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Supporting Sustainable Product-Service System Implementation through Distributed Manufacturing

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Abstract

Despite the potential of Product-Service Systems (PSS) to provide societal and economic well-being and environmental sustainability, they have not been widely implemented. The adoption of sustainable PSS is restricted by a number of implementation barriers linked to organisational, cultural and regulatory challenges. There are some initial yet still very fragmented attempts to support sustainable PSS development through the application of Distributed Manufacturing (DM). Distributed Manufacturing is a production network made of small scale manufacturing units equipped with emerging technologies, which facilitates localised customer-oriented production. This paper aims to fill the knowledge gap and identify the potential to build a systematic analysis for DM-supported PSS development. In order to understand to what extent DM can address some implementation barriers of sustainable PSS, existing PSS barriers and potential DM opportunities were collected. All DM opportunities were applied to each and every one PSS implementation barrier. Most promising pairings were described in initial scenarios. The implications from this research showed that a number of obstacles related to design, development and customer acceptance of PSS can be potentially tackled through the application of DM.

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Keywords: Product-Service System; Distributed Manufacturing; Additive Manufacturing; Localised Production; Customisation

1. Introduction

Properly designed Product-Service Systems (PSS) have the potential to fulfill the needs of customers and provide a competitive advantage for companies, and at the same time reduce resource consumption and lower the environmental impact [1,2]. However, despite all the benefits and drivers, sustainable PSS have not been widely applied [3]. Successful adoption of PSS is affected by a number of implementation barriers related to corporate structures, customer behaviour and regulatory frameworks [4]. In order to facilitate the adoption of sustainable PSS, ways to address these barriers must first be identified.

Distributed Manufacturing (DM) is introduced in this paper as a promising production model to tackle some of the implementation barriers of PSS. DM can be described as a production system where small scale local manufacturing and personalisation of products and services are enabled by emerging technologies [5-7]. Existing attempts to combine PSS and DM can be found in the literature [7,20-24], however, a systematic analysis of how PSS barriers can be addressed by DM is missing.

In order to fill this gap, this paper offers an initial attempt to understand to what extent DM can potentially address some implementation barriers of sustainable PSS. The paper is structured as follows: Section 2 presents literature review findings regarding PSS implementation barriers and potential DM opportunities. Section 3 describes the methodology adopted in this research. Section 4 presents findings and provides initial scenarios of how DM opportunities can tackle PSS implementation barriers. The final section outlines the potential usefulness of the findings and suggests future research.

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2. Literature review

A literature review was carried out in order to identify main implementation barriers of PSS and DM opportunities, and to summarise existing attempts to apply DM to PSS development made by other authors. Scopus was used to locate sources containing the following keywords: *Product-Service Systems, Barrier, Distributed Manufacturing* and *Localised Production.*

2.1. Implementation barriers of sustainable PSS

In total, 49 papers dedicated to PSS were reviewed, of which 22 contained sections about PSS implementation barriers. All of these sources were analysed in a chronological sequence in order to collect a broad range of barriers, identify the ones which are outdated and focus on those which are still relevant to modern businesses. Only barriers identified in early sources and validated in more recent studies are presented in this paper. All selected barriers can be described according to three categories: barriers for companies, barriers for customers and regulative barriers.

One of the most crucial barriers faced by companies is the adoption of a service-oriented culture within the organisation [4,8,9]. In general, companies lack of the knowledge to design, price and deliver a competent PSS [2,4]. Another set of barriers is related to collaborating with a number of partners along the value chain: co-dependence causes fears linked to reduction of core competencies and sharing of confidential information about internal organisational procedures [1,4,10]. Complicated customers' purchase and service acceptance behaviour is another obstacle that prevents companies from implementing PSS solutions [11].

For some product categories customers find it challenging to accept PSS offerings because of the lack of knowledge about the overall PSS concept and anxiety caused by not knowing what to expect [4,11,12]. Customers believe that product ownership is related to social status and achievement in life encourages them to adopt product-oriented solutions [1,4,11]. Concerns linked to independence, hygiene [11] and hidden costs [4,12] of the use of shared products also play a role in preventing customers from accepting PSS offerings.

The final group of PSS implementation barriers is related to the lack of sufficient governmental interventions to encourage environmentally aware business development [13, 14]. PSS innovations are not supported by financial institutions and often experience prolonged time to market [4,15].

The focus of this paper is set on PSS barriers for companies and customers. Regulative barriers are considered not being able to be influenced by PSS companies and not suitable to be tackled through the application of DM in this paper.

2.2. Characteristics and definition of DM

In order to define the characteristics and to formulate the working definition of Distributed Manufacturing (DM), 31 papers describing the concept were reviewed.

DM has been analysed since the early 90's and characterised as *downsizing*, companies' separation into smaller-size independent units and *outsourcing*, purchasing services from external partners [6,16]. More recent sources introduced the importance of technology for manufacturing systems to become distributed: heterogeneous hardware and software, which facilitate communication within the company and with partners [17]. Communication between dispersed manufacturing units and all supply chain actors is essential for DM to operate [16,17]. Comprehensive communication and close factory proximity to the end user allows companies to develop make-to-order manufacturing models [16].

Taking into account the main characteristics of DM, the working definition of the concept has been summarised: *Distributed Manufacturing is a production system made of small scale manufacturing units equipped with physical and digital technologies, which enable localisation of manufacturing facilities and comprehensive communication between all supply chain actors in order to facilitate customer-oriented on-demand production.*

2.3. Opportunities of DM

According to existing literature, DM has the potential to provide opportunities for companies, customers and social and environmental sustainability.

Resilience of manufacturing companies is the principal opportunity named by a number of authors [6,16,18]. Localisation of small-scale manufacturing units enables companies to alter their production processes in case of changes in market needs [6,18]. Application of digital technologies, introduced to facilitate collaboration between manufacturing units, allows companies to monitor, control and optimise stock and material flows [6]. Combination of software and hardware enables digital file transfer and production of goods to be carried out in dispersed geographic locations using local resources [6].

One essential DM opportunity for customers is improved personalisation of products and services [6,16,18,19]. This is caused by localisation of production facilities and customer involvement into product development in person and through the internet [6]. This type of involvement brings the potential for companies to better identify the needs of customers and to produce goods on-demand [6].

DM has the potential to address some of the social and environmental issues related to mass production [5]. Using Just-in-Time strategies for small-scale manufacturing of products only when required by customers helps to avoid waste and reduce the burden of a large inventory [18]. Distribution of digital production facilities enables products and spare parts to be produced at the point of consumption which reduces transportation distances and lowers the environmental impact [6,20].

A more detailed description of DM opportunities that show the potential to address implementation barriers of PSS is provided in section 4.

2.4. Existing DM application for PSS development

Potential applications of DM to sustainable PSS development were identified in 6 papers. All these sources can

be divided into two categories: DM for customisation and DM for product life extension.

In the first category three papers [21-23] present DM as a promising model to enable PSS companies to meet specific requirements of each customer. Personalisation of service-oriented offerings can be obtained through localisation of manufacturing units and customer involvement into design processes [22].

The second category of three papers [7,20,24] highlights the DM potential to prolong life cycle of products involved in PSS solutions. This can be achieved through simplified product repair and re-manufacturing enabled by Additive Manufacturing. Companies such as Caterpillar, GE, Siemens and Rolls-Royce have already employed Additive Manufacturing to facilitate the provision of PSS offerings [20].

However, the attempts to support PSS development through DM are still very fragmented, with a focus on only two features of DM. All the sources are dedicated to the DM topic and none of them focus on the issue from a PSS perspective. Moreover, there is a lack of practical approaches for validation of findings. Limitations of existing literature mean that there is a need for a comprehensive and systematic knowledge about potential DM application to better PSS development.

3. Methodology

The methodology presented in this section describes research activities that were carried out to collect most up-to-date knowledge about Distributed Manufacturing opportunities. This section also outlines the approach used to formulate the findings of this paper.

3.1. Expert interviews

Expert interviews were carried out in order to validate the literature review findings and collect the most recent knowledge regarding opportunities and limitations of DM.

Ten interviews were implemented with participants selected on the basis of their expertise in various areas within the field of DM. Eight interviewees were academics with a proficiency in Additive Manufacturing (I1), sustainable food production (I2), personal fabrication in makerspaces (I3), digital technologies (I4), data-driven innovations and circular economy (I5), micro and self-production (I6), sustainable manufacturing (I7) and factory operations (I8). Two industry experts demonstrated knowledge in Additive Manufacturing for printed electronics (I9) and open-source sustainable housing (I10). During 2 face-to-face and 8 *Skype* interviews experts were introduced to initial literature review findings and asked to agree or disagree with provided information and share their own expertise regarding opportunities and limitations of DM.

The findings from the interviews confirmed that the most promising opportunities of DM named by all interviewees are related to the resilience, speed, flexibility and efficiency of manufacturing processes. Experts also introduced a strong focus on social aspects and described the emergence of DM as a result of changes in society and the need for better customer involvement in production processes [I3,I5-I7,I10]. Most importantly, a number of DM opportunities named by the participants were linked to circularity [I5-I7] and improved product repair and remanufacturing [I1,I5-I7,I10].

Expert interviews helped to identify the potential of DM to facilitate service-oriented offerings and validated the initial hypothesis of the research.

3.2. Distributed Manufacturing research seminar

The Distributed Manufacturing Cross-Network seminar was organised by the academics from Oxford University. It invited researchers from various institutions to exchange knowledge about the main characteristics of DM and ongoing research projects, and to discuss the future research opportunities. Insights collected from the seminar activities were used to validate findings from the literature review and expert interviews and update already gathered information with most up-to-date knowledge.

The seminar findings can be summarised to three main opportunities regarding DM. Firstly, an adoption of DM provides companies with new business opportunities caused by the integration of novel business entities in existing systems. Secondly, DM can potentially reduce consumption of resources and the amount of waste buried in landfill. Finally, DM has the potential to embrace adoption of digital and physical technologies across product life-cycle stages, with opportunity to integrate repair and remanufacturing system components to manufacturing of new products. However, the seminar participants agreed that each case where it is planned to apply and introduce DM has to be critically evaluated to avoid unwanted rebound effects.

3.3. Matching PSS barriers with DM opportunities

Data, collected from the literature review, expert interviews and attendance to research seminar was employed to build initial scenarios where DM can be applied to better PSS development. In total, 24 PSS implementation barriers and 55 potential DM opportunities were gathered and analysed. The initial scenarios were generated by applying all DM opportunities to each and every one PSS implementation barrier. The most logical, feasible and promising pairings were identified as DM potentials to address PSS barriers and improve PSS development. The findings of this process are introduced in the following section.

4. Initial findings

This section summarises the research findings into six scenarios, which represent an initial set of near-future scenarios that will be developed during further research. Scenarios presented in this paper provide samples of pairing PSS barriers with DM opportunities. Each scenario describes a specific PSS implementation barrier and provides an overview of how the undesirable situation can be changed through the application of promising features of DM.

The table below provides the summary of 6 PSS barriers, selected for scenario development, 15 DM opportunities

applied to address specific barriers and title of each scenario representing added value.

Table 1. A sample of PSS implementation barriers addressed by DM opportunities.

PSS implementation barrier	DM opportunity
1. Low capital cost of entry to distributed network:	
Lack of financial resources of SMEs to implement and run PSS business models.	Technologies allow digital file transfer and production of products around the world without the need to own a manufacturing unit.
	On-demand production prevents companies from costs related to unsold goods.
	DM-enabled last mile low-emission delivery reduces transportation costs.
2. Close relationship with customers to better know their needs:	
Challenges of companies to define customers' purchase and service acceptance behaviour and develop PSS for a specific local context and culture.	Digital design tools allow customers to create goods they need and to send the production request to a local manufacturing facility.
	Open access workshops allow customers to get involved in product development.
	In-store manufacturing facilities allow companies to develop products on-demand.
3. Simplified product design process and open-source innovations:	
Lack of know-how of designing and developing a product for PSS-oriented use.	Use of Additive Manufacturing encourages the optimisation of product design with focus on end-of-life and less material used at the point of manufacturing.
	DM encourages free open-source libraries where designs of products can be draw from, used and improved by everyone.
4. Personalised parts of products for individual use:	
Concerns of customers related to hygiene of used or shared products.	Personalised products or parts of products can be produced using 3D printing technique in local manufacturing facility.
5. Simple maintenance of products done by customers:	
Concerns of customers regarding their privacy caused by the requirement for PSS provider to access their personal data or even enter into their property.	Sensors applied to products show customers how products are used to optimise consumption and service.
	DM encourages free open-source libraries where designs of products and spare parts can be used by all.
	Self-manufacturing of spare parts available in makerspaces, shops or even facilities at customers' home.
	New community-sharing places, such as repair cafes, co-working spaces and makerspaces help people to learn skills needed to maintain products.
6. Simplified product's end-of-life:	
Lack of external infrastructure for product end-of-life stage including collection, recycling and remanufacturing.	DM enables development of small-scale sites for maintenance and production of spare parts globally.
	Additive Manufacturing enables product re-manufacturing with focus on end-of-life.

4.1. Initial Scenario1: Low capital cost of entry to distributed network

Small and medium size enterprises (SMEs) often have very limited financial resources needed to start production of goods and to implement additional services [25]. High initial investment and financial risks related to a longer period of time that is needed to cover the investment prevent SMEs from implementing service-oriented business models [25].

DM provides an opportunity for SMEs to set up new PSS businesses by being integrated into a bigger value chain. SMEs are able to set up localised service provision facilities and support maintenance of products supplied by already existing successful PSS providers.

When it comes to the manufacturing of products for PSS-oriented solutions, becoming a part of DM network allows SMEs to outsource production services and run manufacturing without owning a factory. This way of organising production enables enterprises to locate manufacturing close to the point of need and to produce products only required by customers. On-demand production reduces overall amount of produced goods. As a result, SMEs are freed from owning warehousing facilities and costs related to storing unsold products. Furthermore, close manufacturing proximity to the point of need ensures reduction of transport and delivery costs.

Integration into DM networks and localisation of manufacturing units provide SMEs with an opportunity to set up PSS business without the large initial investment.

4.2. Initial Scenario 2: Close relationship with customers to better know their needs

Customers' purchase and service acceptance behaviour is complicated and highly under-researched [11], influenced by emotions, beliefs, social status and external drivers [4]. For this reason companies' task of designing and delivering PSS is even more challenging.

Adoption of DM allows companies to design PSS together with their customers. PSS companies initiate digital design libraries and local co-manufacturing facilities to enable

customers to get involved in product and service development processes. Customers are capable to create new or personalise existing products using computer programs and send digital files directly to manufacturers. Fabrication laboratories, so called makerspaces, invite customers to collaborate with PSS providers and build goods with a potential to develop services around them. Manufacturing facilities in stores help companies to fulfill needs of customers by developing bespoke products and services in real time.

An improved relationship between the PSS provider and customer through digital technologies and localised manufacturing facilities enables companies to identify and fulfill real needs of their customers.

4.3. Initial Scenario 3: Simplified product design process and open-source innovations

Product development for PSS-oriented use is different from design of the products for traditional use [10]. Companies find it challenging to meet the requirement to focus on the complete life cycle when designing products for PSS offerings.

Application of Additive Manufacturing technology enables companies to redesign existing products and create new ones with a strong focus on product's end-of-life. Additive Manufacturing allows the production of products that can be easily repaired using additionally manufactured spare parts. Design ideas can be found in open-source libraries available under a Creative Common license. As a result, companies can adapt products created by others to meet the needs of their customers. Open-source libraries can also be accessed by customers who wish to input to product development processes in order to receive personalised offerings.

Technological development and a strong customer-oriented approach enable companies to design more personalised, durable and easy-to-maintain products.

4.4. Initial Scenario 4: Personalised parts of products for individual use

Ownerless access to shared products causes concerns of customers related to hygiene, health and safety [11]. Not being able to control how clean products are, customers find it difficult to adopt the use of shared products.

DM facilities equipped with Additive Manufacturing machines are used to produce personalised products on demand. Customers order parts of shared products which they find unhygienic and unpleasant to handle. When using shared products, customers touch only individually produced parts.

Additive Manufacturing allows customers to personalise shared products and avoid concerns related to health and safety.

4.5 Initial Scenario 5: Simple maintenance of products done by customers

In order to support products involved in PSS offerings, PSS providers need to monitor their performance. This often requires service providers to access to customers' personal information or even enter into their property [10]. Customers, being sensitive to privacy and trust issues, find it challenging to accept such services.

Products involved in PSS offerings are equipped with sensors, which provide customers with the information about product performance and identify the need of maintenance. If something breaks down and a new spare part is needed, the customer can find a digital production file in the open-access library established by the PSS provider. The spare part can then be manufactured in a local production facility, makerspace or even in customers' home using personal manufacturing equipment. Furthermore, fabrication laboratories and other co-working spaces allow customers to exchange skills and knowledge about product repair and maintenance.

Technological development and localisation of manufacturing enable customers to maintain products without the direct intervention of PSS providers.

4.5. Initial Scenario 6: Simplified product's end-of-life

Companies that wish to implement service-oriented business models often face a challenge linked to the lack of external infrastructure and technologies related to product collection, recycling and remanufacturing [1]. Product support at the end of its life is essential for successful PSS.

Geographically distributed localised factories eliminate the need to collect products over long distances. Small-scale manufacturing facilities equipped with Additive Manufacturing machinery can enable the production of spare parts. A global network of this type of factories shares the same technological standards and production files in order to be able to run maintenance and manufacturing of spare parts in real time at the point of need.

Localisation of manufacturing units equipped with digital and physical technologies enables maintenance of products at their end-of-life.

5. Conclusions

The Product-Service System (PSS) is a promising business model that has the potential to bring societal and economic well-being and environmental sustainability. However, a sustainable PSS has not been widely implemented because of the number of organisational, cultural and regulatory barriers. The research described in this paper represents an initial attempt to identify to what extent Distributed Manufacturing can support PSS development.

Twenty four PSS implementation barriers and fifty five DM opportunities were collected and analysed. The samples of promising combinations of DM opportunities addressing PSS barriers were described in initial scenarios. Each presented scenario introduced a specific PSS implementation barrier and provided an overview of how the situation can be improved by applying the promising features of DM. The initial scenarios demonstrated DM potential to support every life cycle stage, relevant to PSS companies, corresponding to early business implementation, understanding about customers, product development, concerns during the use stage and end-of-life.

Additional scenarios will be developed to explore areas for potential development.

Despite all the potential opportunities DM can bring to PSS implementation, there are a number of limitations that need to be considered. Challenges related to application of DM include the high costs of adoption and the need to upgrade of new technologies and provision of employees with technical and design skills [6]. Another group of challenges is related to regulations, legislations, taxation and insurance [18]. Lack of official data-sharing agreements can cause issues with privacy and intellectual property for companies that wish to share their digital designs with customers [6]. There is also a challenge to maintain the quality of products manufactured in geographically dispersed facilities, especially those produced by customers [6]. Finally, a DM network has to be properly designed to avoid negative environmental impact caused by manufacturing processes and distribution.

This research is only a first attempt at systematically applying DM to better PSS implementation. There is a need to develop more comprehensive guidelines on how PSS-oriented companies can adopt DM to their business processes. A close collaboration with PSS and DM companies and experts is needed in order to build applicable and value creating guidelines. Successful DM integration in PSS business processes has the potential to improve the relationship between PSS providers and customers, deliver offerings in real demand and facilitate product maintenance at the end-of-life stage.

Future research should focus on the development of a more comprehensive and detailed set of near-future scenarios and systematic guidelines on how these scenarios can be applied in practice.

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