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Data Mining in Product Service Systems Design: Literature Review and Research Questions

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Abstract

The paper presents a literature review about data mining applications in Product/Service-Systems (PSS) design. A systematic literature review, combined with snowballing techniques, has been run to identify relevant contributions in the area. The analysis has focused on the categorization of the contributions according to their impact on the PSS design process and according to their theoretical or empirical nature. A picture of the different research achievements for each stage of the PSS design process have been drawn, identifying the research gaps in respect to the challenges of PSS design. Based on the analysis the paper proposes a set of research questions for each PSS design stage with the intent of facilitating the application of data mining techniques in PSS design, and ultimately push forward the state of the art.

Keywords: Product service systems design; data mining; research questions; literature review.

1. Introduction

Information and communication technologies have revolutionised lifestyles, global interaction and industrial working practices. Companies are nowadays potentially capable of collecting data about any product lifecycle activity and performance. Devices and sensors may become “smart” and are used in a variety of contexts: from monitoring the performances of machines, to predict failures and run preventive maintenance, to provide driving assistance and to manage a whole fleet of vehicles based on GPS (see for instance [1-3]). The use of data mining in combination with the development of IT infrastructures and with increased data storage capabilities, has propelled a profound shift toward more transparent, informed and autonomous decision-making [4]. However, while companies are often in the situation of being capable of collecting a huge amount of data, their use is often limited to maintenance and management purposes; more rarely those data become useful knowledge and insights in the design phase of a new products or services. A challenge is given by the multi-dimensional and multidisciplinary nature of the design process, generating a large amount of heterogeneous data for which suitable mining methods are not readily available [5], accentuated by a generic lack of context around the situation where data is collected. In the development of products and services combinations, i.e. product/service-systems (PSS), a formalized approach on how to use data to develop new and more value adding solutions is missing. This is due to the relative novelty of both the PSS design field and of the data mining field, which have developed with different focuses requiring different expertise.

The research presented in this paper has the purpose to explore the potential that resides in the integration of data mining techniques into methods and tools for PSS design. The aim of the paper is therefore to investigate, and review, the theoretical and empirical applications of data mining in PSS design literature, by:

- Mapping and analyzing the current contributions into the PSS design process.

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- Highlighting a list of research questions to be addressed to enable a wider application of data mining into PSS design.

The paper first describes the methodology applied in the literature review by briefly presenting the PSS design process used as a reference for the analysis. In section 3 the literature review and the analysis are presented together with a number of identified research questions. Section 4 closes the paper by drawing the final conclusions.

2. Methodology

The research was initially approached through a literature search run on a major research database (i.e. Scopus[1]). The scope of the search was deliberately limited to those papers presenting the use of data mining techniques referring to the design of PSS or to the conjunct design of products and services. The concept of "machine learning", although not synonym of data mining (as explain in section 3) was also included in the research, to assure the completeness of the results.

In a first step a systematic research for papers was performed. The search was directed toward titles, abstracts or keywords containing the term "product service systems" in combination with either "data mining" "machine learning" or "data science". This first round of analysis led to the identification of only 13 unique papers. Due to such limited number of publications the literature base was expanded by applying a snowballing technique [6] on the initial set of papers. The reference list of each of the paper was screened for relevant contributions and 21 papers were selected for detailed analysis at the end of the process.

Those papers were later analyzed by classifying their content and contribution in relation to the PSS design process. To define the categories for analysis the "Generic IPSS/PSS development process model" by Müller and Stark [7] was adopted as reference. The model is "V-shaped" and encompasses 4 levels of detail: market/customer/environment level, value level, system level, module and component level. For each level, different activities take place involving different stakeholders. The following five main activities have been identified in accordance to the model and have been used to provide a first classification of the literature:

- Planning
- Idea generation
- Embodiment design for subsystem
- Detailed design
- Delivery and use phase

The papers were further categorized by adding a distinction between those describing a framework or a conceptual method and those providing examples of real case study applications. The classification was run in a way that each paper could be assigned only to one category. The discriminant for the selection was the "main contribution" of the paper, evaluated based on the content and on the terminology stressed by the authors in the "conclusion" section of the papers.

The analysis of the literature and the research questions derived are the result of an analytical process applied to a critical literature review (similarly to what described by Jessons and Lacey [8]). The theoretical contributions were analyzed in respect with the available examples in applied research. This has allowed the production of a general framework of analysis in consideration of the main issues and challenges recognized in literature for the design of PSS, encompassing weak and sweets spots of the main PSS design methods and tools. Upon this basis, the direct impact on applied practice was the driving criterion for the definition of the questions, with a focus on the empirical benefits of developing more advanced method and tools for PSS design.

3. Data mining in PSS design: contributions and research questions

Data mining is defined as the discovery of non-trivial, implicit, previously unknown, and potentially useful and understandable patterns from large datasets [9]. When it comes to application of data mining in industrial environments, the term is often associated with the concept of machine learning, i.e. the study of computer algorithms that improve automatically through experience [10]. Data mining and machine learning are used in engineering both with the predictive goal of forecasting the value of a variable and with the descriptive goal of understanding and discovering patterns in the available data [9]. The following sub-sections provide an account of the application of data mining and machine learning available in literature highlighting applications explicitly referring to the context of PSS design.

3.1. Summary of state-of-the-art and paper categorization

The papers identified in the literature review have been first categorized based on if their main contribution in respect to the PSS design process, and then based on the type of academic contribution, that is, if the paper presented a conceptual framework or method, or if it concerned the presentation of a real case implementation of an approach. A further distinction was made based on the terminology used when referring to the design of product and service combinations, i.e., the papers explicitly referring to PSS in the text, and the papers not directly using the PSS terminology even if dealing with relevant topics for the investigation. The reason for doing this last classification was to verify the popularity of the data mining topic in the major publication arena for PSS research.

The results of the classification are visualized in Figure 1. The numbers in the white circles indicate the number of publications for each category directly or indirectly related to the development of PSS, the numbers in the grey circles indicate instead the number of those publications explicitly referring to a PSS terminology.

[1] www.scopus.com

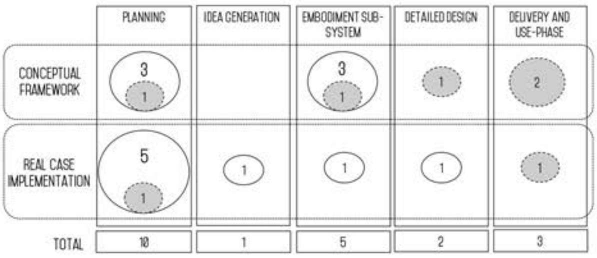

Fig. 1. Number of publications dealing with data mining in PSS and their categorization according to the PSS development process by Müller and Stark [7]. White circle = all publications, Grey circle = Publications explicitly referring to PSS.

In general the analysis highlighted a quite limited number of published contributions about data mining in the PSS area. It also shows that the contributions explicitly referring to PSS have focused more on the delivery and usage phase. Figure 1 shows a gap toward proposing either conceptual methods or case applications where the use of data mining is linked to the idea generation phase of a PSS design. The fact of being a quite early activity in the development process with limited availability of data does not seem to be a consistent explanation for the gap, given the high amount of contributions focusing on the "planning" phase happening before the idea generation phase. The following sub-sections analyze the results of the review for each of these phases in relation with the literature available. They further identify a number of questions to be addressed for further investigating the use of data mining in PSS design.

3.2. Planning the design of a PSS

The most discussed applications in literature concern the use of data mining technique to enable a more effective planning of the PSS development. This activity encompasses the identification of relevant customers, highlighting the different needs concerning different customers' groups, but also the identification of the functional requirements best satisfying an established set of customers. To achieve the first goal Lei and Moon [11] have proposed a decision support system that uses an Adaboost algorithm to identify the market segment to which a new design belongs, with the intent to support the management selection of the target market. Pajo et al. [12] have instead proposed a model making use of the data collected through social media and apply data mining and machine learning to identify the correct customers' needs.

A different strategy consists in extracting knowledge from customers in order to create product maps for new product development: such approach has been tested by Liao et al. [13] by applying an Apriori algorithm to describe association relationships between product map knowledge and customer data. Association rules were also used by Agard and Kusiak [14] for the design of products family but, in this case, data mining was applied on an already selected set of customers to analyze the requirements for a new product design. Additional application encompasses the classification of functional requirements to preliminary classify existing design [15] and of functional attributes to identify the most relevant attributes influencing the product purchase [16].

Association are also applied by Liao et al. [13] in a PSS development context to create product maps aligning users' characteristics with product characteristics. The approach is meant to ease the identification of specific needs for different users, based on the available data. At last, the work of Geng et al. [17] is among the most interesting approaches explicitly stating the contribution to PSS development. They highlight how designers' individual experience is insufficient to fulfill the goal of domain mapping, because of the highly complicated relationships between customer requirements and design requirements. They use an Apriori-based association rule algorithm to elicit parameter-translating rules for aiding the PSS conceptual design. They also introduce the idea of using a dynamic database as data source; they propose an algorithm (named Fast Update Algorithm) capable of evaluating newly inserted records to determine whether re-scanning the original database is needed.

In summary, association rules have been proposed in several approaches as a way either to discover relationships between product characteristics and customer needs, or to understand the segmentation of the potential customers. From the review it emerges that the methods proposed explicitly targeting PSS development do not sensibly differ from the method proposed for generic new product development, although a higher level of complexity in matching customers' and design requirements is recognised for PSS. This highlights a gap in the available methods toward integrating a service perspective when applying data science for the planning of PSS design. The shift from traditional products to PSS offerings shall be pursued with the intent of providing higher value to the customers through multiple channels; however current applications of data mining for PSS design lack of the capability of identifying the "unspoken needs" of the customers in respect to new functions or service channels. The work from Pajo et al. [12] is an example of the attempt of expanding the knowledge base by indirectly deriving unspoken needs from social media interactions, and it is the only contribution of this kind found in the review.

Based on the analysis the following questions arise as worth investigating concerning the use of data mining in planning the design of PSS:

- What data are relevant to identify unspoken needs when planning the design of a PSS?
  - Which data collection channels shall be explored?
  - Where the data about the unspoken "desire for a service" shall be collected?
  - How do data and channels differ between a business to consumer and a business-to-business scenario?

3.3. Idea generation for PSS development

The idea generation phase follows the identification of customer needs and it is where a brief concept architecture is ideated together with an overall project definition and the specifications of the system level. It is the most creative stage of the development where several ideas are proposed and quickly evaluated. Such evaluation is often based on models to assess the value of a design idea mostly based on qualitative estimation and expert judgment.

A first challenge of the idea generation phase for PSS is the necessity of generating ideas for new solutions that can be very heterogeneous in nature, since the range of solutions spans from pure products to pure services. Given a set of identified customer needs there is no established method for value quantification to guide designers toward developing a product, a service, or a certain degree of combination of the two. The expertise of engineers and designers involved has a strong influence on the individual capability of generating new ideas, that is, engineers accustomed with product development will be most likely prone to propose product oriented solutions, while engineers that are experts on service development will do vice versa [18]. Such issue is also reflected in a second challenge of the idea generation phase, i.e. the capability to quickly assess the value of several PSS ideas to decide which one to promote for further development. Here experts' judgment requires a heterogeneous knowledge based both on products and service skills, something usually outside the technical horizon of an engineer [19]. Furthermore, trade-offs need to be made between ideas that can span from pure products to complete functional offers, with a high risk of lacking common terms of comparison to base an objective evaluation upon.

The use of data mining techniques to facilitate idea generation is an area poorly explored in literature, not addressing the challenges described above. There are no specific methods developed in the PSS field making benefit of data mining, neither for idea generation nor for idea evaluation. An attempt has been done in the engineering design field by Shi et al. [20], using data mining to assist the design knowledge retrieval based on keywords association. However, such work does not directly focus on PSS and remains quite unique in its kind. Despite a clear need for design support the use of data mining in idea generation for PSS development is far for being a reality. A set of relevant questions is in need for investigation to build a consistent knowledge, prior to the development of specific methods. Those are:

- How can data from available products and services be used as inspiration source in the idea generation phase?
- How can the qualitative assessment of experts be replaced by data-driven assumptions about the performance of a product or a service?
- Can data on available PSS be mined to create a generic model for product and service performances in the presence of different contextual variables?

3.4. Embodiment design for sub system design

In the embodiment design for sub system design phase the development focus shifts toward the subsystems that will be integrated in the PSS offer. The PSS system level specifications have already been defined thus the goal is to integrate the best combination and best design of the sub-systems. This phase has attracted the attention of several authors in both the PSS and engineering design field, with a number of them proposing the use of data mining methods to improve the efficiency and the effectiveness of the activity. Among those Wickel and Lindemann [21] focused on engineering changes by applying association rules to derive recommendation from a database of engineering changes. Song and Kusiak [22] instead mined customers' orders to identify the frequently ordered attachments and identify sub-assembly patterns to cut out design analysis attachments seldom ordered. Lützenberger et al. [23] identified the transfer of usage information to design requirements as one of the major challenges in the development of a successful PSS and proposed the use of data mining from the usage phase to improve design parameters in this stage. Concurrently Isaksson et al. [25] proposed a framework for the use of machine learning to generate response surfaces to be integrated in the CAD simulations with the final goal to develop a model based decision support for value and sustainability. Their work highlighted the need for models capable of projecting the impact of a change at a sub-system level into the overall system performances.

The review highlighted that the need to retain the "big picture" of the overall PSS value, even when working at sub-system embodiment design, is a major challenge to be addressed by PSS design methods. However, the multi-disciplinary nature of the design and the parallel work of different design teams do not make the communication easier, and the integration of the assessment models is far from being reached. This leads to a set of questions complementary to those listed in section 3.3, those are:

- How can the output of multiple data analysis models be integrated in a unique decision support system?
- How can the results from different analysis be communicated effectively to a heterogeneous group of stakeholders?
- How can a unique decision support system work as a boundary object to ease the communication of information among cross-functional design teams?

3.5. Detailed design of a PSS

In detailed design, requirements for both products and services are defined and the focus is on optimizing the design in relation to the original design intent. To this concern, Vale and Shea [24] have proposed an approach based on data mining relying on two agents, a 'data modeler' and a 'modification advisor'. In the approach the data modeler observes and analyses the effects of sequences of modifications on the design objectives, and rates them accordingly with an associated figure of merit. The modification advisor ranks potential imminent modifications, such that highly ranked modifications facilitate high scoring sequences. More recently Quintana Amate et al. [26] proposed the integration of a knowledge based engineering implementation into a knowledge-sourcing framework encompassing the automatic execution of machine learning methods to generate new knowledge. They proposed a case of design optimization for a wing cover, modeling how the change in one value parameter affects the time required to manufacture a wing structure.

In general, the cases of application of data mining for this stage of PSS design are very limited. As for what observed in section 3.2, while it is possible to find cases of application related to design products, it is much harder to find cases of applications related to the detailed design of the service part of a PSS. The shift toward a more service-oriented perspective requires detailed design modifications to be analyzed in respect to their robustness; this encompasses a scenario (i.e. the service one) that is more dynamic compared to a product-oriented scenario, traditionally not dealing with lifecycle and end-of-life-related issues. This recalls the concept of "ilities", introduced in the Systems Engineering literature [27] as a category of criteria expression of system robustness under changing process conditions. The PSS detailed design phase expands the necessity of considering criteria such as "ilities" (i.e. survivability, adaptability, flexibility, scalability, versatility, modifiability and robustness [27]) also for what concerns the service side of the offer.

The gaps highlighted by this analysis can be summarized in the following questions:

- How can service data be fed back to the design team to better estimate the performances of future services?
- How can usage data be mined to increase engineers' awareness of product and service performances in the presence of contextual changes?
  - How can the impact of a detailed design modification be assessed in terms both of product and service robustness?

3.6. Delivery and use-phase of PSS

The last step of the analysis focused on the delivery and use phase of a PSS. Retaining the ownership of a product by providing it as a PSS increases exponentially the possibility to collect data about its performances, in comparison with the selling of a product including the "traditional" transfer of ownership and control. Potentially a large amount of data can be collected at this stage both in a business to consumer and in a business-to-business context. In result-oriented PSS where the availability of a certain function is granted by contract, such data collection becomes in many cases a necessity to allow preventive maintenance and best manage the available resources. The contributions for this phase presented in literature are of different nature. Abramovici et al. [28] have focused on information retrieval by proposing a semantic information retrieval framework based on text mining. Beckmann and Dzaack [29] focused on the incorporation of motion data and cognitive models in PSS; their idea is to run automatic assessment of human actions by using machine learning on motion caption data to prevent the execution of improper actions. Akhavian and Behzadan [30] have instead presented a prototype of a ubiquitous data sensing and analysis system based on simple sensors embedded into a smartphone. Their approach transforms raw data into knowledge to be ultimately incorporated into a data-driven simulation methodology.

Nowadays the collection of data does not represent a technological barrier any longer, and in many cases data are collected with low or no cost. What is however still a challenge is how to make the best use of such data. While many examples for product or service maintenance and management are available, it is still very uncertain how can those data be used to impact the decision-making activities in the design of new PSS concepts. No established method is available to integrate the use of data from the use-phase in decisions making when it deals with the ideation of new and innovative PSS. Such challenge shows a clear link with what discussed in section 3.3 about how to improve the idea generation phase. This leads to the formulation of the following questions complementary to those presented in 3.3:

- What are the relevant data to be collected and analyzed in the PSS usage phase to be integrated in decision-making models?
- What are the data mining algorithms to be best integrated in the current design models to render reliable results for decision-making?

Furthermore, to successfully merge methods from a different discipline, such as data science, in an environment which is largely engineering-oriented, it is necessary to overcome what Freitas [31] defines as "comprehensibility barrier" of data-science algorithms, that is, the results need to be clear and easily understandable to engineers. This leads to the following final question:

- How can the results from data mining analysis be effectively communicated in a PSS design environment?

4. Concluding remarks

The use of data mining has been recognised since more than a decade as potentially able to create a profound shift toward more transparent, informed and autonomous decision-making. While this has become a reality in many application fields, the same cannot be said about its use in PSS design. Some initial approaches and attempts of application have been proposed in the engineering design field, with some works specifically oriented toward the development of PSS. However, the extent of its application is still limited, leaving the field open to opportunities and challenges. The competences and the knowledge basis of people involved in data science, on one side, and PSS design, on the other side, are rather different, so a conjunct research effort is needed to fill the gap between the two areas, and create methods and tools to bring consistent contribution to the PSS design process.

This paper has presented an analysis of the literature currently discussing the use of data mining and machine learning for PSS design. Both theoretical contributions and real case implementations have been analysed and discussed in relation to the PSS design process. Based on such analysis a list of research questions has been identified with the scope of proposing directions for further investigation.

The paper contributes to academy by stimulating the cross disciplinary discussion between the research fields of PSS design and data science. The consideration of the research questions proposed will allow the development of methods and tools exploiting the benefit of data mining in a decision making context where those techniques are seldom applied, ultimately pushing forward the state of the art of PSS design.

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