

A Design Tool to Apply Distributed Manufacturing Principles to Sustainable Product-Service System Development

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The Product-Service System (PSS) concept is considered a promising type of business models that has the potential to couple social, economic and environmental sustainability. However, there are a number of organisational, cultural and regulatory barriers that hinder a wide PSS implementation. The research hypothesis of this paper is that Distributed Manufacturing (DM), described as a network of localised and customer-oriented production units, can be applied to PSS to address some of the previously mentioned barriers. In order to understand to what extent DM can improve PSS implementation, existing PSS barriers were gathered and coupled with collected potential DM opportunities. Most promising pairings were described in a set of near-future scenarios which were later integrated into the first version of the PSS+DM design tool. The first testing of the tool was carried out with 45 design students and initial findings suggest that, with further improvements, the PSS+DM design tool has the potential to support PSS solutions development process.

Sustainable Product-Service System; Distributed Manufacturing; Future Scenarios; Design Tool

1 Introduction

A Product-Service System (PSS) can be defined as an integrated offering of products and services which represent the shift from selling a physical product to providing a system that aims to fulfil a specific customer demand (UNEP, 2002; Baines et al., 2007). An appropriately designed PSS has the potential to provide companies with competitive advantage, and at the same time improve production processes and consumption patterns towards environmental sustainability (Cooper & Evans, 2000; Mont, 2002a). PSS business implementation extends PSS provider's responsibility of the product in all life cycle stages, encouraging reduction of material usage and energy consumption, development of more durable and easy to maintain product components as well as collection of the



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product at its end-of-life, remanufacturing or recycling (Tukker & Tischner, 2006; Beuren et al., 2013). However, PSS implementation requires companies to adopt different ways of managing business processes compared to traditional business models, as a result, creating a number of obstacles for companies to overcome (Besch, 2005). Sustainable PSS business models can be complex to implement because of a number of implementation barriers, related to organisational resistance to change, lack of customer acceptance and lack of appropriate regulations (Ceschin, 2013; 2014; Vezzoli et al., 2015). This paper investigates Distributed Manufacturing (DM) and to what extent this production model can tackle existing PSS implementation barriers. DM can be defined as a network of small scale production units equipped with advanced manufacturing technologies, which facilitate localised and individualised production (Petruilaityte et al., 2017). From this definition three main DM features can be highlighted: *application of physical and digital technologies*, *localisation of manufacturing units* and *customer-orientation*. Application of physical and digital technologies refers to the use of manufacturing hardware, such as Additive Manufacturing or Computer Numerical Control machinery, and data capturing and transferring equipment, such as Information-Communication Technologies (ICT) or sensors (Srai et al., 2015; Rauch et al., 2015). Localisation of manufacturing units describes close proximity between manufacturing facilities and customers or manufacturing resources (Pearson et al., 2013; Matt et al., 2015). Customer-orientation refers to personalisation of products and services according to customer needs (Moreno & Charnley, 2016; Rauch et al., 2015). These features bring certain advantages that can potentially improve PSS development, to name a few: better design, production and maintenance of products, personalised services and closer PSS provider-customer relationship (Matt et al., 2014; Srai et al., 2015; Rauch et al., 2016; Petruilaityte et al., 2017). Through improving PSS business model implementation, DM has the potential to improve sustainable development: to reduce transportation and, at the same time, CO₂ emission; to minimise number of produced goods through personalised and bespoke production, at the same time reducing material usage and waste production; to contribute to social sustainability through employing local communities and sourcing local materials (Ford & Despeisse, 2016; Rauch et al., 2015).

A few scholars have proposed initial attempts to apply DM principles to PSS development (Suominen et al., 2009; Arup, 2015; Despeisse & Ford, 2015; Ford et al., 2015; Moreno & Charnley, 2016; Ford & Despeisse, 2016). However, these attempts are still very fragmented. The literature where DM application to PSS is mentioned focuses on a small number of DM features, mainly describing the potential of customisation and product life extension. All sources being initially dedicated for DM topic do not focus on the issue from the PSS perspective and miss a clear identification of existing PSS implementation obstacles. Authors agree that a systematic in-depth analysis of DM application for improved sustainable PSS development is missing (Ford et al., 2015). In addition, there is a need to translate this knowledge into practically applicable guidelines for PSS designers. This research, framed in a three-year project *LeNSin* funded by the European Union Erasmus+ programme, aims to fill this knowledge gap by answering the following research questions:

- 1) How the features of DM can help to address implementation barriers of PSS?
- 2) How to support a practical application of DM for improved PSS development?

This paper is structured in eight sections. Section 2 presents the methodological framework applied in this research. Section 3 provides an overview of the problem and the list of PSS implementation barriers. Section 4 introduces the potential of prospective DM opportunities. Section 5 details how DM opportunities can address some PSS barriers, and presents the development of PSS+DM near-future scenarios. Section 6 focuses on the integration of the scenarios into the PSS+DM design tool. Section 7 describes the first practical application of the tool and lastly, Section 8 concludes by providing recommendations for future research.

2 Methodological framework

The aim of this article is to identify the potential of DM to address PSS implementation barriers, and to translate these insights into a PSS+DM design tool, to support design practitioners and PSS companies. The methodological framework of Design Research Methodology (DRM) (Blessing & Chakrabarti, 2009) has been chosen to outline the research activities. The DRM provides a plan of action in order to support the development of theoretical knowledge and its practical application. This approach is particularly essential for this research since it frames the development of the design tool and supports the iterative process of testing and revising. Each research stage, with corresponding sections, research activities and outcomes, is presented in Figure 1.

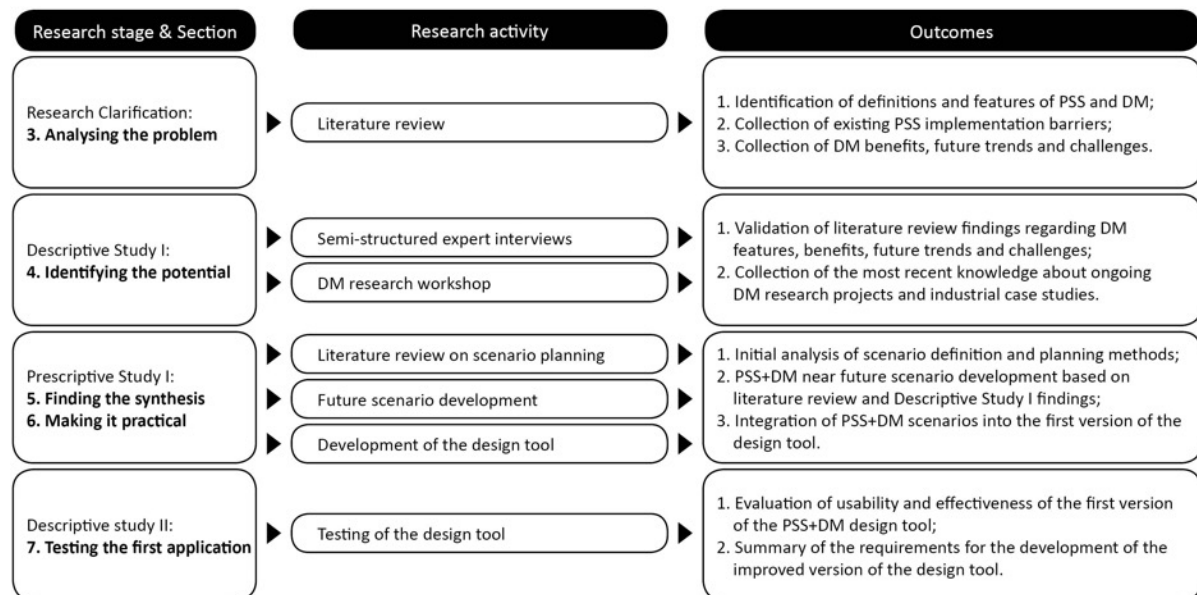


Figure 1 Research activities according to Design Research Methodology

Analysing the problem: identifying existing PSS implementation barriers. The development of the first version of the PSS+DM design tool required a collection and an in-depth analysis of existing PSS implementation barriers on the one hand, and the identification of current and future potential DM opportunities and challenges (with a 10-year timeframe). The comprehensive literature review was carried out to collect this data. It has been identified, that the literature is a sufficient source of information for the collection of existing PSS implementation barriers. However, the literature on DM is still fragmented, regarding benefits and challenges related to DM model, with a limited overview of the future vision.

Identifying the potential: collecting prospective DM opportunities. In order to collect most up-to-date knowledge and contributions regarding DM, semi-structured expert interviews and a research workshop were conducted. Ten participants with expertise ranging from Additive Manufacturing to open-source fabrication and personal production in makerspaces, were interviewed for an average of one hour each. Interviewees were asked to answer five prearranged questions related to DM benefits, challenges, future trends and existing case studies. Additional questions were provided depending on participant expertise and focused on sustainability of DM, the role of manufacturing technology and DM model suitability for different contexts. The research workshop activities included presentations of DM feasibility studies followed by group discussions about DM definition, drivers, benefits and future vision. The workshop invited 28 academics involved in six DM research projects: 1] 3D printing-enabled DM; 2] Big Data for DM; 3] The role of makerspaces; 4] Sustainable local food, energy and water; 5] DM for resilient, sustainable city; and 6] DM in healthcare. Descriptive Study I research activities helped to validate literature review findings and, most importantly, identify DM near future trends for the next 10 years. More detailed results have been published in Petrulaityte et al. (2017).

Finding the synthesis and making it practical: developing PSS+DM design tool. Initial research proved, that there are yet no existing solid examples of DM applied to PSS development. For this reason, future scenario technique was chosen to illustrate the potential. Data gathered during the first two research stages was used to generate a set of PSS+DM near-future scenarios. Firstly, the initial literature review on scenario development was carried out in order to explore scenario planning methods and analyse elements used in existing scenario examples. Secondly, a theory building approach (Meredith, 1993) was applied in the development of PSS+DM near future scenarios. The aim of this approach is to explore the relationship between PSS and DM and develop new insights by matching all existing PSS implementation barriers with DM opportunities and challenges in all possible combinations. In other words, each identified PSS barrier was systematically coupled with each individual DM opportunity to understand if the latter could tackle the former. The most promising and feasible pairings were described in short scenarios illustrating promising DM features and their application to address specific PSS implementation barriers. Later, all of the created scenarios were revised, illustrated and presented on 35 near future Scenario Cards. Finally, the Cards were categorised and mapped in the Innovation Diagram, compiling the first version of the PSS+DM design tool.

Testing the first application: identifying recommendations for further improvements. The first practical application of the tool was carried out during a 10-day Pilot Course on PSS and Distributed Economies organised by the European project *LeNSin* and implemented in Tsinghua University in Beijing (China). The Course comprised three days of theoretical lectures explaining concepts of PSS and Distributed Economies, one-day field trip, five days of design exercise and the final day committed for exhibition and presentations. The course was attended by 45 undergraduate and postgraduate students from various design-related backgrounds: product design, architecture, design management and PSS design. One day of the Pilot Course was appointed for the testing of the PSS+DM design tool. Ethics of the study has been approved by the Research Ethics Committee of Brunel University London and consent forms have been signed by all participants. Students, working in 10 groups, were given a task to use the tool to incorporate DM principles into their initial PSS solutions. Students spent the first half of the workshop reading and analysing Scenario Cards and, after a break, they started generating ideas onto Innovation Diagrams. Before starting the 10-day Pilot Course, the majority of the students did not have knowledge about PSS business models and Distributed Manufacturing. The tool testing workshop intended to bring mutual benefits: 1] to help the researcher to collect valuable data; 2] to provide students with knowledge about sustainable PSS design and DM features. Five data collection methods were applied: 1] verbal feedbacks from workshop participants; 2] questionnaires evaluating usability and effectiveness of the design tool; 3] analysis of initial ideas generated by the students; 4] analysis of ideas selected to be incorporated into final PSS solutions; and 5] researchers' observations. Insights gathered from the testing were collected, summarised and applied to identify improvements needed for an updated version of the design tool.

3 Analysing the problem: existing PSS implementation barriers

A literature review method was carried out to collect existing barriers which prevent companies from successful PSS implementation. Scopus was used to locate 62 sources containing keywords *Product-Service Systems, Product-Service Mix, Servitisation, Performance Economy and Barrier, Limitation, Obstacle*. All of the papers were analysed in chronological sequence in order to collect a broad range of barriers, discard the ones which are obsolete and select those barriers which are still relevant for the present time. Both B2B and B2C barriers were taken into consideration. In total, 41 barriers were found in at least two sources. All PSS implementation barriers collected for this research were grouped according to three categories: 1] PSS barriers for companies; 2] PSS barriers for customers and 3] Context-related PSS barriers. PSS barriers for companies are linked to organisational mind-set, lack of knowledge and know-how of product and service development, financial resources, internal organisational procedures, partnership with stakeholders, relationship

with customers and their behavior. Barriers for customers are related to PSS acceptance and include customer mind-set and cultural status, lack of knowledge about PSS offerings, relationship with PSS providers, financial concerns as well as convenience using products and accessing services. Context-related barriers of PSS are related to financial constraints and other regulations. Table 4, provided in the appendix of this paper, lists all the barriers collected to be addressed in the next steps of this research.

4 Identifying the potential: prospective DM opportunities

Prospective DM opportunities, presented in this section, are combined of DM benefits and future trends for up to 10 years' time. These were collected during the literature review, semi-structured expert interviews and the research workshop. Each DM opportunity was accompanied by a number of challenges, which were collected along with DM benefits and future trends. DM challenges hinder successful DM implementation and must be taken into account when exploring potential DM applications. DM opportunities and challenges were divided according to three categories: 1] opportunities, related to application of physical and digital technologies; 2] opportunities brought by localisation of manufacturing units and 3] opportunities, linked to customer-oriented production. Application of physical and digital technologies present the potential of using Additive Manufacturing, real-time monitoring as well as data and information sharing. Localisation of manufacturing units provides opportunities of reduced transportation and flexible, resilient and rapid manufacturing close to end customer. Customer-oriented production presents the potential of customer involvement in design and manufacturing processes and various levels of customisation of products and services. Table 5, placed in the appendix of this paper, presents all the DM opportunities and corresponding challenges collected in this research.

5 Finding the synthesis: coupling of PSS barriers with DM opportunities

This section presents the process of how the initial set of the PSS+DM near future scenarios was built. In order to systematically arrange the collected data (PSS implementation barriers and DM opportunities) into possible future events, cognitive mapping method, identified from the literature review, was applied (Goodier and Soetanto, 2013). According to this method, opportunities, trends, challenges and other collected data has to be mapped in an empty space between present issues and desirable futures. In the case of this research, PSS implementation barriers were identified as undesirable situation that needs to be addressed. A desirable future was related to better PSS implementation from company's point of view and customer acceptance. Collected DM opportunities were named as a link between present issues and ideal futures. In total, 41 PSS implementation barriers were coupled with 48 DM opportunities and 28 DM challenges in all available combinations to explore ways to achieve desirable futures (Figure 2). Most promising and feasible pairings were described in short near future scenarios, with multiple scenarios addressing individual barriers. As a result, 35 scenarios illustrating up to ten years future of DM-enabled PSS development were built. Figure 3 represents examples of different PSS barriers addressed by DM opportunities and challenges and summarised into five near-future scenarios. A complete list of the titles of all PSS+DM scenarios are provided in Figure 4.

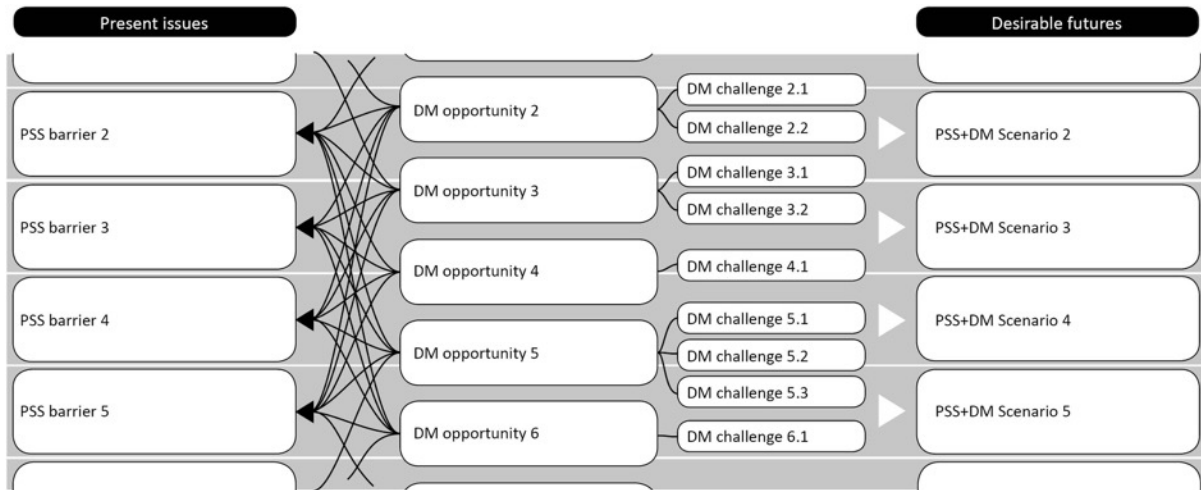
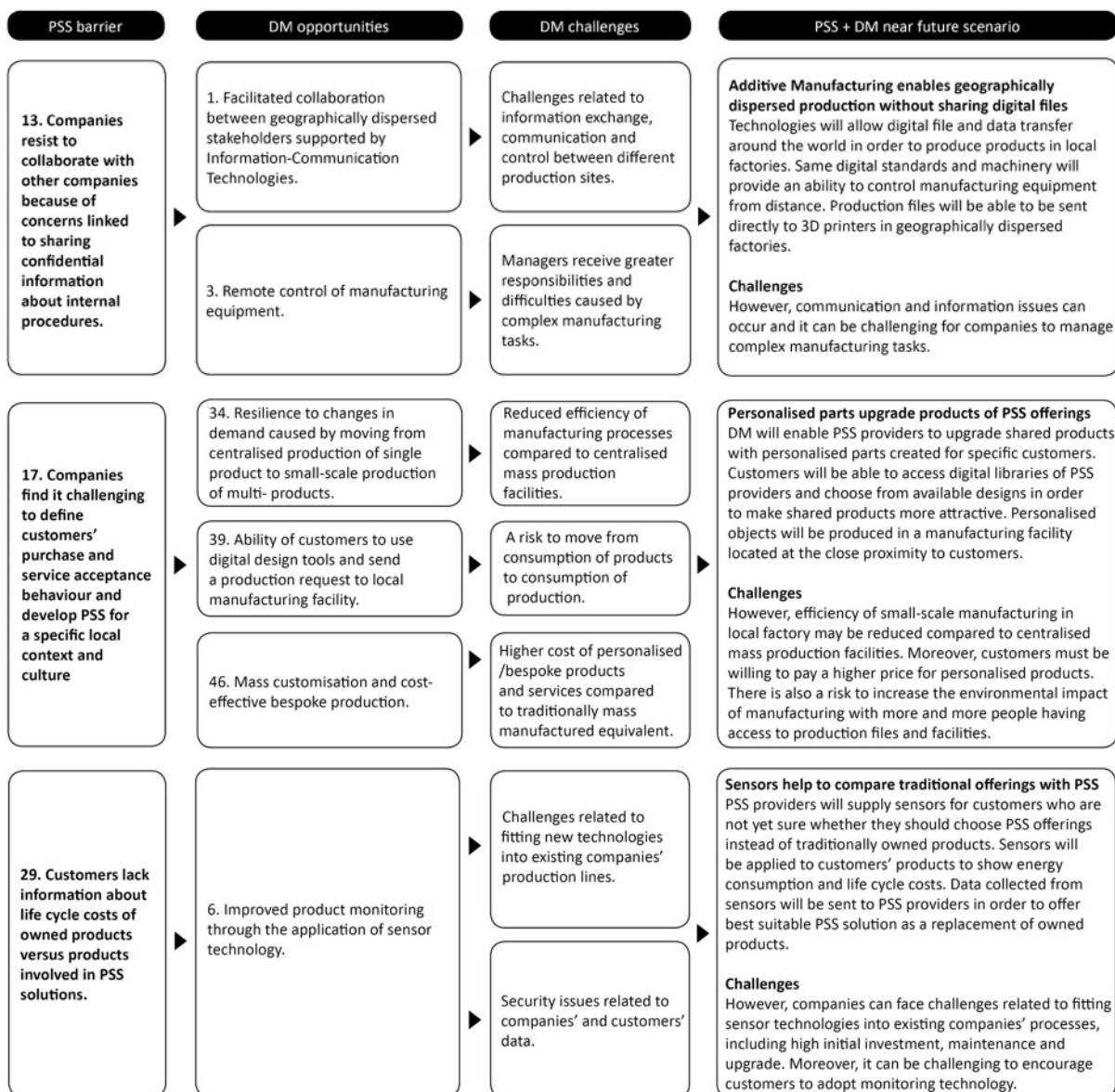


Figure 2 Schematic illustration of PSS+DM scenario building applying cognitive mapping method



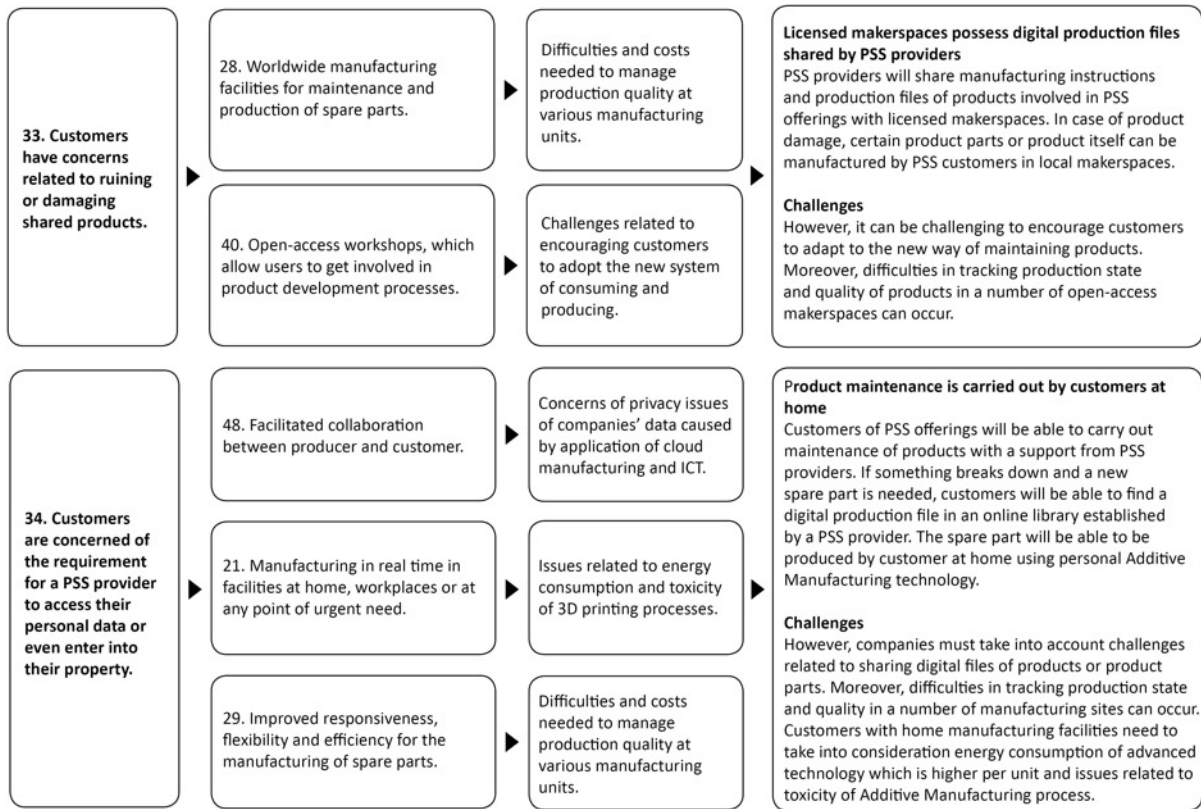


Figure 3 PSS+DM near future scenario examples

| | | |
|---|---|--|
| 1. Personalised PSS offerings bring higher profit for PSS companies | 13. Localised manufacturing reduces supply chain | 25. Independent makerspaces invite customers to share and gain knowledge |
| 2. The PSS database contains PSS designs made by customers | 14. Additive Manufacturing reduces resource consumption | 26. Product maintenance is carried out by customers in independent makerspaces |
| 3. Open-source digital libraries of PSS designs can be accessed and modified by customers | 15. Outsourced manufacturing enables on-demand local production | 27. Product maintenance is carried out by customers at home |
| 4. Independent makerspaces enable collaboration between PSS providers and customers | 16. Additive Manufacturing enables geographically dispersed production without digital file share | 28. Localised manufacturing simplifies distribution |
| 5. Makerspaces owned by PSS providers invite customers to create PSS offerings | 17. Additive Manufacturing enables remanufacturing of simplified product components | 29. Information about PSS offerings available in local factories |
| 6. Personalised PSS offerings available on high street | 18. Independent makerspaces enable PSS providers to support PSS offerings | 30. Sensors provide information about product use to PSS providers and customers |
| 7. Entirely bespoke products available for customers | 19. Licensed makerspaces possess digital production files shared by PSS providers | 31. Sensors provide information about product condition only to customers |
| 8. Sensors help to compare traditional offerings with PSS | 20. Personalised product parts ordered by customers improve hygiene of shared products | 32. Sensors indicate the level of hygiene of leased products |
| 9. Personalised parts upgrade products involved in PSS offerings | 21. Home-manufactured personalised product parts improve the hygiene of shared products | 33. Sensors indicate product end-of-life |
| 10. Additive Manufacturing enables production of lightweight products | 22. Customers run manufacturing, PSS providers carry out service provision | 34. Obsolete products are turned into personalised offerings |
| 11. Communities provide PSS for local people | 23. Standardised replaceable product parts improve hygiene of shared products | 35. Localised recycling facilities simplify product collection and recycling |
| 12. Becoming a partner of a bigger PSS provider facilitates business implementation | 24. Sensors improve development of future products | |

Figure 4 Titles of 35 PSS+DM near future scenarios

The next section describes the integration of the near future scenarios into practically applicable PSS+DM design tool.

6 Making it practical: development of PSS+DM design tool

PSS+DM design tool aims to support idea generation processes for PSS development through the use of near future scenarios. Each of 35 scenarios was described on a double-sided card, consisting the following elements: a title and a short description, an illustration, a summary of challenges and potential benefits and a question supporting idea generation (Figure 5).

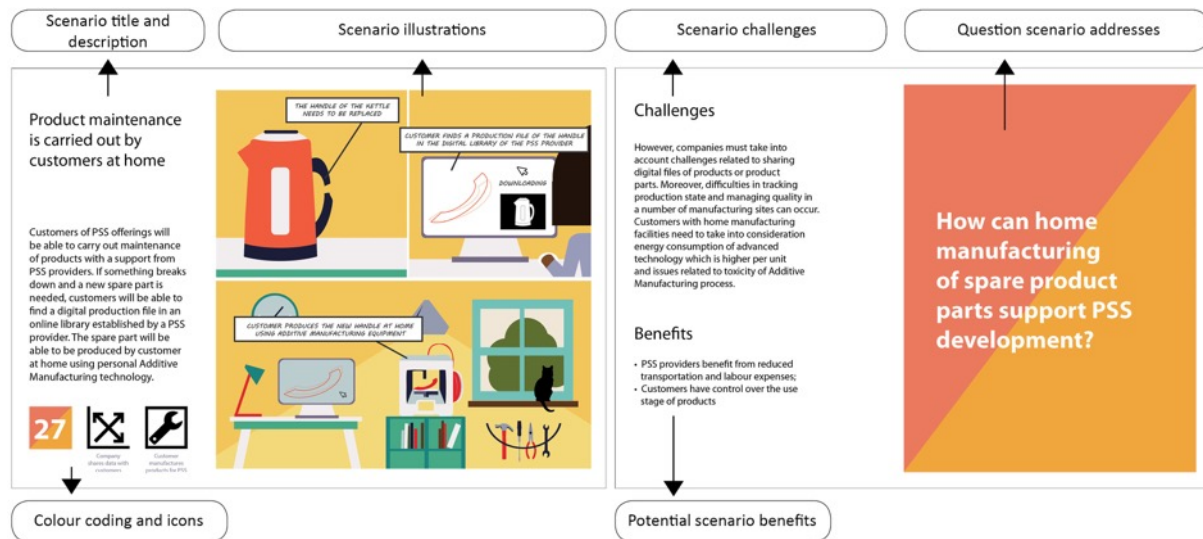
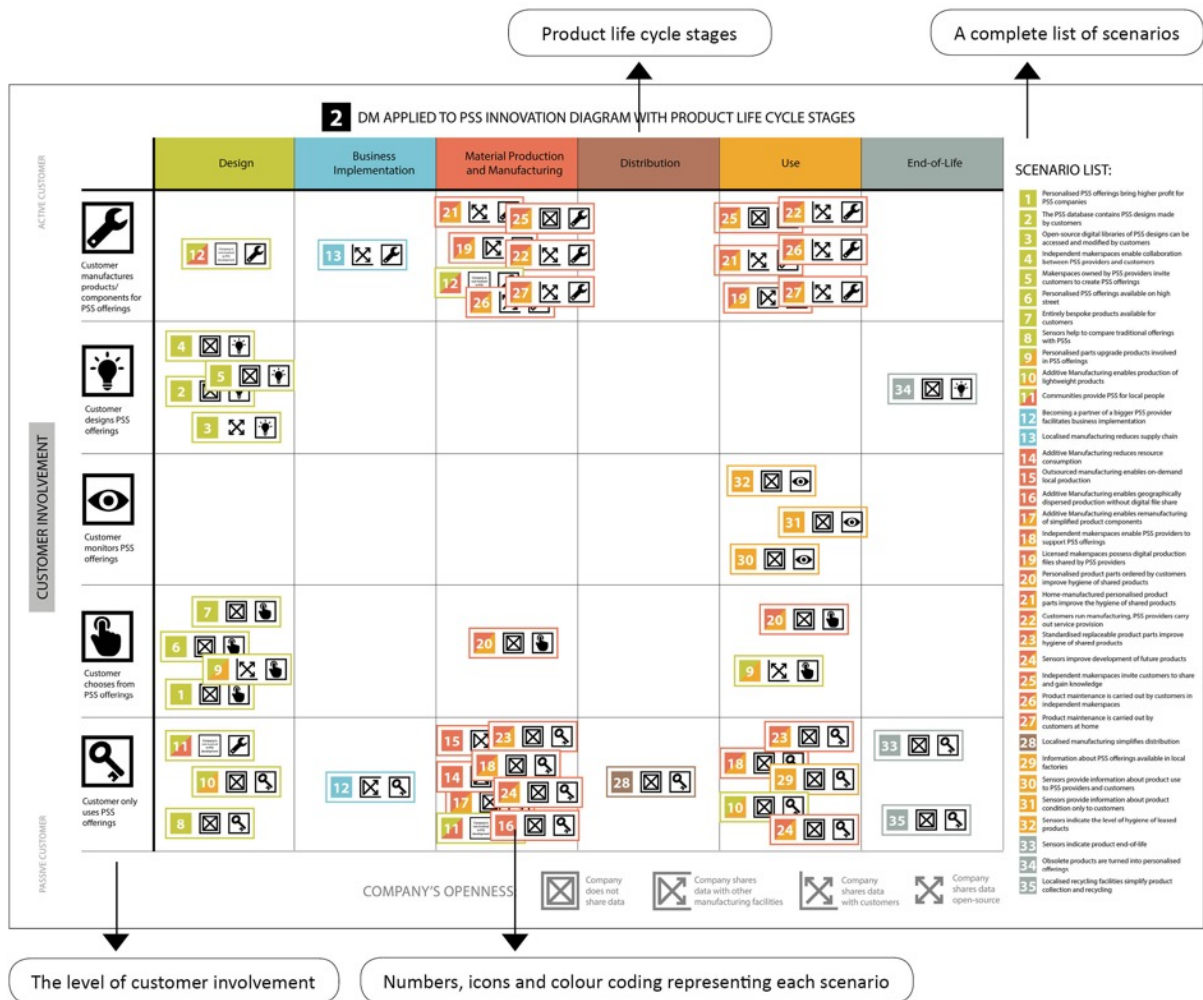


Figure 5 PSS+DM near future Scenario Card example

In order to make scenarios work as an idea generation tool, categorisation was crucial. For this reason, all 35 Scenario Cards were mapped on an Innovation Diagram to help users to identify areas which scenarios intend to address. The Diagram comprises two polarities: one addressing PSS and one focusing on the DM feature. According to Lelah et al. (2014), attention to PSS life-cycle phases is essential for the development of sustainable PSS. For this reason, Scenario Cards were classified according to six identified PSS life cycle stages: *Design, Business Implementation, Material production and Manufacturing, Distribution, Use and End-of-life*. Concerning the focus on DM, the level of customer involvement was chosen as a second polarity. Matt et al. (2015) describe DM as *democratisation of design* and emphasise customer involvement in product development and manufacturing processes. Customer involvement for Scenario Card categorisation is described in five levels: *Customer only uses PSS offerings, Customer chooses from PSS offerings, Customer monitors PSS offerings, Customer designs PSS offerings and Customer manufactures products/components for PSS offerings*. For customer involvement to be possible, manufacturing companies have to be willing to cooperate and enable customers to operate blueprints and manufacturing facilities. For this reason, the level of company's openness was also taken into account when categorising Scenario Cards. This describes with whom company shares open production files of products or product components and instructions on how these products or their components must be produced. Four levels of openness were identified: *Company does not share data, Company shares data with other manufacturing facilities, Company shares data with customers, and Company shares data open-source*. To summarise, the Innovation Diagram consists of two polarities, a complete list of scenarios and numbers, icons and colour coding representing the position of each scenario (Figure 6).



- SCENARIO LIST:**
- 1 Personalised PSS offerings bring higher profit for PSS companies
 - 2 The PSS database contains PSS designs made by customers
 - 3 Open source digital libraries of PSS designs can be accessed and modified by customers
 - 4 Independent makerspaces enable collaboration between PSS providers and customers
 - 5 Makerspace owned by PSS providers invite customers to create PSS offerings
 - 6 Personalised PSS offerings available on high street
 - 7 Entirely bespoke products available for customers
 - 8 Sensors help to compare traditional offerings with PSS
 - 9 Personalised parts upgrade products involved in PSS offerings
 - 10 Additive manufacturing enables production of lightweight products
 - 11 Communities provide PSS for local people
 - 12 Becoming a partner of a bigger PSS provider facilitates business implementation
 - 13 Localised manufacturing reduces supply chain
 - 14 Additive manufacturing reduces resource consumption
 - 15 Outsourced manufacturing enables on-demand local production
 - 16 Additive manufacturing enables geographically dispersed production without digital file share
 - 17 Additive manufacturing enables remanufacturing of simplified product components
 - 18 Independent makerspaces enable PSS providers to support PSS offerings
 - 19 Licensed makerspaces possess digital production files shared by PSS providers
 - 20 Personalised product parts ordered by customers improve hygiene of shared products
 - 21 Home manufactured personalised product parts improve the hygiene of shared products
 - 22 Customers run manufacturing. PSS providers carry out service operations
 - 23 Standardised replaceable product parts improve hygiene of shared products
 - 24 Sensors improve development of future products
 - 25 Independent makerspaces invite customers to share and gain knowledge
 - 26 Product maintenance is carried out by customers in independent makerspaces
 - 27 Product maintenance is carried out by customers at home
 - 28 Localised manufacturing simplifies distribution
 - 29 Information about PSS offerings available in local factories
 - 30 Sensors provide information about product use to PSS providers and customers
 - 31 Sensors provide information about product condition only to customers
 - 32 Sensors indicate the level of hygiene of shared products
 - 33 Sensors indicate product end-of-life
 - 34 Obsolete products are turned into personalised offerings
 - 35 Localised recycling facilities simplify product collection and recycling

Figure 6 PSS+DM Innovation Diagram

The tool can be approached in two different ways depending on user experience and intentions. Users without initial PSS solutions should start from reading and analysing contents of all Scenario Cards from each life cycle stage starting from left to right, taking the level of customer involvement into account. Users with initial PSS solutions or previous PSS development experience can start using the tool from reading Scenario Cards from a specific life cycle stage they wish to address or the level of customer involvement. In any case, ideas triggered by Scenario Cards must be written down on post-it notes and placed on an empty Innovation Diagram.

The next section provides an overview and the findings of the first empirical testing of this initial version of the PSS+DM design tool.

7 Testing the first application: workshop with design students

The first version of the PSS+DM design tool, including Scenario Cards and Innovation Diagram, has been tested in order to evaluate its usability and effectiveness as an idea generation tool. The summary of findings and recommendations for an updated version of the tool are presented in the following paragraphs.

7.1 Findings

Effectiveness and usability of the first version of the PSS+DM design tool were evaluated using the insights from verbal feedbacks, questionnaires, initial and final ideas provided by workshop participants and researchers' observations.



Figure 7 Students analyse all PSS+DM Scenario Cards and, later, place generated ideas on the Innovation Diagram

7.1.1 Effectiveness

Tool's effectiveness aimed at demonstrating how well the tool can: 1] support idea generation and integration into final PSS concept; and 2] help the users to understand potential benefits of DM application.

Generating ideas and integrating them into final PSS concept. The design challenge, introduced to workshop participants, invited them to create PSS lighting solutions for Chinese context. Students generated initial ideas and, later, chose the most promising ones to be integrated into their final PSS solutions. In total, 190 ideas were generated by students working in ten groups and 86 ideas were incorporated into their final PSS proposals. Initial ideas, triggered by Scenario Cards, were recorded on post-it notes and placed on the Innovation Diagram. Figure 8 illustrates DM ideas developed for PSS lighting equipment for pest control and shows that initial ideas cover a complete PSS lifecycle, as well as various levels of customer involvement. After developing a number of initial ideas, students were free to choose their own way of incorporating most promising ideas into final PSS solutions. In Figure 9, the concept of supporting field workers using drones, provides an example of how DM features were summarised for the final presentation. Here students indicated ideas for each PSS life cycle stage, clearly identifying levels of customer involvement and company's openness. Furthermore, students provided a map illustrating distribution of central facility, local entrepreneurs and resources. Highlights of DM benefits for their specific PSS business model are also summarised.



Figure 8 Example of initial ideas generated for each PSS life cycle stage

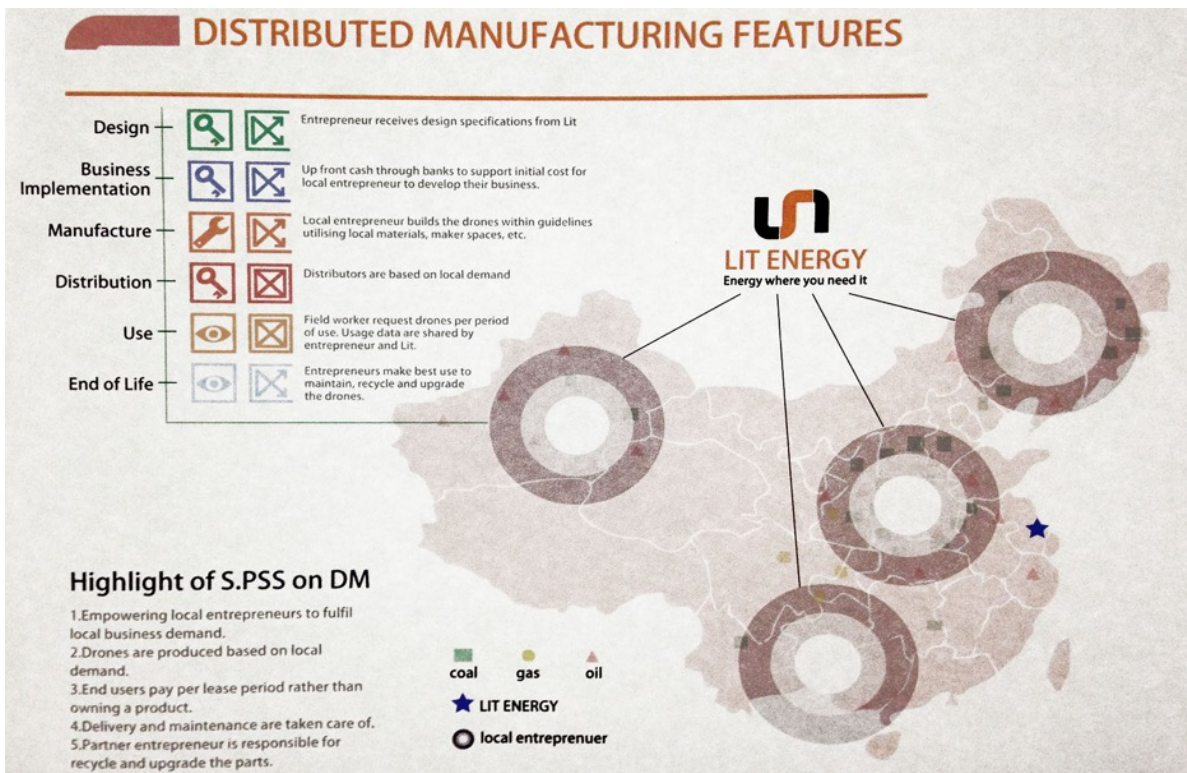


Figure 9 Example of a final presentation showing DM features integrated into final PSS concept

Understanding benefits of DM. Analysis of initial and final ideas showed that the tool helped workshop participants to grasp potential benefits of DM model. Firstly, the Innovation Diagram supported students in considering democratisation of manufacturing by choosing different levels of customer involvement (Figure 8). Secondly, icons representing levels of company’s openness were included in the majority of the final presentations (Figure 9). Finally, developed ideas reflected all

three key DM features: application of physical and digital technologies (“Sensors show efficiency and end-of-life of water filters and solar panels and indicate leaks in pipes.”), localisation (“Farmers make products in makerspaces from materials provided by local recycling station.”) and customer-orientation (“Our business model includes different levels of satisfaction which create a long-term relationship with a client”). Table 1 summarises feedback from the evaluation questionnaires collected to evaluate tool’s effectiveness.

Table 1 Feedback collected to evaluate effectiveness of the Scenario Cards and the Innovation Diagram.

| Scenario Cards | | | | | | |
|--|---------------------|----------|--------------|------------|-------------|------------|
| Question | Evaluation / Answer | | | | | |
| | 1 Very poor | 2 Poor | 3 Sufficient | 4 Good | 5 Excellent | Average |
| 1. To what extent the Scenario Cards helped you to <u>understand the potential benefits of DM</u> applied to PSS? | 0 | 0 | 3 (7%) | 23 (53.5%) | 17 (39.5%) | 4.3 |
| 2. To what extent are the Scenario Cards useful to <u>generate ideas</u> ? | 0 | 1 (2.4%) | 6 (14.6%) | 17 (41.5%) | 17 (41.5%) | 4.2 |
| 3. To what extent the Scenario Cards helped you to <u>stimulate the discussion</u> in your group? | 0 | 1 (2.4%) | 5 (12.2%) | 25 (61%) | 10 (24.4%) | 4 |
| Innovation Diagram | | | | | | |
| Question | Evaluation / Answer | | | | | |
| | 1 Very poor | 2 Poor | 3 Sufficient | 4 Good | 5 Excellent | Average |
| 1. To what extent is the DM + PSS Innovation Diagram useful to <u>generate ideas</u> ? | 0 | 0 | 5 (12%) | 21 (50%) | 16 (38.1%) | 4.3 |
| 2. To what extent has the Innovation Diagram helped you to take into account a <u>complete life cycle</u> of your concept? | 0 | 1 (2.4%) | 7 (16.7%) | 17 (40.5%) | 17 (40.5%) | 4.2 |
| 3. To what extent the Innovation Diagram helped you to <u>stimulate the discussion</u> in your group? | 0 | 2 (4.9%) | 6 (14.6%) | 16 (39%) | 17 (41.5%) | 4.2 |

7.1.2 Usability

Tool’s usability aimed at assessing visual and textual communication elements of Scenario Cards, the layout of the Innovation Diagram and overall ease of use of the tool. Since the students already had initial PSS concepts before starting using the Scenario Cards and Innovation Diagram, they were able to choose their own way to approach the tool. Verbal feedback from workshop participants and researchers’ observations showed that the majority of ten groups firstly analysed all of the Scenario Cards, and later started generating ideas for each life cycle stage, starting from the first one - Design (Figure 7). One group started their idea generation process from analysing the Innovation Diagram (“We jumped from one stage to another, one stage triggered ideas for another stage.”). Questionnaires completed by each participant provided a more detailed feedback, summarised in Table 2.

Table 2 Feedback collected to evaluate usability of the Scenario Cards and the Innovation Diagram.

| Scenario Cards | | | | | | |
|----------------|---------------------|--------|--------------|--------|-------------|---------|
| Question | Evaluation / Answer | | | | | |
| | 1 Very poor | 2 Poor | 3 Sufficient | 4 Good | 5 Excellent | Average |

| | | | | | | |
|---|---------------------|----------|--------------|------------|-------------|------------|
| 1. To what extent are the <u>illustrations</u> on the Scenario Cards easy to understand? | 0 | 0 | 5 (11.4%) | 24 (54.5%) | 15 (34.1%) | 4.2 |
| 2. To what extent are the <u>descriptions</u> of the scenarios easy to understand (including Limitations and Challenges)? | 0 | 2 (4.7%) | 13 (30.2%) | 23 (53.5%) | 5 (11.6%) | 3.7 |
| 3. To what extent are the <u>colour coding</u> and the <u>icons</u> easy to understand? | 0 | 0 | 8 (18.6%) | 15 (34.9%) | 20 (46.5%) | 4.3 |
| 4. To what extent, in general, is the <u>layout</u> of the Scenario Cards relevant to its contents? | 0 | 0 | 6 (14.3%) | 22 (52.4%) | 14 (33.3%) | 4.2 |
| 5. To what extent are the Scenario Cards <u>easy to use</u> ? | 0 | 0 | 8 (19%) | 25 (59.5%) | 9 (21.4%) | 4 |
| Innovation Diagram | | | | | | |
| Question | Evaluation / Answer | | | | | |
| | 1 Very poor | 2 Poor | 3 Sufficient | 4 Good | 5 Excellent | Average |
| 1. To what extent is the Innovation Diagram <u>easy to understand</u> ? | 0 | 0 | 7 (16.7%) | 30 (71.4%) | 5 (11.9%) | 4 |
| 2. To what extent is the Innovation Diagram <u>easy to use</u> ? | 0 | 0 | 1 (2.3%) | 26 (60.5%) | 16 (37.2%) | 4.3 |

7.2 Discussion

The initial testing proved that the PSS+DM design tool helped students to understand potential opportunities of DM and generate a variety of ideas, describing how their initial PSS concepts can be enriched through the application of DM features. Feedback from workshop participants, analysis of PSS+DM ideas and researchers' observations helped to identify successful tool features and aspects which need improvements.

The majority of students identified scenario illustrations as inspiring and narratives of each scenario easy to understand. However, participants shared that icons, representing customer involvement and company's openness, in some cases restricted idea generation process. The study also showed, that the tool is missing more detailed presentation of DM features, including DM case studies and focus on technological aspects. It is also required to simplify textual information and support each scenario with more questions. The majority of the students agreed that the Innovation Diagram encouraged them to consider each life cycle stage of their PSS concepts and supported group discussion. However, categorisation of Scenario Cards according to two different DM features created confusion and, in some cases, restricted idea generation process. There was also lack of guidelines provided on where to start and finish, as well as how to integrate initial ideas into final PSS solutions. Some PSS life cycle stages were identified as not being well supported with an efficient number of Scenario Cards. Drawing conclusions from the first testing, recommendations for new features to be integrated in the updated version of the PSS+DM design tool are summarised in Table 3.

Table 3 Recommendations for new features for the updated version of the PSS+DM design tool.

| Scenario Cards | Worked | Did not work | Suggestions from participants | Recommendations for new features |
|----------------|--------|--------------|-------------------------------|----------------------------------|
|----------------|--------|--------------|-------------------------------|----------------------------------|

| | | | | |
|---------------------------|--|--|---|---|
| Effectiveness | 1. Illustrations were engaging and easy to understand. 2. Overall DM concept and the way it was presented aroused students' interest. | 1. Descriptions in English were difficult to understand for Chinese students. 2. DM categorisation (customer involvement and company's openness) was too specific and restricted idea generation process. | <i>"A good case study as an example could help us to better understand DM concept"</i> <i>"More in-depth information about the technologies."</i> | 1. Include case studies to better illustrate DM potential. 2. Provide descriptions of advanced technological features. |
| Usability | | | <i>"Reduce the amount of text, add bullets and highlight key points."</i> <i>"Give more questions to inspire us."</i> | 1. Highlight key message each scenario delivers, including clear identification of environments and stakeholders. 2. Provide more questions in each Scenario Card to trigger idea generation. |
| Innovation Diagram | Worked | Did not work | Suggestions from participants | Recommendations for new features |
| Effectiveness | 1. Focus on a complete PSS life cycle. 2. Lively group discussion. | 1. Lack of guidelines where to start and where to finish idea generation process. 2. Confusion linked to two different DM categorisation: customer involvement and company's openness. | <i>"It is not easy to map on the diagram. [Customer involvement icons] need to be simplified or re-categorized and help user to understand the contents easier."</i> <i>"There could be some PSS+DM innovation examples provided."</i> | 1. Simplify the Diagram, keeping PSS Life Cycle Stages and removing Customer Involvement and Company's Openness, potentially replacing them by different axis. 2. Support the Diagram with DM/PSS case studies. |
| Usability | | 3. Insufficient number of scenarios in some PSS life cycle stages (e.g. Distribution). | <i>"If the diagram could have more rules and activities it will be better."</i> <i>"Beginning at random stages of life cycle – starting at end of life might change the final design – order can matter."</i> | 1. Provide more specific step-by-step guidelines of the tool application process, particularly emphasizing where to start and where to finish. 2. Customise guidelines for different potential tool user groups (design practitioners, PSS companies, students). |

8 Conclusions and further research

Product-Service System is considered a promising type of business models to improve production and consumption towards social, economic and environmental sustainability. Nevertheless, the implementation and acceptance of PSS business models are still limited by a number of organisational, cultural and regulatory barriers. The research hypothesis of this paper is that Distributed Manufacturing, described as a network of localised and customer-oriented production units, can be applied to PSSs to address some of its implementation barriers. Existing attempts to combine PSS and DM can be found in the literature, however, a systematic analysis of how PSS barriers can be addressed by DM is still missing. An ongoing research, presented in this paper aims at filling this knowledge gap as well as providing PSS companies and design practitioners with practically applicable PSS+DM idea generation tool. This article has described the research process

which was carried out to develop the first version on the design tool, created to support PSS solutions development through the application of Distributed Manufacturing features.

The initial version of the PSS+DM design tool contains 35 near future Scenario Cards which illustrate DM opportunities and their application to PSS development. All the Scenario Cards are classified and mapped on the dual-axis Innovation Diagram, facilitating idea generation process by encouraging tool users to consider a complete PSS lifecycle. Since the scenarios for the integration into the design tool were developed by coupling existing PSS implementation barriers with near future opportunities of DM, they intend to address real world obstacles for PSS integration and acceptance. The first testing of the design tool carried out with 45 undergraduate and postgraduate design students demonstrated that, with further improvements, the Scenario Cards and the Innovation Diagram has the potential to support PSS solutions development processes.

Future research will focus on the iterative process of the development of improved versions of the PSS+DM design tool and empirical tool testing with various user groups. The next testing of the updated version of the tool will be carried out with experts from PSS-and DM-related fields. Later, PSS industry professionals will be invited to apply the tool in their business processes. Upcoming testings will aim at evaluating effectiveness, usability as well as completeness of the tool's contents. The aim of empirical applications of the PSS+DM design tool is to create a versatile tool which can support design practitioners, PSS companies and students in PSS development processes.

9 Appendix

Table 4 PSS implementation barriers.

| No | Subcategory | PSS implementation barrier | Literature source |
|-----------------------------|----------------------------|---|--|
| PSS barriers for companies: | | | |
| 1 | Organisational mind-set | Companies might find it challenging to adopt mutual PSS-oriented mind-set and embed PSS culture across the organisation. | UNEP, 2002; Martinez et al., 2010 |
| 2 | | Companies might resist to change and adapt new ways to manage business processes within organisations. | Besch, 2005; Martinez et al., 2010 |
| 3 | | Companies might resist to make long-term decisions needed for PSS implementation. | Bartolomeo et al., 2003; Kuo et al., 2010 |
| 4 | Lack of know-how | Companies might lack of know-how, knowledge and expertise in methods and tools needed to develop, evaluate and deliver a competent PSS. | UNEP, 2002; Bartolomeo et al., 2003; Baines et al., 2007 |
| 5 | | Companies might lack of know-how of designing and developing a product for PSS offerings. | Mont, 2002b; UNEP, 2002 |
| 6 | Finance-related challenges | SMEs might lack of financial resources to implement and run PSS type business models. | Besch, 2005; Vezzoli et al., 2015 |
| 7 | | Companies might find it challenging to cover the initial investment required for PSS offerings. | Mont, 2002a; Barquet et al., 2013 |
| 8 | | Employees might lack of knowledge and practice in pricing PSS offerings and taking into account costs related to the use stage of products. | Barquet et al., 2013; Mont, 2002b |
| 9 | | Companies might find it challenging to estimate cash flows and financial savings in completely new system of gaining profits. | Mont, 2002b; Bartolomeo et al., 2003 |

| | | | |
|-----------------------------|---------------------------------|--|---|
| 10 | | Companies might find it difficult to quantify environmental saving of PSS acceptance. | UNEP, 2002; Ceschin, 2012 |
| 11 | Internal organisational issues | Organisational bodies within companies might face disagreements caused by the lack of communication. | Martinez et al., 2010; Vezzoli et al., 2015 |
| 12 | | Service providers, the intermediaries and other bodies might lack of organisational commitment. | Bartolomeo et al., 2003; Mont, 2004a |
| 13 | Collaboration with stakeholders | Companies might resist to collaborate with other companies because of concerns linked to sharing knowledge, expertise and confidential information about internal procedures. | Cooper & Evans, 2000; Mont, 2004 |
| 14 | | Companies might face organisational fragmentation, caused by multiplicity of actors in service chains, none of whom may have an overview of the entire chain and/or the ability to influence other actors. | UNEP, 2002; Bartolomeo et al., 2003 |
| 15 | | Companies might be concerned of weakened administration of core competencies caused by co-dependence of partners. | Mont, 2000; UNEP, 2002 |
| 16 | | Companies might be concerned of conflict of economic interest caused by different partners. | Cooper & Evans, 2000; Vezzoli et al., 2015 |
| 17 | Relationship with customers | Companies might find it challenging to define customers' purchase and service acceptance behaviour and develop PSS for a specific local context and culture. | Mont, 2002b; Catulli, 2012 |
| 18 | | Companies might be concerned of the requirement for PSS provider to access customers' personal data or even enter into their property. | Källrot, 2001; Mont, 2001 |
| 19 | | Possible mismatch between the characteristics of contracts being offered by PSS companies and the needs or desires of their potential customers. | Catulli, 2012; Hannon et al., 2015 |
| 20 | | Companies might find it difficult to provide PSS offerings with higher or equal level of performance than traditional solutions. | Mont, 2002b; Martinez et al., 2010 |
| 21 | Customer behaviour | Ownerless consumption might lead to careless behaviour. | Mont, 2002b; Barquet et al., 2013 |
| 22 | | Companies might face challenges of customers not being willing to return the product at the end of contract. | Mont, 2002; Catulli, 2012 |
| PSS barriers for customers: | | | |
| 23 | Mind-set and cultural status | Customers might lack of PSS-oriented mind-set needed for cultural shift to accept some of PSS solutions and believe that product ownership is related to social status and measure of achievement in life. | Manzini et al. 2010; Catulli, 2012 |
| 24 | | Individualisation trend: customers might believe that quantity and quality of accumulated goods is perceived as a measure of success in life. | Mont, 2004a; Besch, 2005 |
| 25 | Lack of knowledge about PSS | Customers might lack of understanding and knowledge about the overall PSS concept and believes that PSS solutions are less comfortable. | Ottosson, 2000; Mont 2002b; Catulli, 2012 |
| 26 | | Customers might believe that high initial investment when purchasing a product guarantees better reliability and overall level of satisfaction. | Mont, 2004a; Besch, 2005 |

| | | | |
|-------------------------------|--------------------------------------|--|---|
| 27 | Relationship with PSS provider | Customers might resist to accept long-term relationship with PSS provider. | Bartolomeo et al., 2003; Hannon et al., 2015 |
| 28 | | Possible mismatch between the characteristics of contracts being offered by PSS companies and the needs or desires of their potential customers. | Catulli, 2012; Hannon et al., 2015 |
| 29 | Financial concerns | Customers might lack information about life cycle costs of owned products versus products involved in PSS solutions. | White et al., 1999; Cooper & Evans, 2000 |
| 30 | | Customers might believe that owning a service “package” is more expensive than owning a product. | Rexfelt et al., 2009; Catulli et al., 2012 |
| 31 | Use of product or access to services | Customers might have concerns of independence and convenience related to the access of shared products. | Cooper & Evans, 2000; Mont, 2004b |
| 32 | | Customers might have concerns related to hygiene of used or shared products. | Mont, 2004b; Catulli, 2012 |
| 33 | | Customers might have concerns related to ruining or damaging shared products. | Rexfelt et al., 2009; Catulli, 2012 |
| 34 | | Customers might be concerned of the requirement for PSS provider to access customers’ personal data or even enter into their property. | Källrot, 2001; Mont, 2002b |
| Context-related PSS barriers: | | | |
| 35 | Finance-related challenges | Externalities (environmental impacts) might not be included in the market price. | UNEP, 2002; Mont & Lindhqvist 2003 |
| 36 | | Financial institutions might lack of knowledge about PSS concept. | Mont & Lindhqvist 2003; Barquet et al., 2013 |
| 37 | | Financial institutions might not be willing to support PSS development. | Mont, 2004; Barquet et al., 2013 |
| 38 | | Low cost of resources might encourage manufacturing of products using raw materials instead of recycling. | Mont, 2002b; Enckell & Isgran, 2017 |
| 39 | | High labour prices might prevent customers from choosing labour-intensive PSS offerings, which can be more expensive than purchasing a product. | Mont, 2002b; Ceschin, 2012 |
| 40 | Regulatory barriers | There might be a lack of external infrastructure for product end-of-life stage including collection, recycling and remanufacturing. | UNEP, 2002; Kuo et al., 2010 |
| 41 | | PSS time-to-market can be prolonged compared to traditional product-based offerings. | Mont, 2002a; Kuo et al., 2010 |

Table 5 Prospective DM opportunities and corresponding challenges.

| No | DM opportunities | Source | DM challenges | Source |
|---|------------------|--------|---------------|--------|
| Application of physical and digital technologies: | | | | |

| | | | | |
|--------------------------------------|--|---|---|--|
| 1 | Facilitated collaboration between geographically dispersed stakeholders supported by Information-Communication Technologies. | Basmer et al., 2015 | Challenges related to information exchange, communication and control between different production sites. | Durão et al., 2017 |
| 2 | Spread of workloads across a number of manufacturing units sharing same digital standards. | Srai et al., 2015 | Managers receive greater responsibilities and difficulties caused by complex manufacturing tasks. | Durão et al., 2017 |
| 3 | Remote control of manufacturing equipment. | Basmer et al., 2015 | | |
| 4 | Opportunity for companies to start selling technological knowledge instead of providing physical manufacturing service. | DS1 | Lack of official data-sharing agreements between digitally connected supply chain actors. | Srai et al., 2015 |
| 5 | Improved monitoring, control and optimisation of stock and material flows. | Srai et al., 2015 | Challenges related to fitting new technologies into existing companies' production lines. | Rauch et al., 2015i |
| 6 | Improved product monitoring through the application of sensor technology. | Srai et al., 2015 | | |
| 7 | Optimised production, consumption and service through the application of sensor technology. | Kühnle, 2015 | Security issues related to companies' and customers' data. | Kühnle, 2015; Rauch et al., 2015 |
| 8 | Improved development of future products through the application of "digital brain". | Lerch & Gotsch, 2015 | | |
| 9 | Better understanding of user behaviour through the data collected by sensors. | Ardolino et al., 2017 | | |
| 10 | Potential reduction of the time-to-market through the ability to manufacture in small lot sizes. | Durão et al., 2017 | High initial investment costs, related to adoption of new technologies, their maintenance and upgrade. | Srai et al., 2015 |
| 11 | Small-scale production of more complex products and their components provided by Additive Manufacturing technology. | DS1 | | |
| 12 | Consumption of less material and less waste at the point of manufacturing using Additive Manufacturing technology. | Ford et al. 2015 | Energy consumption of advanced manufacturing technology is higher per unit. | DS1 |
| 13 | Optimisation of recycling and closed-loop systems in order to enable circular economy using Additive Manufacturing technology. | Ford et al. 2015; Moreno & Charnley, 2016 | | |
| 14 | Simplified and optimised design of products produced using Additive Manufacturing technology. | Ford et al. 2015 | Challenges related to training of employees who are required to have a wide range of technical and design skills. | Pearson et al., 2013; Srai et al., 2015; DS1 |
| 15 | Self-disassembly and self-repair of product components available with the application of 4D printing technology. | Momeni et al., 2017 | | |
| 16 | Volume reduction of packed 4D printed products. | Momeni et al., 2017 | | |
| 17 | Low cost desktop 3D printers equipped with advanced materials (e.g. metal powder) | DS1 | Perception that 3D printing certain components is not reliable. | DS1 |
| Localisation of manufacturing units: | | | | |
| 18 | Reduced transportation costs and delivery times. | Durão et al., 2017 | Difficulties related to managing same quality | Srai et al., 2015 |

| | | | | |
|-----------------------|--|---|---|--|
| 19 | Reduced environmental impact of transportation, caused by only digital production files and raw materials being shipped over long distanced. | Gyires & Muthuswamy, 1993 | delivery at various manufacturing units. | |
| 20 | Last mile low-emission delivery implemented by companies to their customers. | Ford & Despeisse, 2016; Srαι et al., 2015 | | |
| 21 | Manufacturing in real time in facilities at home, workplaces or at any point of urgent need. | DS1 | Regulating small number of large scale production is easier than regulating a large number of small production sites. | Pearson et al., 2013; DS1 |
| 22 | Combination of production and entertainment in manufacturing facilities in public spaces. | DS1 | | |
| 23 | Production in-store with manufacturing units on high street. | Foresight, 2013; DS1 | | |
| 24 | Home manufacturing of products which are no longer produced by companies. | DS1 | Issues related to energy consumption and toxicity of 3D printing processes. | DS1 |
| 25 | Production of products and their components carried out anywhere in the world using local resources and access to technologies. | Srαι et al., 2015 | Challenges to sensibly adapt new manufacturing units to the local context. | DS1 |
| 26 | Re-evaluation of a global network design of companies. | Rauch et al., 2015 | Difficulties and costs needed to manage production quality at various manufacturing units. | Srαι et al., 2015; DS1 |
| 27 | Facilitated movement and re-location of manufacturing facilities in case of market or environmental changes. | Rauch et al., 2015; DS1 | | |
| 28 | Worldwide manufacturing facilities for maintenance and production of spare parts. | Durão et al., 2017; DS1 | | |
| 29 | Improved responsiveness, flexibility and efficiency for the manufacturing of spare parts. | Durão et al., 2017 | Change of mind within the company is needed to maintain operational transition towards DM implementation. | Pearson et al., 2013 |
| 30 | Higher employment rate achieved by supporting local producers who employ local communities. | Pearson et al., 2013; Srαι et al., 2015 | Limited independence of companies caused by other network units and their processes and objectives. | Kühnle, 2015 |
| 31 | Low capital cost of entry to distributed network. | DS1 | Challenges related to training of employees. | Pearson et al., 2013; Srαι et al., 2015; DS1 |
| 32 | Opportunity for developing countries to produce goods on their own demand. | Basmer et al., 2015 | | |
| Customer-orientation: | | | | |
| 33 | Small-scale manufacturing of only products required by customers. | Rauch et al., 2015; Srαι et al., 2015 | Reduced efficiency of manufacturing processes | Matt et al., 2015 |

| | | | | |
|----|---|---------------------------------------|---|------------------------|
| 34 | Resilience to changes in demand caused by moving from centralised production of single product to small-scale production of multi-products. | Rauch et al., 2015; DS1 | compared to centralised mass production facilities. | |
| 35 | Reduced warehousing costs related to unsold products, caused by on-demand production. | Rauch et al., 2015 | | |
| 36 | Open-source innovations encouraged by customer involvement in design and production processes. | Srai et al., 2015 | Lack of regulations increase risk of illegal copying of objects through access to digital files and open-source information. | Foresight, 2013; DS1 |
| 37 | Free open-source libraries from which designs can be downloaded and improved by everyone. | DS1 | | |
| 38 | Customer involvement in production of personalised products. | Rauch et al., 2015; Srai et al., 2015 | A risk to move from consumption of products to consumption of production. | DS1 |
| 39 | Customers able to use digital design tools and send a production request to local manufacturing facility. | Srai et al., 2015; DS1 | | |
| 40 | Open-access workshops, which allow users to get involved in product development processes. | Matt et al., 2015; Srai et al., 2015 | The choice of location of openly-accessible manufacturing facilities must take into account the radius in which people are reached. | Basmer et al., 2015 |
| 41 | New community-sharing places to learn skills: repair cafes, makerspaces, co-working spaces etc. | DS1 | | |
| 42 | Distribution of knowledge and share of skills. | DS1 | Home and DIY production distinguish by limited manpower, tools, skills and investment capacity. | Bonvoisin et al., 2015 |
| 43 | Education of consumers, which provides a better understanding of production and efficient use of products. | Srai et al., 2015 | | |
| 44 | Personalised services supporting personalised products. | Kohtala, 2015 | Higher cost of personalised/ bespoke products and services compared to traditionally mass manufactured equivalent. | Srai et al., 2015 |
| 45 | Facilitated companies' enter to niche markets. | Rauch et al., 2015 | | |
| 46 | Mass customisation and cost-effective bespoke production. | Srai et al., 2015; DS1 | Potential conflicts within organisations caused by choices to offer standardised, personalised and inclusive or bespoke products. | Srai et al., 2015 |
| 47 | Long-lasting companies' relationship with customers, caused by proximity use of digital technologies. | Srai et al., 2015 | | |
| 48 | Facilitated collaboration between producer and customer. | DS1 | Concerns of privacy issues of companies' data caused by application of cloud manufacturing and ICT. | Srai et al., 2015; DS1 |

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