Based on the definitions of mass customization and distributed manufacturing that we elicited from extant literature and that were presented in Table 1 and visually presented in Fig. 1, we conclude that neither of them includes significant individual participation in any of the three phases. Hence we conclude that these two terms

[5] Rayna et al. (2015) have presented an alternative co-creation typology with the dimensions design, manufacturing, and distribution.

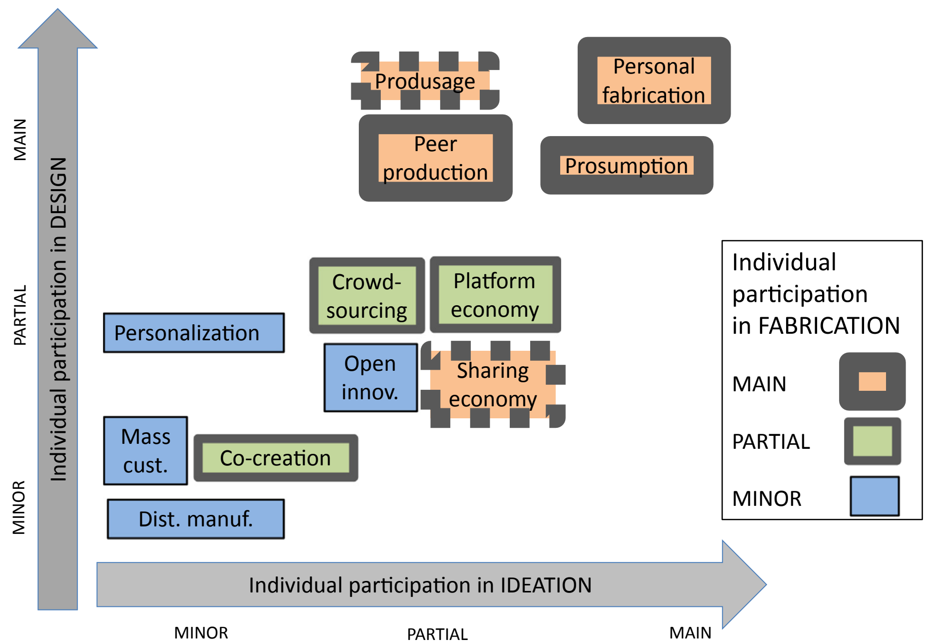

Fig. 1. Different concepts of distributed production analyzed with social manufacturing framework.

ought not be included within the broad concept of social manufacturing.

Our framework suggests that results of sustainability research conducted from one conceptual viewpoint will be transferable to other conceptual analyses to the extent that these concepts focus on similar participation patterns. For example, sustainability research conducted on personal fabrication should apply well to prosumption (especially to the physical version of it), but much less well to open innovation.

3. Empirical study: identifying central properties of our proposed social manufacturing framework

The second barrier we perceived to be hampering research into the sustainability of individual participation in production is that the analytical tools used in sustainability studies have generally been designed for application to firm-centric production. Our two research questions in this regard were, first, What are the particular properties of the social manufacturing framework that could set it apart from firm-centric manufacturing?, and second, How could these properties be used to modify existing sustainability analysis frameworks?

In this section we attempt to answer the first question, using empirical knowledge to expand the social manufacturing framework that we created conceptually in the previous section. In the Discussion section that follows we will deal with the latter question.

3.1. Method to conduct the empirical study

To widen our understanding of the social manufacturing framework that we built based on the literature on distributed production, we conducted a case study. Case study research creates an understanding of the detailed dynamics of a phenomenon by looking at particular settings (Eisenhardt, 1989; Yin, 2013). This type of study is especially suitable when the main research questions are of the "why" or "how" type, when the researcher has little control over events, and when the focus is on a contemporary phenomenon. Since we were more interested in the functional properties of social manufacturing than in its causal or psychological underpinnings, we conducted a descriptive case study, concentrating especially on the question "how." Our sample consists of six cases, three of which were analyzed based on publicly available secondary data. For three cases where, due to their novelty, few written sources were available, we complemented secondary data with interviews and participant observation.

3.1.1. Specific empirical research questions

Case study research typically starts with propositions that are based on the literature (Yin, 2013). These propositions, in turn, help define the research questions, based on which the unit of analysis is defined and the actual cases selected. The propositions in our study are included in the social manufacturing framework that was established in the previous section. In short, the propositions are (1) that individuals can participate in physical production in any of the phases of ideation, design, and fabrication and (2) that the level or significance of their contributions can vary. Based on these propositions, we came to the following specific research questions:

How does participation begin, and how does it proceed?
How is the specific phase of the value chain chosen for contribution?
How does the level of contribution develop?
Which actors are included in the cooperation?
How are ownership and rewards distributed?

3.1.2. Case selection

In case study research, the unit of analysis is a case. Within this study, the unit of analysis was individual participation in physical production in any of the phases of ideation, design, or fabrication. Hence, our cases were not the six selected organizations in their totality, but rather instances of individual participation in each of them during one or more of the three phases mentioned. However, for the sake of simplicity, we will talk about these cases by referring to the name of each organization.

The cases were in various industries: Lijjat Papad in the bakery business, Kumpula solar energy in energy production, Quirky in the consumer goods industry, SeeedStudio in electronics production, and Shapeways and Fabbly.com in the emerging field of additive manufacturing. More detailed information for these cases is provided in Appendix A.

We chose cases from several different industry types because we wanted to study the properties of social manufacturing as they apply to firm-individual collaboration in general, and not limit the applicability of the social manufacturing framework to some specific area. The number of cases was also a strategic choice: it is within the optimum range for multiple case studies (Yin, 2013). The samples were selected with the logic of theoretical sampling in a manner that provides wide variety regarding both the level of contribution from individuals and the phase in the value chain where this contribution occurred. Rich data from different or even “polar types” facilitate theory building (Eisenhardt and Graebner, 2007). At the same time, we followed simple replication logic (Yin, 2013), concentrating on cases where our propositions of individual participation were demonstrated. Because we were not trying to establish causal connections, it was not necessary to include cases without individual participation.

All our cases were samples of individuals cooperating with firms or other types of economic organizations. We had several reasons for this approach. First, some research already existed regarding the sustainability of physical production by single and networked individuals (Kohtala and Hyysalo, 2015). Second, the inclusion of organizational participants enabled us to have cases with varying levels and phases of individual contribution, as suggested by the social manufacturing framework. Third, the evidence of the service industry with firms such as Uber and AirBnB has shown that models with firm-individual cooperation have potential to make significant societal impact – for better or worse.

Basically all the writings about social manufacturing have treated it as making wares using advanced technology. Four out of six cases in our study match this criterion. However, we wanted also to include one sample of “low-tech” social manufacturing; we thus selected Lijjat Papad to represent a more traditional cottage industry (Devor et al., 2012). Furthermore, we wanted to include a sample in which the production was not about separate unitary wares, but rather about a continuous production flow. Hence, we included the Kumpula solar power project as a sample of social energy generation.

With the four cases that were characterized by high-tech production of wares, we aimed to have samples with different combinations of the phases during which the individual contributions took place. We included two samples of 3D printing because this technology has been suggested to be central in the transition to social manufacturing (Markillie, 2012). In the case of Shapeways, 3D printing is taken care of by the service provider, whereas with Fabbly.com, each individual prints his or her products. In the other two cases, the products were more complex than what could be directly produced by 3D printers. With Quirky, both the prototypes and final products were produced by the platform, whereas with SeeedStudio, the individuals were responsible for providing functional prototypes.

Although the cases present rather different types of manufacturing (such as energy generation vs. the manufacture of tangible consumer goods), they exemplify transitions from corporate-centric production to social manufacturing. They all represent industries that, in a corporate context, have included the processing of physical resources in large-scale production units and, hence, have been generally out of the reach of private individuals. However, with alternative business models and often facilitated by new technologies for knowledge-sharing and fabrication, in all these cases private individuals are now participating in the production as active contributors, cooperating with firms on at least one level of the value chain, whether in ideation, design, or fabrication.

3.1.3. Data sources

In case study research, a specific unit of analysis calls for a specific data collection strategy. We do not attempt to cover the area of study in its totality but rather only to the extent that it serves to answer the research questions (Yin, 2013). In our study, we concentrated on a phenomenon that was a relatively visible part of each studied organization, namely, individual participation in different phases of the value chain. Further, we studied this phenomenon on a relatively gross level, looking mostly at the level of contribution. We were able to retrieve most of this information from publicly available documents.

Although case study research is often confused with specific methods of data collection, such as ethnography, elaborate approaches are often not necessary; rather, it is possible to “do a valid and high-quality case study without leaving the telephone or Internet” (Yin, 2013: 21). Furthermore, when interviews are needed, “(they) may be more focused and only take 1 h or so” (Yin, 2013: 111).

We gathered data on each organization using several sources. With SeeedStudio and the Kumpula solar power project, we used a combination of interviews and publicly available material. With SeeedStudio, we conducted one 60-min interview with the division leader of US operations. With the Kumpula solar power project, we conducted three interviews with the technology advisor and mentor of the project, totaling 60 min. With Fabbly, in addition to publicly available material, we also used participant observation: we tested the platform by purchasing 3D files through it. The three other cases – Quirky, Shapeways, and Lijjat Papad – have been well documented by earlier research and media coverage. (With Shapeways, we were additionally able to use, for secondary data, an interview performed earlier for our study of intellectual property rights and design.)

3.1.4. Analytical strategy

When analyzing cases, we followed an inductive or “ground-up” approach, which is one of the four general strategies named by Yin (2013: 136). We defined individual participation as “(potentially) compensated contribution into the value chain of physical production.” We analyzed the cases by dividing them into distinctive events or transactions corresponding to individual participation in the phases of ideation, design, and fabrication. For each event, we compared its specific characteristics and sub-events to similar and contradicting characteristics and sub-events both within the same case and between the cases. We named the observed patterns, thereby inducting categories with properties. Our approach relies on the techniques of the grounded theory method, especially on that of constant comparative analysis (Glaser, 1965, 1978, 1998; Glaser and Strauss, 1967). Constant comparative analysis means that coding and analyzing are performed simultaneously. It is a boot-strapping approach to theory generation: existing codes are used to code incidents in data, and at the same time, new codes are inducted by perceiving (and then naming) similarities between incidents.

In this study, we did not apply the full package of the classic grounded theory method, which begins with no prior conceptions about the studied phenomenon and then lets the core variable emerge from data through open coding. Instead, we began with social manufacturing as our given core variable and proceeded directly to code incidents selectively as they related to this core.

3.1.5. Validity

The quality of case study research and social study research in general depends on four elements: construct validity, internal validity, external validity, and reliability (Yin, 2013). While internal validity is connected with causal situations and, hence, is inapplicable to descriptive studies, the other three dimensions have been carefully considered in our study. Regarding construct validity, we have explicitly defined individual participation as taking place in one of the three phases of ideation, design, or fabrication and consisting of a contribution that is at least potentially compensated. Actual compensation may depend on the success of the project, which, at the time of contribution, may be undeterminable. External validity has to do with the analytical generalizability of the results, which generally results from research questions of the "how" and "why" types. Our research questions correspond to this requirement. The reliability element depends on the transparency and reproducibility of the research. For this purpose, we have presented the essential data for each case in Appendix A, also showing references to the secondary data.

3.2. Results of empirical study

We analyze the cases first on a gross level by explicating individual participation within each of them, then on a more refined level by using the constant comparative method to elicit the main properties of social manufacturing as exemplified by these cases.

3.2.1. Individual participation in the six cases

Each of the six cases had its own way of intertwining the individual contributions to its value chain. Similarly to what we did earlier with different concepts of distributed production in Fig. 1, we visually map the six cases in Fig. 2. Individuals' participation in ideation is on the x-axis, participation in design is on the y-axis, and participation in fabrication is expressed by the boundary thickness, with a thin boundary line meaning a minor, a medium line meaning a partial, and a thick line meaning a main contribution. For example, in the case of Lijjat Papad, individuals had a minor role in the ideation and design of the product (Papad bread), but a dominant role in its production. In contrast, in the case of Shapeways, individuals had a dominant role in design and ideation of new products, but no role in their fabrication.

A comparison of the two figures shows that the studied concepts are not particularly suitable to describe the cases. For example, Shapeways' business model, where individuals are in charge of ideation and design, with the firm taking care of the fabrication (thin boundary in the upper-right corner), does not match the typical use of any of the studied concepts. Concepts in the upper-right corner, such as prosumption and personal fabrication, typically also have the fabrication taken care by the individual. As a further example, Lijjat Papad's example of individuals concentrating on fabrication (thick boundary in lower-left corner) does not match concepts in the same corner. The concepts in this corner, such as mass customization and distributed production, are typically used with the idea that fabrication is handled by companies. However, comparing the two figures can also identify novel real-world manifestations of the concepts. For example, Fabbly provides a version of personal fabrication and prosumption that is facilitated by a corporately owned platform.

Electricity generation is an interesting case for distributed production because it allows for inverted trade, not only because the product is highly standardized but also because the existing logistics chain requires only minimum changes to invert the directionality. With consumer goods, such an inversion would generally be impossible. The dynamics that result from such invertibility are interesting and are beyond the scope of the concepts used for distributed service and content production. With the Kumpula solar energy project, the direction and volume of trade vary freely from moment to moment, depending on weather conditions. However, financial compensation is calculated on an hourly basis, which means not only calculating the net amount of energy traded within that hour but also determining which party is the buyer and which party is the seller. In some way, the participants in the project are continuously prosuming, i.e., producing at least a part of their own consumption. Conversely, they are not shying away from being "traditional" consumers, flexibly buying any additional energy that they might need. Nonetheless, there is more complexity to this model than the mere ambiguity between prosumption and consumption: when the weather is favorable, the individual solar panel systems begin producing more energy than what is needed in the house, and this excess energy is traded to the electric company. Technically speaking, from the perspective of the electric company, this inverted trade is similar to crowdsourcing. However, it lacks

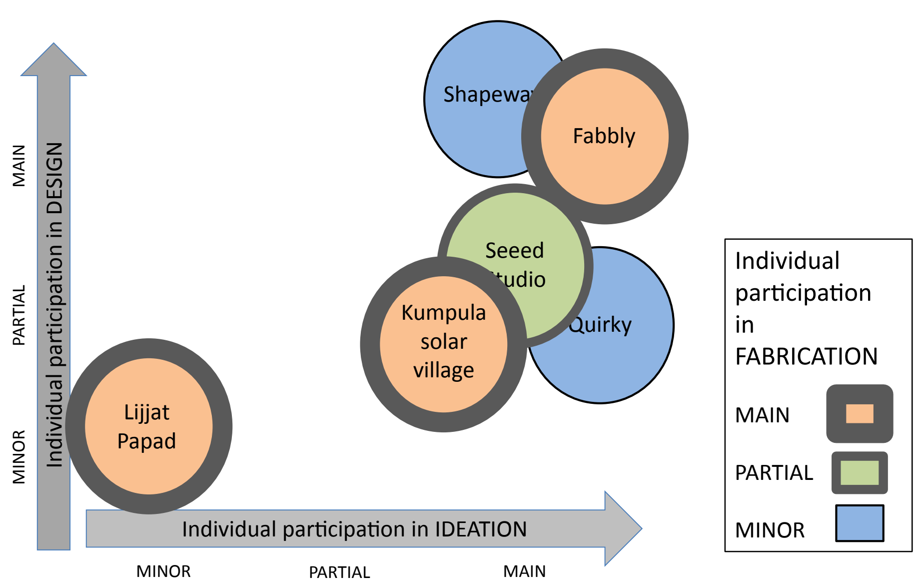

Fig. 2. The six sample cases mapped based on the individual participation in the production value chain.

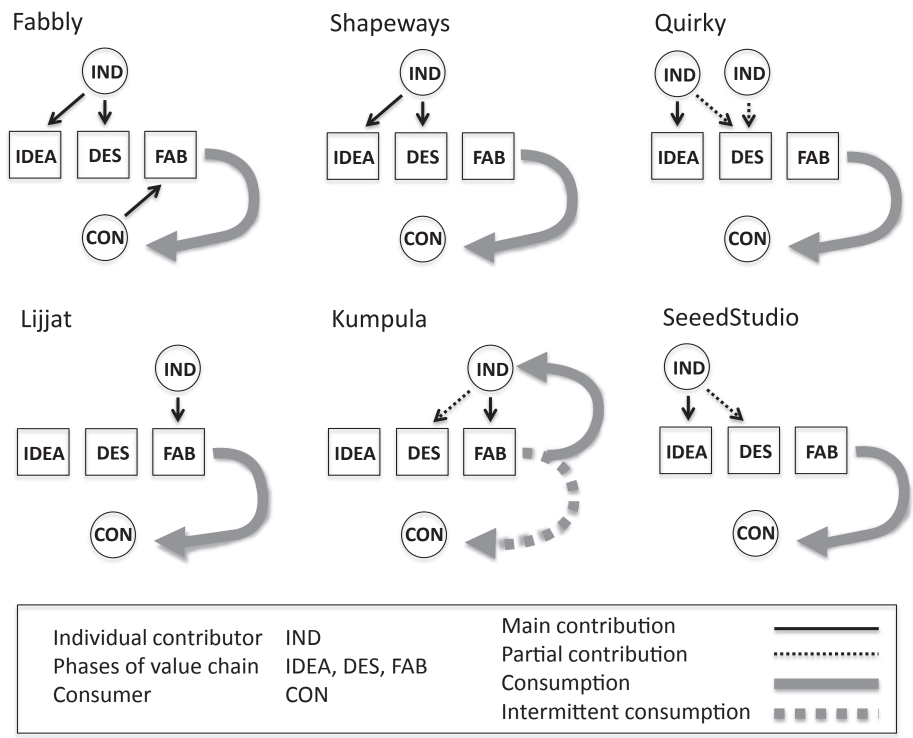

Fig. 3. Elaboration of individual contributions and consumption within each case.

the exploitative undertone that often inheres with crowdsourcing.[6] The electric company pays fair compensation for the product, and the price is defined based on the Nord Pool Spot power market by subtracting a margin of 2% from its hourly rate.

A more detailed presentation of individual participation in all six cases is given in Fig. 3. Major contributions coming from an individual are shown with a solid black arrow pointing to various phases in the value chain where the contribution takes place. When the contribution is partial, the arrow is dashed. In addition to the information included in Fig. 2, Fig. 3 also shows the consumption of the final product and the idea that two or more individuals can contribute to the same system in different ways.

3.2.2. *Properties of social manufacturing*

Upon cursory observation, Quirky, Shapeways, and Fabbly.com have such obvious similarities in their services that it might even be argued that they have too much overlap to provide good data for a comparative study. However, a closer analysis reveals striking differences in the structure of their value chains. Whereas the product ideas at Quirky, Shapeways, and Fabbly.com derive from private individuals whose peers then later become end-users, there are significant differences between the levels of cooperation and locus of agency between these two “endpoints.” In the case of Quirky, the original ideas come from private contributors, but these individuals do not have the final say as to whether a project is taken into production. Instead, Quirky reserves the final decision-making rights for itself, although it uses crowdsourcing as a decision-making tool by asking users to vote for their favorite products. Furthermore, the work in the design phase is performed largely by professionals working for Quirky, although crowdsourcing is used again to obtain comments from potential users. Quirky handles the fabrication phase by hiring appropriate contractors based on product design and technology.

From the point of view of private contributors, the concept provided by Shapeways is decisively different from the one upon which Quirky is built. On one hand, the individual who approaches Shapeways has no uncertainty regarding whether his or her vision will be realized. On the other hand, the responsibility for R&D and design remains with the individual who must provide a readily printable 3D file of the product.

Fabbly.com goes one step further regarding the intensity and agency of private contributions by handing over to individuals the actual fabrication of the end products and by withdrawing from the actual business transactions; these processes are undertaken by the individual sellers and buyers. In so doing, Fabbly.com becomes a marketplace that is not very different from a flea market in which the organizer rents out spaces for sellers to bring their own tables and merchandise. Shapeways, Quirky, and Fabbly demonstrate different ways and levels of interplay between private contributors. Whereas with Shapeways only one individual contributes to the production of a particular product, with Fabbly the consumer becomes an active participant in fabrication, and with Quirky multiple individuals cooperate during the ideation and design. We code this variation as *multilateral participation*.[7]

Not all manufacturing is similar to 3D printing (i.e., easily

[6] Jeff Howe began his seminal article “The rise of crowdsourcing” (2006) with an example of an organization saving over 99% of costs by canceling a deal with a professional photographer and using the crowdsourcing platform iStockphoto instead. The article ended with an example of a company that formerly paid 2000 dollars per job to contractors who wrote software repair flows for them. After switching to crowdsourcing, they paid 5 dollars per job to individuals who had “quit their jobs to raise their kids” and “were happy just to put their skills to some use.”

[7] This property of social manufacturing is congruent with the "degree of collaboration” that Piller et al. (2010) suggested as one characteristic for co-creation with customers, further explicating that it can take place either within firm-customer dyads or within networks of customers.

reducible to small-scale and fully automated production technologies). Even in fields that are not so easily scalable, such as the manufacturing of different types of electronic gadgets, new models of cooperation are emerging that demonstrate increased roles played by individual contributors. Here, it is insightful to observe the transition from the Quirky model to that provided by SeeedStudio, which is building a bridge between small-scale "fab labbing" and industrial mass production. As opposed to Quirky, at SeeedStudio the innovator is "the king" because his or her idea will be realized by the firm without any additional rounds of assessment or other hurdles. However, as with Shapeways, this agency comes with increased responsibility: the individual must deliver a functioning prototype. Although SeeedStudio facilitates the building of prototypes by offering modularized electronic components backed up with information and code sharing by a peer community, it is ultimately the responsibility of the individuals to demonstrate, with prototypes, the functionality of their product ideas. We coded the different levels of agency for contributing at different phases of value chains within SeeedStudio, Shapeways, Quirky, and Fabbly as *inclusion through self-selection*.

As Quirky, Shapeways, Fabbly.com, and SeeedStudio resemble one another in that they all involve developing unique ideas into novel products, the Kumpula solar energy project and Lijjat Papad are alike in the sense that they present the distributed production of a highly standardized product. Of these two, Lijjat Papad offers less agency to individual contributors who are not very different from paid in-house employees in other organizations in which wages are based on work performance, although in Lijjat's case they can freely choose their daily workload. The Kumpula solar power project, however, represents a much more flexible example of cooperation between a firm and individuals, in which both parties can shift flexibly from buyers to sellers, and vice versa. If they so prefer, individual homeowners might begin storing their own production instead of selling it to electric companies. Although gaining complete independence from electric companies would be difficult in Finland's climate (even with advanced battery systems), achieving such independence would be possible in many other areas of the world. Alternatively, an electric company might choose not to purchase the "home-generated" electricity, perhaps as a strategic move to discourage competitive production. However, the electric company in Helsinki willingly cooperates with this pioneering group of private solar energy producers, seeing it as an alternative resource trove that comes with plenty of goodwill for their public image, and private producers gladly seize the opportunity to sell their excess production rather than make costly investment in battery technology.[8] We coded the varying levels of contribution and possibility for inverted trade between the organization and the individual as *expansive prosumption*.

The three properties that we suggest – inclusion through self-selection, multilateral participation, and expansive prosumption – have not been explicitly included in the existing literature on social manufacturing. However, these properties of social manufacturing have direct implications for how sustainability research in this area should be conducted. The level of inclusivity is tightly coupled with the social aspect of sustainability, addressing aspects such as meeting needs and increasing equality. Additionally, the phases in which individuals are contributing can have different effects on the environment, e.g., whether it is design or fabrication or both that come from individuals. Multilateral participation of many individuals also has a social connection because it can lead to stronger communal ties. It can also have ecological outcomes, when sub-groups of individuals with different environmental orientations cooperate, possibly adopting the preferences of one sub-group as a dominant approach. Finally, including expansive prosumption as one of the properties adds the important time aspect to the framework, emphasizing that the level of sustainability reached at any one point in time may soon change to something else.

Combining these three empirically discovered basic properties with the two aspects that we elicited conceptually from the literature review, we suggest the following definition for a social manufacturing framework:

Social manufacturing is a form of physical production in which one or more individuals contribute to the process in any of the phases of ideation, design and fabrication. The contributions of individuals can vary in their intensity and significance, from providing minor inputs to being partial or main contributors. Furthermore, each individual can operate by him/herself or in cooperation with organizations or other individuals. The participation in social manufacturing is inclusive, multilateral, and expansive, meaning that individual participants may self-select themselves into the process, that they may collaborate not only with organizations but also with other individuals, and that their roles can change dynamically from consuming to producing and back.

An illustration of the social manufacturing framework is provided in Fig. 4.

4. Discussion

There is a lack of research into the sustainability impacts of distributed production (Kohtala, 2015), of which social manufacturing is a part. The implications for social sustainability are particularly understudied (Chen et al., 2015), although recent research suggests that new production technologies and individual participation in production could have much to offer, since they support the formation of online communities that build on fairness and reciprocity (Van Holm, 2015; Wolf and Troxler, 2016), and since they offer new opportunities for marginalized populations and countries (Chen et al., 2015; Browder et al., forthcoming). We argue that one reason for the absence of such research is that the existing sustainability analysis frameworks, i.e. the tools for doing sustainability analysis studies, are generally constructed for studying firm-centric forms of production. In this section, we attempt a partial remedy by answering our fourth research question, How can the social manufacturing framework be applied to commonly used sustainability analysis frameworks that were originally designed for firm-centric analysis in order to make them applicable to analyzing participation of individuals in production?

We have selected three existing sustainability analysis frameworks or methods for closer observation. These frameworks are *life cycle assessment*, *international sustainability analysis taxonomy*, and *sustainability reporting*. These approaches emphasize different levels of analysis, and thus constitute a rich sample for the application of our social manufacturing framework.[9]

Life cycle assessment is an internationally standardized method used to estimate the emissions, resource use, and environmental and health effects of a particular product or service (see, e.g., Kreiger et al., 2014; Moro Piekarski, Mendes da Luz, Zocche and De Francisco, 2013; Welz et al., 2011). Specific emphasis is given to

[8] In the case of the Kumpula solar power project, the payback time of an investment in the Tesla Powerwall system was calculated to be over 20 years, which makes it impractical for a private individual, particularly when the limited lifetime of battery technology is considered.

[9] Further sustainability analysis tools can be found in Chen et al. (2015).

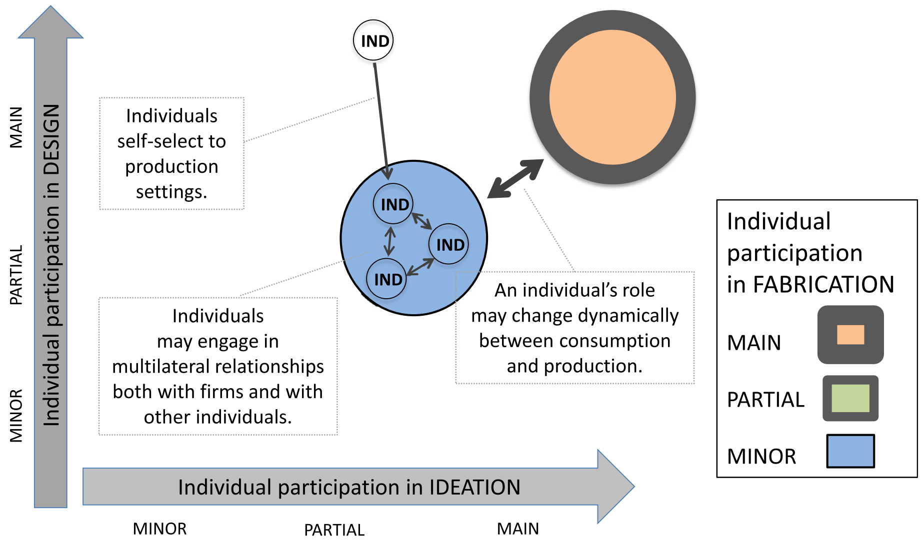

Fig. 4. Social manufacturing framework.

covering the whole temporal span of production effects, beginning with the extraction of raw materials all the way to the disposing and recycling of end products.

Sustainability reporting, in contrast, is typically used on the level of an organization. In their empirical paper, Lozano and Huisingh (2011) developed comprehensive guidelines for assessing and reporting organizational sustainability. Building on Lozano's (2008) holistic perspective, which includes both the traditional environmental, social, and economic dimensions, as well as a time perspective, Lozano and Huisingh inducted an additional category by analyzing the sustainability reports of three organizations. This new “inter-linked category” includes the relations of issues both within particular dimensions (environment, social, and economic) and between two or three different dimensions.

International sustainability analysis taxonomy, as suggested by Olsen and Fenhann (2008), goes one level higher still, giving guidelines for assessing sustainability on a country level. Their integrated conceptual framework is designed to help reach the dual aim of achieving sustainable development in developing countries and simultaneously reducing greenhouse gases in developed countries. The framework classifies possible benefits of sustainable development by organizing them in several subcategories depending on whether they relate to environmental, social, or economic aspects.

Our suggestions for modifying these three methods or frameworks — life cycle assessment, international sustainability analysis taxonomy, and sustainability reporting — are guided by what we have learned about social manufacturing, giving special attention to its central properties: inclusion through self-selection, multilateral participation, and expansive prosumption. In Table 2 we present the central dimensions of each of the three frameworks and the related modifications suggested by the social manufacturing framework. In the table, we refer to several sources in the sustainability literature that relate to practices, mindsets, and technologies in the context of personal fabrication and distributed production. We introduce this literature here shortly. In their recent study, Kohtala and Hyysalo (2015) showed that the maker movement appears to have two sub-cultures, one pro-environmental and the other more oriented to new technologies. We suggest that this dichotomy has significant implications in the social manufacturing context, where individuals from these sub-cultures may self-select to participate in production with a particular organization. The possibility for multilateral participation through direct or indirect cooperation between contributing individuals makes the situation especially interesting. What happens when these two sub-cultures cooperate in social manufacturing? In Table 2 we make several suggestions for studying this interesting composition.

However, individual participation in production can have sustainability outcomes even without participants' explicit sustainability considerations. By studying the textile and clothing industry, Niinimäki and Hassi (2011) suggested that even more limited forms of individual participation, such as customization and personalization, can lead to deeper product attachment and a longer product lifespan. Moreno and Charnley (2016) went one step further along the timeline and examined the reuse and refurbishment of used products. Their review of the literature shows that this possibility has been approached mostly from the corporate perspective, but we perceive that this kind of cradle-to-cradle approach might be further empowered through the participation of private individuals in the production process. Furthermore, we argue that the effect of increased individual participation should also be considered when assessing the sustainability outcomes of new manufacturing technologies, such as 3D printing. In their integrative sustainability assessment of this emerging technology, Ford and Despeisse (2016) note that 3D printing holds promises for sustainability, e.g., through recycling of materials and manufacturing products only if and when they are needed. The context of social manufacturing might pose specific problems, however: different sub-groups may have different interests in recycling, and, for some, it could be easier to reprint a product each time it is needed. Ford and Despeisse also introduced the interesting case of the 3D Hubs network, which shares the capacity of printer owners, many of whom are prosumers. They anticipate that “ill-defined roles and responsibilities could result in conflicts and incompatibilities.” This relates closely to the multilateral participation in the social manufacturing framework, and in Table 2 we elaborate the possibility of incompatibilities from many angles. On the other hand, a recent study of 3D Hubs by one of us and a colleague (Hamalainen and Karjalainen, 2017) showed that the collaboration between firms and individuals can also follow a positive dynamic of deepening collaboration.

Table 2
Summary of how sustainability analysis frameworks could be modified as informed by social manufacturing framework.

Sustainability analysis framework	Dimension	Social manufacturing impact
Life Cycle Assessment	Extracting and preparing raw materials & Composition of machinery in fabrication	Inclusive: There may be individuals with different attitudes towards ecological issues; they might prefer to use different kinds of materials (Kohtala and Hyysalo, 2015). Which groups does this particular organization attract? Expansive: Is there a lot of variation in the participation, i.e. can similar products have significantly different footprints when participation comes from different groups of individuals?
	Use	Inclusive: Is there more product attachment due to individual participation, and does this postpone product replacement or enable reuse? (Niinimäki and Hassi, 2011; Moreno and Charnley, 2016)
	Recycling	Inclusive: What is the sustainability orientation of individual participants (Kohtala and Hyysalo, 2015), e.g. are they open to recycling 3D printing materials, or using 3D for remanufacturing instead of new production? (Ford and Despeisse, 2016) Multilateral: Does individual cooperation during production create a culture of sustained use?
International sustainability analysis taxonomy	Environmental benefits	(included in life cycle assessment)
	Social benefits (health, welfare, learning, employment)	Inclusive: Many contributing individuals could be working outside of the firm walls. What are their working conditions? The idea of employment through jobs should be updated. What is the activation level of the population, when, in addition to traditional employment, self-selected contributions also are taken into consideration? Multilateral: The idea of learning through formal education should be updated. For participating individuals, how do peer networks enable and inspire learning?
	Economic benefits (growth, energy, balance of payment)	Inclusive: In social manufacturing growth is not based only on organizational strategies but also on emergence. How open are the organizations to new ideas and work contributions coming from self-selecting individuals? Multilateral: To what extent do the individual participants share a growth mindset? Expansive: How volatile is the individual participation in organizations? Do individuals remain active contributors in a maturing project that moves from exploration to exploitation phase?
	Other benefits (sustainability tax, corporate social responsibility)	Inclusive: Is sustainability tax collected and used in a way that supports sustainability development when individual participants are a significant part of the system? Is the tax used to support corporate social sustainability activities in a way that emphasizes the importance of the individual participants?
Sustainability reporting	Relations within economic dimension (e.g. exceeding customers' expectations leading to higher dividends)	Inclusive: A broader stakeholder approach is necessary. How do customer satisfaction and profit-sharing relate to monetary and non-monetary payoffs to individual participants? Expansive: How do changing levels of contribution from individuals affect profitability? Is inverted trade possible within the organization and, if so, how does it affect customer satisfaction and profitability?
	Relations within environmental dimension (e.g. increased energy efficiency leading to reduced emissions)	Inclusive+Multilateral: Some of the individual participants are environmentally oriented while others give more emphasis to technology (Kohtala and Hyysalo, 2015). How do the orientations of one group affect the attitudes and behavior of the other group? Does the tech group over time assimilate environmental values, or does the opposite happen? Are there lock-in effects: can the choices made by tech individuals prevent attention to the environmental considerations of others, or conversely, can earlier environmental choices guide technologically oriented participants also to follow sustainable procedures? Or is there a possibility of incompatibility between the participants, which might hamper the whole organization? (Ford and Despeisse, 2016)
	Relations within social dimension (e.g. employee training leading to increased safety)	Inclusive+Multilateral: When private individuals are participating in production, there is increased need to pay attention to safety issues. However, an organization has less fiat over individual participants than it has over its employees, hence top-down training may not work. What is the organization doing to improve the safety orientation and skills of the participants? Is safety part of the peer culture among the participants?
	Relations between economic and environmental dimensions (e.g. eco-efficient solutions leading to cost savings)	Inclusive: Do individuals have a say in the importance of environmental considerations, as compared to making profits? Multilateral: Could frugality become an element in the organizational culture that connects environmentally and technologically oriented individuals? (Kohtala and Hyysalo, 2015)
	Relations between environmental and social dimensions (e.g. respecting local communities and local and global environment)	Inclusive: To what extent is participation open to all individuals in the community, and how could barriers to entry be reduced? Are the individuals' practices being environmentally assessed? Does the organization have a plan to develop such assessments? Multilateral: Is the participation of multiple individuals contributing to the resilience of the community by strengthening its ties?
	Relations among all three dimensions (e.g. accidents and remediation)	Inclusive: With individual participants, major productive contributions may take place outside company walls. Is the organization keeping count of accidents? Are the extra-mural individuals insured? Multilateral: Do the participants share a culture of safety?

5. Limitations and future research

The case study methodology of our empirical study prevents us from assessing the larger question of whether there is a general trend toward increased individual contributor participation and agency at different levels of the manufacturing value chain. That is, although opportunities for social manufacturing have multiplied due to development of novel manufacturing technologies and business models, we did not attempt to address the extent to which this growth is actually being realized. Furthermore, due to the limited number and range of our cases, we cannot claim that we have completely charted out the properties, aspects and dimensions of social manufacturing as they apply to this phenomenon in general, or even to the particular industry types of which our cases were examples.

What these cases do show, however, is that new types of business models are becoming *available* in the manufacturing field, and, based on the dramatic changes that similar models have induced in the service industries and in content production, this is a phenomenon that should not be ignored.

Future research should address whether there is a more general trend toward individual participation in manufacturing, as exemplified in the cases that we studied. Furthermore, the properties of such participation should be elaborated by more thoroughly investigating specific industry areas. It is also necessary to assess empirically the environmental sustainability outcomes of these models, as Kohtala and Hyysalo (2015) have urged.

Our study provides a tool to be used in such future assessments, but the empirical part of our study was not sufficiently extensive to hazard any estimates regarding the sustainability of social manufacturing. It is noteworthy, however, that some recent research (Hirscher et al., 2018) suggests that diffuse social manufacturing, in particular, could have favorable sustainability implications.

Another question that should be assessed is how social is social manufacturing? In particular, research should address such questions as: How are profits shared between an organization and the participating individuals? Does work get less communal as people move away from employment to becoming independent contributors, possibly working through social platforms but without any direct contact with other people?

Our mapping of existing terminology on distributed production, presented in Fig. 1, also suggests that this terminology does not "evenly" cover all the different combinations of individual participation, among the phases ideation, design, and fabrication. In particular, significant individual participation in fabrication seems to be conceptually locked into the "upper right corner," which is populated with terms that emphasize individuals taking care not only about the fabrication, but also about ideation and design. It could be useful to study and conceptualize the sustainability implications of cases in which individuals take care of fabrication but leave ideation and design to organizations, or in which individuals help firms both design and fabricate their products. An example of the former was provided by one of the cases in this study, Lijjat Papad, as a form of modern cottage industry. The latter could be exemplified by 3D Hubs (Hamalainen and Karjalainen, 2017), where private individuals share their 3D printing resources and also provide design services.[10]

6. Conclusion

Despite increasing opportunities for private individuals to participate in physical production, scant research has been conducted on the sustainability of these practices. In this paper, we argue that specific barriers have restrained sustainability research in this area. We have identified two such barriers, relating to terminological multiplicity and to firm-centricity of available analytical tools. To overcome these two barriers we build a social manufacturing framework in two steps, first with a conceptual literature study, and then with an empirical case study of six organizations. We suggest a new definition for the emerging concept of social manufacturing, by observing (1) that individual participation can happen in any of the phases of ideation, design, and fabrication, (2) that the level of this participation can vary from minor to major, and (3) that individual participation can be inclusive, multilateral, and expansive. We then use this social manufacturing framework to organize the terminology for individual participation in distributed production, hence improving the cross-term applicability of sustainability research in this area; we also modify three sustainability analysis frameworks to make them better suitable to studies of such individual level phenomena.

While individual participation in manufacturing is not new, recent examples from service and content production have shown that the combination of individual participation with the availability of the Internet and digitally enabled tools can quickly revolutionize whole industries. With manufacturing, however, the sustainability effects of this change are likely to be significantly greater – for better or worse. In this study, we have attempted to provide sustainability researchers and practitioners with preliminary tools for assessing and managing the change process. By making future investigation in this area more accessible, our work contributes to both sustainability research and to emerging research on social manufacturing.

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Appendix A. Case descriptions and secondary data sources

SeeedStudio is a Chinese-founded company based in Silicon Valley. It began its operations in 2015 and provides support to individual makers in three different ways. First, it offers modularized and easily programmable plug-and-play electronic components that makers can use to build prototypes of various products. Second, it offers a platform through which a peer community can share ideas and support. Third, SeeedStudio offers productization services to turn the prototypes into actual products that are suitable for production. Further, SeeedStudio will then manufacture these products in flexible batch sizes.

Secondary data sources:

https://www.seeedstudio.com.

https://theblueprint.com/stories/eric-pan.

Shapeways is a New York-based 3D printing service and marketplace that allows individual makers and designers to upload their 3D specifications files and then either print them for themselves or make them public for others to buy. In either case, Shapeways prints the products and ships them to users. The designer is compensated when others buy the product. Shapeways began its operations in 2007 as a spin-off of Royal Philips Electronics.

Secondary data sources:

(Wirth and Thiesse, 2014)

http://www.shapeways.com/terms_and_conditions.

http://www.shapeways.com/terms_and_conditionshttp://

[10] An extensive list of 3D printing platforms is presented in Rayna et al. (2015).

www.shapeways.com/how-shapeways-works.

https://helda.helsinki.fi/bitstream/handle/10138/157808/scarabattoli.pdf?sequence=4.

https://en.wikipedia.org/wiki/Shapeways.

Interview on June 2nd, 2015 around the theme "Intellectual property rights and design in Shapeways".

Quirky is another New York-based company that offers product development and manufacturing supported by peer networks. Individuals suggest their product ideas to Quirky, who then introduces them to the public through their webpage and via social media. Using peer voting, Quirky then selects the most promising products and develops them into actual products, with potential users reviewing the process online and contributing to that process. As a final step, Quirky then subcontracts the manufacturing and sells finished products to users. The originator of the idea is compensated for each unit sold. Quirky filed for bankruptcy in September 2015, following six years of operation. The company relaunched in May 2016.

Secondary data sources:

(Wu et al., 2013)

https://www.quirky.com/terms-of-service.

https://www.quirky.com/terms-of-service.

http://www.inc.com/christine-lagorio/what-happened-to-quirky.html.

http://www.theverge.com/2015/4/24/8488531/quirky-invention-powered-by-quirky.

https://en.wikipedia.org/wiki/Quirky.

Fabbly.com is a German company based in Munich that offers a marketplace for buying and selling 3D print files. Unlike Shapeways, it does not participate in actual production; instead, the physical objects are 3D printed by individual customers. The transactions take place directly between individual 3D file sellers and buyers, with Fabbly.com charging the seller a transaction fee equal to 5% of the item's price. The company launched in May 2015.

Secondary data sources:

http://3ddeconference.com/market/fabbly-launches-online-3d-printing-template-market-gains-national-attention/

http://www.fabbly.com/pages/fees.

http://www.fabbly.com/pages/tos.

Lijjat Papad is an Indian cooperative organization that manufactures consumer goods – bakery items, in particular. It is India's largest manufacturer of papad, a round and crispy flatbread. An essential part of the organization's culture is that every woman who wants to join is welcome. The organization employs approximately 43,000 women who work in their homes using raw materials provided by the cooperative. In the case of papad breads, the cooperative provides the women with dough each morning and then collects the finished products in the evening. Compared to the other cases described in this study, Lijjat Papad is much older, as it was founded in 1959.

Secondary data sources:

http://www.rediff.com/money/2005/apr/15spec.htm.

http://www.wipo.int/ipadvantage/en/details.jsp?id=3619.

http://www.pcr.uu.se/myrdal/pdf/Malathi_Ramanathan.pdf.

https://en.wikipedia.org/wiki/Shri_Mahila_Griha_Udyog_Lijjat_Papad#cite_note-25.

The Kumpula solar power project is a local initiative in an environmentally aware neighborhood in Helsinki that currently includes 20 households who have installed or are installing solar panels on their roofs. The excess electric power that is not used by the homeowners is directed to the power grid and sold to the local electric company. The project began in 2014, when the participants planned their individual solutions together with a consultant. The first solar panel systems were installed and connected to the power grid in March 2015.

Secondary data sources:

http://www.sahkoala.fi/koti/aurinkoenergia_ja_tuulivoima/fi_FI/kumpulan_aurinkopaneelit/

http://www.fortum.com/en/mediaroom/pages/fortum-to-deliver-solar-power-plant-for-finnish-meteorological-institutes-site-in-helsinki.aspx.

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