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A Systematic Design Approach for Service Innovation of Smart Product-Service Systems

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Abstract

Recent development and implementation of advanced information and communication technologies (ICT) (e.g. Internet-of-Things (IoT), Cyber-Physical System (CPS)) has triggered a promising market of smart, connected product (SCP), and hence, enabled the prevailing tendency of manufacturing value proposition towards a service-oriented manner, viz. Smart product-service systems (PSS). Smart PSS, as a unique type of PSS, aims to achieve individual customer satisfaction with less environment impact by utilizing SCP as the media and tool, to generate various e-services as a bundle. Its service innovation is enabled by a platform-based approach and generated in a data-driven manner. Moreover, the digitalization of users, things, manufacturers and service providers in the cloud-based environment also provides potential service innovation opportunities. Nevertheless, only few existing works discuss about the Smart PSS, let alone an effective manner with valid cases to support its service innovation. Aiming to fill this gap, this research provides a novel definition of Smart PSS, and proposes a systematic design framework for its service innovation with an elaborated case study of a personalized smart wearable. Meanwhile, other potential industrial applications are discussed as well to offer valuable insights to manufacturers in their servitization for value creation.

Keywords: *data-driven design; smart, connected product; digital twin; product-service systems; value creation*

Nomenclature

B2B	Business-to-Business	IoU	Internet-of-Users
B2C	Business-to-Customer	IT	Information Technology
CAD	Computer-Aided Design	OEM	Original Equipment Manufacturer
CPS	Cyber-Physical System	PLM	Product Lifecycle Management
FFT	Fast Fourier Transform	PSS	Product-Service Systems
ICT	Information and Communication Technologies	RFID	Radio Frequency IDentification
ID	Identification	SCP	Smart, Connected Product
IMU	Inertial Measurement Unit	SQL	Structured Query Language
IoS	Internet-of-Services	SoC	System on Chip
IoT	Internet-of-Things	URL	Uniform Resource Locator
		WSN	Wireless Sensor Network

1. Introduction

In today's highly competitive market, manufacturing companies are striving to achieve higher user stickiness, profitability and sustainability with more environment concerns (e.g. low carbon strategy (Ma et al. 2017)), by providing personalized products with value-added services (Parida et al., 2014). This servitized value proposition is known as PSS (Mont, 2002; Tukker and Tischner, 2006), which is a business

strategy for value creation with lifecycle concerns, realized through cooperation and interaction of the different stakeholders (e.g. customers, OEMs, and suppliers) (Meier et al., 2010). Since first coined, PSS has been widely investigated in both academia and industry as an economic, environmental, and social sustainable approach to innovate product-based offerings with competitiveness (Tukker 2015). By adopting PSS, manufacturers' emphasis has progressively shifted from the product-centered manner to the service-oriented one, i.e. *servitization* (Song et al., 2015), where product is the tool generated for service innovation (Kuo and Wang, 2012). Hence, the goal is to deliver other than a product (by ownership), but its performances (e.g. pay-per-performance) and usage (e.g. pay-per-use, renting, etc.) as a bundle (Marilungo et al., 2017).

In the technical aspect, IoT (viz. WSN and RFID) is largely accepted as the enabling technology with the highest economic impact for PSS development (Marilungo et al., 2017). It has been widely adopted in manufacturing enterprises (e.g. automobile, medical devices, etc.) to enhance product value and create novel services for stakeholders, segmented into a B2C or B2B market (Takenaka et al., 2016). Nevertheless, driven by the rapid development of ICT, low cost, high performance embedded components are ever increasingly introduced by manufacturers, so as to embracing a promising market of information densely product, i.e. SCP (Porter and Heppelmann, 2014). Apart from the mechanism of IoT by providing a ubiquitous connectivity at a low cost for information transmitting, SCP represents the third-wave of IT competition. And it changes the way how value is created by embedding IT (i.e. smart and connectivity components) into the product itself (Porter and Heppelmann, 2015). Owing to its capabilities of collect, process, produce information and somehow to "think by itself" (Rijsdijk and Hultink, 2009), SCP as the medium and tool, enables the active interactions between manufacturers and end-users, and also the generation of new services (Zheng et al. 2018).

Hence, a new paradigm, viz. Smart PSS, has been proposed and was defined as "*the integration of smart products and e-services into single solutions delivered to the market to satisfy the needs of individual consumers.*" (Valencia et al., 2015). In this context, huge amount of data is generated by SCP from multiple sources across ad hoc connections, and ultimately transmitted to stakeholders through various analytic tools and business intelligence (Rymaszewska et al., 2017). Informatic-based approach serves as the key for value creation by providing the ability to identify user behavior patterns or latent needs (Lim et al., 2015). Nevertheless, scarcely any work provides a clear distinction of Smart PSS with other types of PSS, and few discusses about an effective design approach for Smart PSS service innovation. Moreover, as pointed out by Kuhlenkötter et al. (2017), expect for the IT-driven innovation, the digitalization of products and services (i.e. digital twin) should also be considered for Smart PSS new solution design as well, which again lacks enough support in literature.

Aiming to address the above issues, this paper proposes a novel platform-based, data-driven and digital twin-enabled design approach for Smart PSS service innovation in the B2C business model with a practical case study. The rest of the paper is organized as below: Section 2 gives a holistic introduction of basic notions and related works. Section 3 gives a novel definition of Smart PSS and proposes a conceptual

framework with key aspects to support its service innovation process. Section 4 illustrates a smart wearable case to validate the feasibility of the approach. Section 5 discusses the result of the case study and other potential industrial applications, while conclusions and future works are summarized in Section 6 at last.

2. Basic notions

This section introduces several related concepts and their recent works to deduce the research gaps this work aiming to deal with.

2.1 Smart wearable

One of the biggest recent trends shaking up the mobile devices market is the introduction of smart wearable devices, with the industry expected to triple in size to be worth a total of \$25 Billion USD by 2019 (CSS Insight 2015). Wearable technology or “wearables” are generally known as devices with processing capabilities designed to be worn on the body (Chen et al., 2016). Devices for a variety of purposes designed to be worn on different parts of the body are steadily seeping out into the market, with major players such as Google (Google Glass), Apple (Apple Watch), Fitbit (Fitness Band) along with smaller startups developing platforms such as Mbientlabs’ MetaWear for the DIY/Maker market. Continued reduction in unit costs for these devices greatly increases the accessibility of these devices for many groups of people in many different markets. MIT’s LiveNet (Pantelopoulos and Bourbakis, 2010), a research platform for long term health monitoring via body placed sensors such as ECGs, accelerometers, etc. is utilized for long-term health monitoring with real-time data processing capabilities. Since wearables may include network attached sensors, giving them the ability to transmit and receive data, such wearables are also classified as IoT devices. Modern research into this field has yielded a few advancements such as embedding sensors into clothing for long term health analysis (Chen et al., 2016) or the fusion of data from multiple sensors into a single coherent output (Gravina et al., 2017). Moreover, the availability of the cloud creates a relatively effortless way to achieve large scale data-mining and analytics, generating opportunities for many fields such as user experience improvement and/or research trials. However, as a remarkable type of SCP with promising market share, there is scarcely any systematic approach supporting the effective generation of its service innovation in the literature.

2.2 Product-service system

The concept of PSS was first proposed by Goedkoop (1999) as “*a system of products, services, networks of “players” and supporting infrastructure that continuously strives to be competitive, satisfy customer needs and have a lower environmental impact than traditional business models*”. Since then, tremendous works have been done in its definitions, features, benefits, applications, design methodologies and system implementations (one may refer to (Baines et al., 2007) and (Beuren et al., 2013) for more details). In the bundle of PSS, intangible services can jointly fulfil specific customer needs which cannot be

achieved by exclusively adopting tangible products (Brandstotter et al., 2003). As a matter of fact, the integration of services not only aims at function fulfilment for customers, but also generate economic value for manufacturers and service providers as well (Baines et al., 2009). One example of this type of “product plus service” mode is the smart phone with apps and data plans which are provided by mobile software vendors and Internet providers (Wang, 2015). Meanwhile, another type of PSS is the “product-as-a-service” business model which stress the sale of the use of the product than on the product itself and minimize the side effects of production and consumption (Lee and AbuAli, 2011). Since products in recent years are carrying more and more smart features (i.e. smart and connectivity components), the services embedded in PSS are becoming smarter as well. Unlike conventional services, smart services are able to forge closer links with customers via identifying latent customer needs intelligently by using IT in a data-driven manner (Miche et al., 2009). Meanwhile, the digital twin established along the product-service lifecycle also provides potential ways for value creation (Tao et al., 2017). The term Smart PSS was first proposed (Valencia et al., 2015) by leveraging SCP as the media and tool, to generate various e-services as a bundle. However, the authors did not take digitalization techniques into consideration. Considering the advancement of ICT, AI techniques and service innovations, digitalization services will dominate most industrial sectors in the near future leading manufacturing companies to the 4th industrial revolution (Abramovici et al., 2015).

2.3 Data-driven design for servitization

Data-driven design is a newly brought up term with the arrival of IoT, CPS and Big Data. Unlike traditional IT-based cases which “delivers information efficiently”, this informatics-based design manner emphasizes “creating valuable information” (Lim et al., 2015). Opresnik and Taisch (2015) concluded that servitization is a data-intensive process, and effective approaches should be adopted to exploit data for new revenue stream in manufacturing companies. Massive user/product generated data serves as the key for value creation, while effective data analytics tools enable its success (Rymaszewska et al., 2017). Though lacking a unified definition in literature, data-driven design for servitization has been widely adopted in many fields, such as e-commerce, online education, medical health, and etc. This section picks those product-enabled services in the engineering field, which can be further classified into two categories based on their data sources: *user-generated* and *product-generated*.

User-generated data stands for those acquired from online reviews/comments, audio or video-based text, and etcetera based on the product. For example, Kusiak (2009) proposed a data-driven approach to evaluate the innovativeness of planned introductions of design changes and design of new products and services from a market perspective. Tanev et al. (2015) proposed a business intelligence approach by utilizing web search tools and online data reduction techniques to examine the value of product-enabled services. Takenaka et al. (2016) conducted an analytical study including to clarify users daily behaviors for new services design based on 600 users’ smart appliance logs and their response of the survey on their lifestyles.

Product-generated data stands for the one obtained through the end-products (e.g. machines, wearables). For instances, Lee et al. (2014) discussed the smart service innovation in the Industry 4.0 environment, which CPS and industrial big data serves as the key. Lim et al. (2015) analyzed vehicle health and operations data collected from inboard devices to derive new service knowledge to enhance the experience of drivers and passengers. Zhang et al. (2017) implemented the big data analytics to enable the complex product manufacturing and its maintenance services. Moreover, with the emergence of cloud manufacturing (Zheng et al., 2018), manufacturing resources (e.g. machine tools, robots) are encapsulated into the cloud to form a resource pool as the on-demand services to meet individual user requests in a “pay-per-use” manner. Hence, their intelligent resource planning and allocation driven by real-time machine data can be regarded as a product-enabled service as well.

Despite the above IT-driven approaches for potential service innovation, few works discuss a systematic design approach for Smart PSS service innovation, especially in the B2C environment.

2.4 Digital twin-enabled service innovation

The concept of digital twin was originally coined by Grieves in a university presentation in 2003 (Grieves, 2011), and defined as a virtual representation of what has been produced for PLM. According to (Grieves, 2014), it mainly contains three parts: “*a) physical products in Real Space, b) virtual products in Virtual Space, and c) the connections of data and information that ties the virtual and real products together.*” Since then, several different definitions or expressions have been brought up. Nevertheless, the core characteristics maintain the same, and have been summarized by Tao et al. (2017) as: 1) real-time reflection, 2) interaction and convergence in: physical space, between historical data and real-time data, and physical and cyber space, and 3) self-evolution. They further points out nine aspects for digital twin-enabled service innovation in the manufacturing field: 1) real-time state monitoring, 2) energy consumption analysis and forecast, 3) user management and behavior analysis, 4) user operation guide, 5) intelligent optimization and update, 6) product failure analysis and prediction, 7) product maintenance strategy, 8) product virtual maintenance, and 9) product virtual operation. In literature, most existing studies of digital twin are implemented in the field of aeronautics and astronautics for maintenance purposes in the PLM, such as reducing maintenance cost (Tuegel, 2012), real-time inspection, repair and replacement (Hochhalter et al., 2014), prediction of failure (Cerrone et al., 2014), etcetera. This is due to fact that the digital twin enables a cost-effective simulation, monitoring, control, and prediction of the physical products, especially the ones with large complexity and high-cost. Another fact is that the realization of high-fidelity, real-time simulation and control of digital twin is enabled by CPS, which refers to the “tight conjoining of and coordination between computational and physical resources” (Baheti and Gill, 2011). As pointed out by Lee (2008), “embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa”.

From the above notions and description, one can find that the lifecycle fulfillment of every aspect of digital twin scenario is quite ideal and hardly available at current stage. However, some underline

principles, such as digitalization, cyber-physical interaction, self-evolution can be adapted in a more cost-effective manner for general cases.

3. Design approach for Smart PSS service innovation

To fill those research gaps, this section discusses the fundamental issues of Smart PSS, and hence, proposes a novel systematic framework for Smart PSS service innovation.

3.1 Fundamentals of Smart PSS

3.1.1 IT-driven aspect

Figure 1 depicts the IT-driven evolvement of PSS, beginning from conventional PSS by Goedkoop (1999), which somehow benefits from the wide usage of Internet, to IoT-enabled PSS (Michael et al., 2010) with the adoption of IoT concept proposed (Kevin, 2009), and to today's Smart PSS (Valencia et al., 2015) with the prevailing emergence of SCP (Porter and Heppelmann, 2014) and digitalization innovation (Grieves, 2014). In order to clearly distinguish the three different phases, from technical aspects, two evaluation criteria, i.e. *smartness* (horizontal axis) and *connectedness* (vertical axis) are utilized, and they together represent the IT-driven value creation mechanism. Meanwhile, one thing needs to be claimed is that, the timeline of each phase only represents the hot topic/major concern in academia within that period rather than its lifecycle, and is reasonably determined by the adoption of new IT-driven innovations.

For conventional PSS, it follows the basic principles of PSS which presents a product and service bundle without much intelligence. In this phase, the major concern of IT-driven value creation lies in the efficient delivery of data/information (e.g. 3G/4G) (connectedness) with little intelligence (smartness). A typical example is the integration of a mobile phone as the product, and the data roaming function as the add-on service.

For IoT-enabled PSS, data are collected and interchanged among the networked devices such as vehicles, buildings, sensors, etcetera (ubiquitous connectedness). All of these devices interact with real “things” such as sensors, actuators and RFID, in order to co-operatively achieve a common purpose in the Internet with much intelligence (smartness). A good example will be the industrial application of RFID devices, where RFID readers/tags (product) and their embedded information are connected to the internet for production maintenance purposes (service). In this phase, the IT-driven value creation exceeds the efficient delivery of information of conventional PSS, by taking online smartness into consideration for service innovation (e.g. assembly line condition monitoring).

Smart PSS, are enabled by the SCPs, of which IT are embedded in the product itself for value creation. Hence, as an agent, it occupies the offline smartness, which can self-react to the context by leveraging the embedded systems. For example, a smart warning of low battery of a wristband. Meanwhile, these SCPs communicate with each other, adapted at a component and system level autonomously based on intelligent algorithms and big data (Lee et al., 2014), which represents the online smartness. Moreover, it results from

the digitalization of products and services, where the digital twin established between components allow autonomous interaction and further development of them (inter-connectedness). A typical example is the cyber-physical machine tool or machine tool 4.0 (Xu, 2017), which the physical product (machine tool) and virtual product/service (e.g. CAD model, prediction service, etc.) are interconnected synchronously in a cyber-physical manner. In this phase, despite the IT-driven value creation as IoT-enabled PSS, digital-twin enabled value is also included. Hence, the potential approaches of service innovation are ever broadened by the digitalization and built-in smartness as well.

Figure 1. IT-driven PSS evolution towards Smart PSS

3.1.2 Business aspect

In business aspect, Smart PSS follows the basic principles of PSS, as a value creation business strategy with sustainability concerns. Meanwhile, owing to the unique characteristics of Smart PSS, it matches well with the prevailing business paradigm of Open innovation 2.0 (Curley, 2016), which utilises disruptive technologies, e.g. IoT, CPS and cloud computing, to solve societal challenges profitably and sustainably. It is a vision of shared value, sustainable prosperity and improvements in human well-beings. For example, the crowd sensed services (e.g. traffic planning, air pollution monitoring) from large-scale smart mobile devices offered by a large number of users to other users/service providers. From industrial perspective, Smart PSS can be seen as an ecosystem-centric view of innovation. In this co-creation business model, users actively interact with manufacturers enabled by the advanced ICT techniques and become an

integral part of the innovation process. Their experience, i.e. user experience, and knowledge drives the innovation, while the value is generated by the shared profit among users, services and service providers.

Based on the above analysis, a novel definition of Smart PSS is given as: “an IT-driven value co-creation business strategy consisting of various stakeholders as the players, intelligent systems as the infrastructure, smart, connected products as the media and tools, and their generated e-services as the key values delivered that continuously strives to meet individual customer needs in a sustainable manner”.

3.2 Conceptual framework of proposed approach

As an IT-driven and digitalized system, a platform-based, data-driven and digital twin-enabled design approach is proposed for Smart PSS service innovation, which is depicted in Figure 2. For brevity, the authors refer to humans interacting with SCPs as users, regardless of which lifecycle stage this interaction takes place. Another thing to claim is that, manufacturers (producing products) and services providers (generating services) are distinguished here for illustration convenience. In real world, manufacturers are usually also service providers, except for the cases of crowdsourcing or outsourcing. Hence, the design process can be further classified into four sequential stages, i.e. *platform development*, *data acquisition (pre-processing)*, *data analytics for service innovation*, and *digital twin-enabled service innovation*, which are illustrated below.

Platform development serves as the foundation for value creation. Previous studies have indicated that adopting a platform approach with modular architecture is very effective for overcoming the servitization paradox (i.e. more service innovation with less revenue) (Economics et al., 2017). Meanwhile, a platform approach can be considered as an organizational business perspective for leveraging the value of IT-enabled interactions and digital technologies based on modularity (Thomas et al., 2014). Hence, the idea of platform approach in this work has two folds: 1) the IT infrastructure platform to be utilized/established, so as to enable the communications and hence service innovation on it; and 2) the modularized product-service family in the platform to handle the various e-services/stakeholders. Similarly, for the prior one, this work adopts a cloud-based IoT platform to enable service innovation (see Figure 2). Cloud technique is adopted due to its advantages of enabling distributed product development process, and instant access to business and technical solutions in a ‘pay-per-use’ manner without capital investment in IT infrastructure (Zheng et al. 2017b). As discussed before, in Smart PSS, SCPs act as the bridge to connect both cyber space and physical space. Meanwhile, it changes the way how users and manufacturers are interacted, in a data-driven manner. For the latter one, users are registered in the cyber space as the cloud users to form the so-called IoU. Meanwhile, manufacturers virtualize their end-products (i.e. SCPs) onto the cloud as the IoT. Again, service providers encapsulated their services (e.g. manufacturing resources) into the cloud-based resource pool, i.e. IoS as well. To this end, modularity of products and services are essential to enable the dynamic change of user requirements for personalization.

Figure 2. A conceptual framework of proposed design approach for smart PSS service innovation

Data acquisition stands for identifying effective sources and accurate collection and storage of massive user/product/manufacturer/service provider generated data, which are critical to the success of final service innovation. In Smart PSS, the major sources of data are generated during user-product interaction and product-manufacturer/service provider interaction in the physical space elicited by SCPs. They can be further divided into 6 categories: *active user-generated data* (e.g. user input), *passive user-generated data* (e.g. breathing data, walking steps), *product-generated data* (e.g. operation status), *manufacturer generated data* (e.g. new functionalities) and *service provider generated data* (e.g. service upgrade information). Another source of data is enabled by the cloud-based IoX-enabled platform, where the users, SCPs and services are digitalized and they interact with each other in the cyber space for new service innovation. For example, a user may request online 3D printing services based on the platform. Moreover, an effective manner for data storage is important as well. The dynamic, heterogonous, and increasing volume data should be stored carefully for further value creation. Some existing database system, e.g. Hadoop distributed file system, SQL data management system can be adopted.

Data analytics for service innovation. In this IT-driven big data environment, tremendous data are generated incrementally, hence, the dynamic data analytics approaches (i.e. design a promising scheme with data mining techniques to uncover hidden patterns, unknown correlations, etc.) can be more effective than static data-mining ones (i.e. statistic methods to discover value). For example, utilizing dynamic pressure data (a scheme) as a reliable data source with mathematical modelling algorithm (a data-mining

approach) for breathing pattern recognition when wearing mask. In the physical space, SCPs embedded system with smart components should have the capability to monitor, record, calculate and even think in a self-organized manner, which can be leveraged to generate *offline service innovation* (e.g. heartbeat detection). Meanwhile, in the cyber space, the cloud platform is also capable to run in the same manner, but with consideration of heterogeneous sources of data and various factors (e.g. affective and cognitive, SCP condition) for prospective *online service innovation* (e.g. air-pollution distribution by crowd sensing).

Digital twin-enabled service innovation. Different from IT-driven innovation generated only from data, the digital twin-enabled service innovation emphasizes more on the cyber-physical interactions. There exists a prevailing discussion of ‘*digital servitization*’ (Vendrell-Herrero et al., 2017) among scholars of business field, by looking at the dematerialisation of physical products into services enabled by digital technologies (Holmström and Partanen, 2014). For instance, the IoT-enabled PTC bicycle (2015). Though unlike the strict definitions of digital twin as a virtual representation of what has been produced for PLM, similarly, the digitalized product and the physical one has the ability to communicate, evolve and reflect with each other in real time. Hence, the authors argue that:

“One can be accepted as a digital twin-enabled service innovation as long as the product’s cyber space and physical space are interconnected in real-time, and to the best extent reflect the physical product in its lifecycle to generate new services.”

By this definition, the original scope of digital twin has been extended with more flexibility. For example, digitalization of manufacturing resources (e.g. machine tools) into the cloud as an on-demand service with real-time monitoring/control of its working status can be regarded as a digital twin-enabled service, even if the digitalized machine tool cannot fully reflect some sources of data, e.g. the spindle speed, due to limited resources.

Based on the above mentioned four steps, service innovation concepts are generated and hence, service providers can make detailed service design on top of the SCPs for value delivery to the users.

4. Case study of a data-driven personalized wearable

The i-BRE respiration mask developed at the University of Auckland (Zheng et al., 2017) is chosen as a companion solution for this study with the intention of it being an easily accessible and relatively simple case for the demonstration purposes. The mask is designed in a modularized structure and embedded with a MetaEnv sensor platform (2016) for real time communication. The embedded system is a Bluetooth 4.0 Low Energy wireless sensor consisting of a Nordic nRF51 SoC and an assortment of sensors for parameters such as pressure, temperature, etc. Power is supplied by a single CR2032 coin cell with an approximate capacity of ~200mAH and power usage is approximately 0.1mW during standby and 6mW during transmit operations. The authors follow the above defined stages for its service innovation.

Figure 3. CAD model and 3D printed physical model of modularized i-BRE mask.

4.1 Platform development

For simplicity and robustness, the topology of the exemplar follows a standard Server-Client architecture (see Figure 4), with the server being a cloud deployable web application in the Amazon EC2 cloud-based environment. For the purposes of demonstration, the server solely handles simple data storage and processing in this case study. As the MetaEnv is incapable of communication to the Internet on its own, a Bluetooth 4.0 Low Energy capable Android device was used as a bridge. Though the wearable is therefore inoperative without the Android device, it can be operated anywhere where an active internet connection exists. The android application uses the Volley framework to handle all network requests as well as a Realm database to handle the local storage requirements of the application.

Figure 4. The system architecture of i-BRE wearable case.

The server side of the exemplar was done in Ruby on Rails with a SQLite3 Backend handled by Rails' ActiveRecord. Ruby on Rails was picked due to the following reasons:

- *Simplicity*. Rails is a very simple framework, making development rapid and simple.
- *ActiveRecord*. It handles all querying operations to the Database in question.

For simplicity, a SQLite 3 database has been used for data storage, which would be insufficient when supporting many concurrent users. However, a switch to a more versatile SQL backend such as

PostgreSQL with load balancing and/or segmented databases on separate servers would mitigate this issue, and all required is to allocate more resources to the cloud application.

4.2 Data acquisition

This work provides an exemplar to which real-time acquisition occurs in conjunction to data processing in a completely seamless manner. Meanwhile, one should determine what types of data are needed. In this case, for illustration simplicity, only pressure data of users' breathing is collected.

4.2.1 Determining optimal sample rate

The Discrete Fourier Transform (DFT) is a method which decomposes a finite sequence of equally-spaced samples into a sequence of complex numbers representing the magnitude of specific frequency ranges. The formal definition of the DFT is as follows:

$$X_D[k] = \sum_{n=0}^{N-1} x[n] e^{-j \frac{2\pi k}{N} n} \quad (1)$$

Where k stands for the sample index, X_D represents the transformed data and x stands for the source data. The result of this however, is an algorithm that runs in $O(n^2)$ time, which increases exponentially in size as the sample length increases, making it somewhat unsuitable for our purposes. Nevertheless, a variation of the DFT known as the FFT, which uses a tree structure and subsequently allows the DFT to be calculated in $O(\log(n))$ time, significantly reducing the required computing resource for longer sequences of data. In order to facilitate the selection of values, the following criteria were imposed:

- Resolution must be better or equal to 6 breaths per minute.
- The lowest sampling speed should be used for power reasons.
- The time required to acquire a "stable" signal should be as short as possible.

The pressure component of the MetaEnv sensor allows for the following sample rates: 0.99Hz, 1.96Hz, 3.82Hz, 7.33Hz, 13.51Hz, 31.75Hz, 46.51Hz, 83.33Hz. To prevent aliasing, the sampling frequency must provide a Nyquist frequency higher than that of the expected maximum breathing rate. While no concrete verified data could be found, a source suggests the maximum breathing rate is between 40-50 Breaths/Min under exercise. This converts to roughly 1Hz and rules out the use of 0.99Hz and 1.96Hz as usable sample rates for our purposes. In order to prevent any missed data from someone with a very high respiration rate, 3.82Hz was also discarded as its Nyquist Frequency is less than 2Hz. Another limitation of the FFT algorithm is that the input length is limited to powers of 2, We will have to acquire additional samples to hit our desired resolution. In order to deliver the required resolution of 0.1Hz on the sampling data, we will need a total of N samples, with N given by:

$$N = \frac{f}{0.1} \quad (2)$$

As the sample size is fixed to the power of 2, the required number of samples for each frequency is given by:

$$N_s = 2^{\text{ceil}(\log_2(N))} \quad (3)$$

Subsequently, the sampling time is given by:

$$T = \frac{N_s}{f} \quad (4)$$

Combining everything into a single equation, one can get:

$$T = \frac{2^{\text{ceil}(\log_2(\frac{f}{0.1}))}}{f} \quad (5)$$

Putting all of this into excel to calculate the required data, we come up with the following table, of which one can immediately find that a sample rate of 46.51Hz with a sample size of 512 will result in the lowest required sampling time.

Table 1. Sample size and time taken for each sampling frequency.

Sample rate	Sample size	Time taken
7.33	128	17.46
13.51	256	18.94
31.75	512	16.12
46.51	512	11
83.33	1024	12.28

4.2.2 Data logging

The data logging aspect of the app handles two tasks, the first one being the streaming of data from the MetaEnv sensor and the second being sending the acquired data to the Rails server. The streaming aspect was achieved using the MetaWear API. Sending the data to the server was done using a JSON formatted POST request. It was decided to send the pressure data to the server every 32 samples, this is due to the following reasons:

- Network requests take up a lot of processor power, subsequently sending more in bursts costs less in battery life compared to slowly trickling them through.
- The FFT can only happen on powers of 2, with a sample size of 512 samples, the FFT can occur after exactly 16 transmissions.

4.2.3 User authentication and data storage

The Ruby on Rails server application handles user registration and access control for the Android app via ActiveRecord and the bcrypt Gem loaded into Rails. Upon login, the server generates a session and allows the user to remain logged in on further access to the server. Data storage is handled by Rails'

ActiveRecord and its SQLite3 Backend, with the individual breath data being stored in a table with the following fields:

- *token*: Unique string indicating the user for which the data is set for.
- *timestamp*: Date/Time field indicating the time which the data was captured. This is accurate down to the millisecond level.
- *pressure*: Raw decimal pressure captured by the MetaEnv sensor.
- *uuid*: Unique ID for each successive capture, separating the different captures.

The server is able to differentiate between different users by the generation of a unique token for each user, allowing data from each user to be identified.

4.3 Data analytics for service innovation

4.3.1 Cloud-based breathing condition monitoring – online service innovation

The Rails application displays raw pressure data as well as estimated breathing rate for the duration of the captured data. The raw data is drawn via the use of the Chart.js library (the upper diagram of Figure 5).

Figure 5. Cloud-based individual user breathing condition monitoring and pattern recognition.

The breathing rate chart is similarly drawn with Chart.js (the lower diagram of Figure 5), but requires a few steps of pre-processing before valid data is derived, they are as follows:

- Segment a 512-sample window from the initial position
- Run a Fast Fourier Transform via the Nayuki FFT library, internally using the Cooley-Tukey Radix-2 algorithm.
- Look for the frequency bin with the maximum magnitude between the second and last sample. We ignore the first sample as it shows us the constant effect and is not useful.
- Check the maximum frequency bin is within the range of 0.2 to 2.0Hz. This is the range considered as “valid”. Failing here could result from many factors, e.g. unfit mask, bad sensor, etc.
- Repeat the above every 46 samples to calculate the breathing rate every second.

Hence, the authors discovered specific breathing pattern of an individual user, where this data visualization package itself can be seen as a new service for user’s subscription. Meanwhile, it can be merged with other users’ data or other sensor data (e.g. barometer, hygrometer, etc.), to generate other services, such as: breathing mode detection, comfortability prediction, or even healthy breathing advice.

4.3.2 Checking mask fitness – offline service innovation

The android app has the capability of checking the fit of the mask via the pressure data coming in from the sensor (see Figure 6). The process is very similar to the acquiring of breath data as the Rails application, but only checks the first 256 samples for correct fit.

Figure 6. Android-based individual user breathing condition monitoring and pattern recognition.

The process is below:

- Stream 256 samples from the sensor
- Run a Discrete Fourier Transform on the sampled data.
- Find the frequency bin with the peak magnitude.
- Check if the found data fulfils the frequency range and minimum magnitude parameters.
- Report correct fit if the above was satisfied, otherwise report incorrect fit.

Analytics of user sensed data can be carried out to generate new mobile app development, such as detection of current exercise state by detecting changes in parameters of breathing rate or pressure fluctuations. It can also be used in tandem with other sensors (e.g. IMUs) for more accuracy as well.

4.4 Digital twin-enabled service innovation

Despite the above IT-driven service innovation. Digitalization in the cloud-based platform enables several other potentials for service innovation. Firstly, the modularized mask is virtualized in the cyber space with direct connection to a product configuration system by a specific URL (Figure 7 (a)) and hence connected to the cloud-based 3D printers, so that the customized order fulfilment is offered as a service to the users. Secondly, users' facial features are captured by 3D scanner and utilized for simulation of wearing conditions combined with the sensor data captured in real life (Figure 7 (b)). Hence, new services can be generated such as: next-generation design optimization, prediction of filter change or comfortability.

Figure 7. An example of i-BRE digital twin-enabled service innovation.

5. Discussion

Masks are usually regarded as consumables without any smartness or connectedness (blank in the body sensor network area). By adopting the proposed framework of the Smart PSS, the i-BRE mask developed by the authors aims to fill the gap, and to showcase how smart services can be added to the product in a systematic manner. For example, smart warning mechanism is an add-on smart service embedded (*offline service innovation*) in the product itself. Meanwhile, the massive sensing data (e.g. PM 2.5) in the cloud can be composited to generate new service package (e.g. air pollution distribution) as well (*online service innovation*). Furthermore, regarding the *digitalization service innovation*, the user sensed data (e.g. pressure data, humidity data) can be utilized for simulation purposes in the virtual space (e.g. CAD environment) to design next-generation services (e.g. remind users to change filter cushions). The project starts by the end of 2016, where there was no existing robust, cloud-based platform to support wearable data acquisition. As an initial attempt, it has been promoted in several Innovation and Entrepreneurship competitions with much concerns from public (www.icocreation.com). Meanwhile, the total cost of establishing such a platform with SCPs and 3D printing devices to enable such service innovation is only hundreds New Zealand dollars (excluding manpower fee). However, nowadays, many platforms with analytical tools have been established, such as Google Cloud IoT solutions, SensorUp, MetaHub, and etc., which even benefit developers to create their own Smart PSS readily.

Furthermore, the author would like to argue that the concept, technical aspects and the design approach can also be extended to wider industrial applications for PLM and servitization concerns (e.g. smart bicycle, automobile, heavy machine, etc.), even in a B2B business model. The digital twin-enabled service innovation (some papers name it *cyber-physical PSS* (Wiesner et al., 2017)) can be established in the smart factory environment, or between the OEM and its suppliers in providing an integrated service package. For example, the suppliers can deliver customized add-on modules (e.g. a navigation module) by adaptable interfaces provided by OEM (e.g. car manufacturer) in a platform with value-added service (e.g. smart route plan or user behavior discovery) integrated with the overall car services throughout lifecycle.

6. Conclusion and future work

The booming of ICT development and implementation has triggered the flourish of a promising SCP market, and also benefit the servitization of manufacturing companies towards a Smart PSS value proposition. In Smart PSS, SCP is the key for value creation, and acts as the portal for user, manufacturer and service provider's physical interactions. Meanwhile, it also motivates the IT-driven and digital-twin enabled service innovation in the cyber world as well. With only few works reported in this area, this research proposes a platform-based, data-driven and digital-twin enabled design approach for Smart PSS service innovation in the B2C business model. The main contributions can be summarized into three points:

- 1) A novel definition of Smart PSS based on both technical and business aspects. A clear distinction of Smart PSS with other two types, viz. conventional PSS and IoT-enabled PSS was depicted based on the

technical aspect. Meanwhile, as a value co-creation business strategy, it follows the principles of open innovation 2.0 as a vision of shared value.

2) A proposed four-stage process for Smart PSS service innovation, viz. platform development, data acquisition, data analytics for service innovation, and digital twin-enabled service innovation. The cloud-based IoT-enabled platform serves as the foundation for connectivity, data-driven design is the core for smartness, and digital twin offers extended service innovation potentials.

3) A clarification of digital twin-enabled service innovation, which broadens the scope of digital twin applications into a more feasible and adaptable manner for service innovation in a cost-effective way.

A real-life smart wearable was applied as a demonstrative case study with technical details to showcase the feasibility of the proposed design approach. Further discussions on the wearable and other potential industrial applications can offer some insights based on the existing work. As an explorative study, this research mainly looks at the technical aspects, while many other factors should be considered in the future as well. Hence, the authors would like to recommend three potential future research directions: 1) System-of-systems service innovation in Smart PSS. SCP has the ability to communicate with other SCPs in a system-of-systems manner, more works can be done to discover new service innovation based on the interactions of SCPs. 2) The impact of digitalization for service innovation. Since digital twin may not be applicable or cost-effective in many case (e.g. real-time control), how to balance the impact of digitalization for service innovation is essential. 3) Integration of human factors with technical aspects into an overall consideration in the servitization concept generation, service design and value delivery process.

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