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Smart, Connected Open Architecture Product: An IT-Driven Co-Creation Paradigm with Lifecycle Personalization Concerns

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Nowadays, the emphasis of manufacturing has shifted from a manufacturer-dominating to a customer-centric manner by actively involving users into the co-creation process to realise individual satisfaction. In such era, the rapid development of information and communication technology (ICT) (e.g. wireless sensor network, and cyber-physical systems) enables a promising market of IT-driven product, i.e. smart, connected product (SCP), and also changes the way of user-manufacturer interaction in the product development process. However, to the best of authors' knowledge, co-creation manner in such context is scarcely reported. Meanwhile, there is a lack of any paradigms given to enable such product open innovation along the lifecycle for personalisation concerns. Aiming to fill this gap, this paper, as an explorative research, proposes a new product development paradigm, i.e. smart, connected open architecture product (SCOAP). It follows the adaptable design principles for product extendibility and lifecycle consideration. Moreover, it enlarges the scope of existing open architecture product by involving IT-driven innovation consideration as well. Hence, the definitions, characteristics, evaluation criteria, development method, and lifecycle co-creation context of SCOAP are presented in details. To make it more concrete, a demo project of a smart, connected open architecture bicycle is given at last.

Keywords: smart, connected product; co-creation; open architecture product; cyber-physical systems; personalisation; product lifecycle management

1. Introduction

The manufacturing industry has evolved through several phases in the past decades, from craft production, mass production to today's mass customisation and personalisation (Tseng, Jiao, and Wang 2010). Meanwhile, its focus has been dramatically shifted from a manufacturer-dominating to a customer-centric manner by involving active user participation along its product lifecycle. As a co-creation process, it aims to realise personalised product development, and hence individual customer satisfaction (Srai et al. 2016). In this era, the rapid development and convergence of information and communication technology (ICT) (e.g. cloud computing, Internet-of-Things (IoT), and cyber-physical systems (CPS)), has enabled a promising market of information densely product, i.e. smart, connected products (SCPs) (Porter and Heppelmann 2014). Hence, manufacturing companies are striving to create so-called sensing, smart and sustainable (S^3) products (Miranda et al. 2017) to satisfy different social requirements with value-added profits. Meanwhile, it changes the way user-manufacturer interaction in the product development process. SCP, as an information technologies (IT)-driven product, can communicate with users (i.e. product-to-user) and other SCPs (i.e. product-to-product) of the ecosystem in a distributed environment. Moreover, it has the abilities to collect, process, produce information and even learn by itself. Hence, users can actively involve in the different phases of product lifecycle, and massive user/product-generated data in the context can be collected and utilised to drive its design innovation along the lifecycle (Zheng, Xu, and Chen 2018).

Despite its prevalence, hardly any IT-driven product development paradigm has been given in the literature, and the co-creation context in the SCP lifecycle for product open innovation is scarcely discussed. Aiming to fill this gap, as an explorative research, this paper proposes a new paradigm, i.e. smart, connected open architecture product (SCOAP), from the perspective of IT-driven innovation. It follows the adaptable design principles for product personalisation and lifecycle consideration. Also, it enlarges the scope of the existing concept of open architecture product (OAP), as an open hardware innovation approach, by merging open software innovation and servitisation into consideration as well. To ensure its implementation, this work limits its focus on engineered, discrete products, while not considering non-machined, continuous ones (e.g. natural gas) (Ulrich and Eppinger 2012). The rest of the paper is organised as follows: Section 2 gives basic notions of related concepts and works. Section 3 describes the definition, key characteristics and evaluation criteria of the proposed SCOAP. Section 4 proposes a data-driven platform-based approach for SCOAP development. Then, in Section 5, co-creation context in the SCOAP lifecycle with personalisation concerns is depicted in details. To make the theoretical concepts more concrete, a project demo of a personalised SCOAP, i.e. MIRAGE bicycle is illustrated in Section 6. Conclusions, limitations and future works are summarised in Section 7 at last.

2. Related Work

To give a better view of background knowledge, this section introduces basic notions of SCP, OAP and open innovation 2.0. Meanwhile, related works of modern product design theories to support product co-creation innovation for personalisation are also summarised with the main research gaps discovered thereafter.

2.1. Smart, connected product

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-driven competition. It changes the way how value is created (Porter and Heppelmann 2015) by embedding IT into the products. According to Porter and Heppelmann (2014), SCPs are mainly composed by three key elements:

1) *Physical components* comprising the product’s mechanical and electrical parts as usual products.

2) *Smart components* consisting of the microprocessors, sensors, controls, data storage, software, and, especially, an embedded operating system and enhanced user interface. Software often can replace some hardware components or allow a single physical device to perform well at multi-levels.

3) *Connectivity components* which contain the antennae, ports, and protocols enabling wireless or wired connections with the product. They enable not only information exchange between the product and the operating environment, but also "product cloud" functions existing outside the product.

The major features (capabilities) of a SCP include: monitoring (e.g. real-time status tracking), control (e.g. a robot arm controlled by the iPad), optimisation (e.g. prediction of tool wear) and autonomy (e.g. automatic guided vehicle). 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, huge amount of data is generated by communications of SCPs from multiple sources across ad hoc connections, and ultimately transmitted to stakeholders through various analytic tools and business intelligence (Rymaszewska, Helo, and Gunasekaran 2017), which represents the online smartness. Hence, informatic-based, viz. data-driven approaches serve as the key for value creation by providing the ability to identify user behaviour patterns or latent needs (Lim et al. 2015). For manufacturing companies, they are forming the so-called S^3 enterprises (Weichhart et al. 2016) and S^3 product reference framework (Miranda et al. 2017) so as to embrace this prevailing market.

2.2. Open architecture product and open innovation 2.0

OAP was first proposed by Koren et al. (2013), in contrast to the closed architecture product that modular interfaces are pre-defined by the original equipment manufacturer (OEM) without access by general public (Zhang et al. 2017) It is defined as *"one with a platform that allows the integration of modules from different sources in order to adapt product functionality exactly to the user's needs."* Large companies, like OEMs, tend to develop the common platform and define the open interfaces. Small and-medium-sized enterprises (SMEs), as third-party vendors produce add-on modules that could be interfaced with the OAP platform (Koren et al. 2015). The customers engage in designing the options of their individualised product by using CAD software package developed by manufacturer or ordering certified modules from different vendors. Hence, it indeed shares a vision of platform-based approach to enable openness, while the open interface serves as the key to its success. Hu (2013) argued that an OAP platform that allowed for product compatibility/interchangeability of its functional features or components is essential for mass personalisation and individualisation.

Open innovation 2.0 (Curley and Salmelin 2013) is a business paradigm that utilises disruptive technologies (e.g. IoT, big data and cloud computing), to solve societal challenges profitably and sustainably, and more quickly and ably than before. It is a vision of shared value, sustainable prosperity and improvements in human well-being (Curley 2016). From industrial perspective, open innovation 2.0 can be seen as an ecosystem-centric view of innovation, where manufacturers' emphasis has progressively shifted towards servitisation, where product is the tool generated for service innovation (Kuo and Wang 2012). Hence, SCPs and their digitised e-services are integrated into single solutions delivered to the market to satisfy the needs of individual consumers (Valencia et al. 2015). In this novel business model, users becomes an integral part of the innovation process (i.e. co-creation) and their experience, i.e. user experience, drives the innovation. From product development perspective, open innovation 2.0 matches well with the OAP concpt, and can be exploited as a principle that takes product open innovation, sustainabilty, intelligence and servitisation into an overall consideration.

2.3. Existing methods to support product co-creation innovation for personalisation

Co-creation is defined as an active, creative and social collaborative process between users and manufacturer, aiming to creating values for customers (Piller, Ihl, and Vossen 2010). Specifically, in the SCP lifecycle context, several existing design theories/systematic approaches can be adopted/adapted as the support for co-creation innovation. They are further classified into two categories: *platform-based approaches* and *data-driven approaches* in the literature, respectively.

For *platform-based approaches*, it has two folds: 1) product family design and platform development; 2) IoT-enabled platform. For the prior one, concurrent engineering provides essential principles to support semantic interoperability between engineering domains across SCP development process for DfX activities (Miranda et al. 2017). Among them, adaptable design (Gu, Xue, and Nee 2009), as a typical approach, can be adopted for co-creation product changeability and lifecycle concerns (e.g. OAP). It provides two categories (i.e. design adaptability and product adaptability) with design principles to systematically enable design flexibility under certain constraints in the early product development stage, and the easy replacing/upgrade of existing product modules in the later product usage or re-configuration stage based on the ever-changing customer requirements. Moreover, product configuration system (PCS), as a knowledge-based system to tailor a product according to the specific needs of a customer, serves as a key role to enable online user-manufacturer interactions (Zawadzki and Zywicki 2016). It benefits the company by reusing existing design elements with shorter lead time to provide customer-perceived product within the product family or in an engineer-to-order (ETO) manner (Zheng et al. 2017a). For the latter one, with the rapid development of IoT techniques, it provides a ubiquitous connectivity infrastructure consisting of high-performance computational entities and physical hardware (Xu, He and Li 2014). Big IT companies, such as Amazon and Microsoft are all providing their IoT platforms and solutions, e.g. Amazon EC2, Azure, etc. Meanwhile, owing to the IoT middleware and CPS, computational entities are connected with or embedded in the physical hardware so that they can monitor, control, operate and coordinate the hardware to achieve specific tasks (Zheng, Xu and Chen 2018). Therefore, by establishing the virtual twin, SCPs can be reconfigured online during usage domain in the IoT-enabled platform as well by communicating with the physical product, and adapted to meet individual needs remotely (Abramovici, Göbel, and Savarino 2017).

For *data-driven approaches* or informatic-based approaches, they leverage pervasive computing resources and artificial intelligence methods to assist product development decision makings. SCPs own the powerful computation and communication capabilities with various built-in sensors that allow them to generate data and communicate to the Internet (Zhang et al. 2016). Meanwhile, massive users equipped with SCPs are enabled to contribute their data/information, so that valuable knowledge can be extracted/generated readily (Lim et al. 2015). The data-driven approaches have been widely applied in many areas, such as final product quality prediction (Wang 2011), predicting the remaining useful life of critical components (Mosallam et al. 2016), and user experience elicitation (Zheng et al. 2018) in the product development context. Moreover, add-on services of SCPs can be created by considering the digitalised service innovation, such as real-time monitoring, product energy consumption, etcetera (Tao et al. 2017).

Despite the existing studies, as an emerging field, little work has been concerned on the IT-driven product open innovation. Moreover, apart from the literature summarised, most existing works still look at product development process as a classic design practice, and no existing approach alone supports the SCP lifecycle co-creation process for personalisation. Therefore, an appropriate product development approach with its lifecycle co-creation context should be provided.

3. Smart-connected open architecture product

Motivated by the concept of OAP, and to embrace the prevailing SCPs and open innovation 2.0, this section proposes a novel IT-driven product development paradigm, i.e. SCOAP. Its definitions, characteristics, and evaluation criteria are presented below.

3.1 Definition

SCOAP is defined as: *"an IT-driven product consisting of physical, smart and connectivity components, with a platform containing both open hardware and software toolkits, that allows the integration of modules from different sources in order to adapt product and its service functionality exactly to the user's own needs throughout lifecycle."*

From the above definition, one can find that SCOAP follows the adaptable design principles, which aims to offer changeable product and its services to achieve the ever-changing user's requirements with an extended product lifecycle consideration.

Moreover, it enlarges the scope of OAP as an open hardware innovation approach, by integrating open software innovation as well. The ultimate goal is to realise mass personalisation or "market-of-one" in a cost-efficient manner.

3.2 Key characteristics

Accordingly, the key characteristics of SCOAP, can be summarised into five aspects, i.e. *smart-connectedness, openness*, *data-driven manner, servitisation,* and *sustainability*. Among them, the first two are the fundamental characteristics of which certain criteria should be achieved to distinguish with other types of products (see Section 3.3). Meanwhile, the other three are the affiliated ones inherently embedded in the SCOAP.

Smart-connectedness is the essence of such IT-driven product with built-in smart and connectivity components. It is capable to collect, process, communicate and even predict information in a user-friendly manner, based on its inherent level of smartness and connectedness. For instance, the driverless car with real-time optimised route planning.

Openness is critical to fulfil ever-changing users' needs to meet their satisfaction. It has two folds: active user involvement and high product changeability supported by various suppliers. The first one is enabled by platform offered by the manufacturer (e.g. a PCS) along the product development process, while the latter one is achieved by adopting adaptable design principles and integrating multiple vendors for product upgrade/change flexibility (e.g. an App store with various developers).

Data-driven manner represents its core value and operation manner all along the product lifecycle management (PLM). As mentioned in Section 2.3, by leveraging the effective communication between user-product and product-product, massive user-generated and product sensed data serve as the key to extract meaningful design knowledge, and hence enable the final product success. For example, personalised product recommendation based on the historical user behaviours (e.g. purchase history).

Servitisation shows that SCOAP can be utilised as the medium and tool for e-service generation. Hence, other than producing a product (by ownership), its performance (e.g. pay-per-performance) and usage (e.g. pay-per-use, renting, etc.) can also be delivered as a solution bundle (Zheng et al. 2018), e.g. shared bikes.

Sustainability is the underlined principle of SCOAP. It is achieved based on the openness of physical components by adaptable change of modules and its servitisation (e.g. change intangible services rather than physical components). Hence, it can achieve extended product lifecycle with less material, energy and manufacturing process by utilizing limited and distributed resources in a cost-efficient manner with less environmental impact (Kuhlenkötter et al. 2017, Zheng et al. 2018). For instance, reconfigure product modules rather than remanufacture the whole product with effective recycling concerns.

3.3 Evaluation criteria of SCOAP

In order to distinguish SCOAP with other types of products, three evaluation factors are set as the foundation, i.e. *smartness, connectedness,* and *openness*. Hence, the classification of three-dimensional product categories is depicted in Figure 1 (a), where 8 types of products can be derived. Except for the above-mentioned *SCP, OAP* and *SCOAP*, the five other types, viz. *usual products (UP)* Ơ*smart product (SP), Connected product (CP), smart open architecture product (SOAP),* and *connected open architecture product (COAP)* are defined below, with examples of each type given in Table 1, respectively.

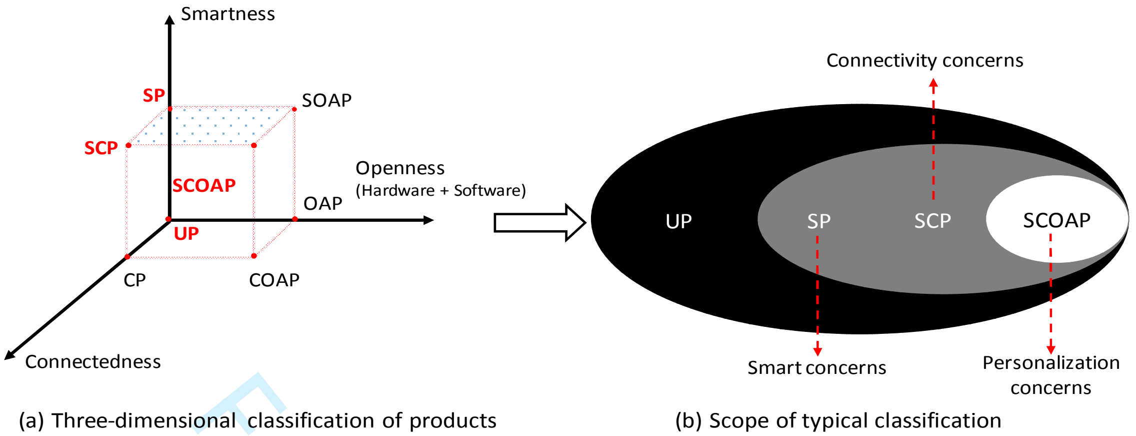
- *UP: physical products without any smart or connectivity components.*
- SP: *physical products with smart components*
- CP: *usual products with connectivity components.*
- SOAP: *smart products with open architecture.*

- COAP: *usual products with connectivity components and open architecture.*

Furthermore, regarding the product evolvement tendency in real-life, 4 typical kinds of products are elicited in Figure 1 (b), where SCOAP only possess a small portion with limited real cases (e.g. a personalised iPad). Here, the classification of each scope is determined only by considering whether the factors of smartness, connectedness, and openness included in the end products. The isolated dots inside the cube in Figure 1 (a), are utilised to indicate the overall performance in regards to the three criteria. Nevertheless, a more rigorous evaluation is given to justify the different levels of SCOAP by adapting the 5C level architecture of CPS (Lee, Bagheri, and Kao 2015) (see Figure 2) and the twofold openness.

Table 1. Typical examples of each product category.

Category	**Type/Definition**	**Examples**
Major tendency	UP	Shoes, doors, knives, etc.
	SP	Automobiles (general), robot arms, etc.
	SCP	Smart phones, iPaDs, Tesla cars, etc.
	SCOAP	Personalised iPaDs, Tesla cars, etc.
Other types	SOAP	Customised automobiles (general), etc.
	OAP	Lego bricks, etc.
	CP	Wired telephones, water pipes, etc.
	COAP	Scalable hubs, etc.



(a) Three-dimensional classification of products (b) Scope of typical classification

Figure 1. Classification of product categories based on smartness, connectedness & openness.

Level 1. Smart connectivity. This is the fundamental level of SCOAP, where the product with built-in smart and connectivity components can sense the environment and communicate with others in the product eco-system in the sensor network. The data can be directly measured by various sensors or obtained from the web/mobile social network by users. Hence, the efficiency of data transmission (e.g. generated/sensed data) and convergence to the Internet (e.g. product monitoring), viz. IoT-enabled platform serves as the main issue.

Level 2. Smart analytics. It represents the self-awareness of SCOAP by artificial intelligence approaches. Heterogeneous data sources collected are fused and conversed to the meaningful information/knowledge (i.e. pattern recognition) to be utilised for product innovation. SCOAP with embedded system and built-in program can meet this level. For example, by calculating the distance of riding, to predict the time to change the wheels.

Level 3. Digital twin. The digitalised product and the physical one have the ability to communicate, evolve and reflect with each other in real time (Grieves 2014). It is claimed that to meet this level, 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 (i.e. selfcomparison). Moreover, the historical data of SCOAP performance can be leveraged to predict its future behaviour. For instance, the bicycle demo to be illustrated in Section 6.

Level 4. Cognition. To meet this level, the product ecosystem (i.e. system-of-systems) other than a single product/system (e.g. one product family) should be established with abundant complex knowledge of it, including both extracted product-related knowledge and domain expert's knowledge. Hence, optimal decision support can be achieved by machine learning approaches with visualisation support to the users. For example, the recommendation of a riding solution, which consists of bicycle, destinations, facilities, etc.

Level 5. Autonomous. This is the highest level of SCOAP in regards to smartness and connectedness, where feedback made in cognition level from the cyber space will control the physical space in real-time with autonomous. Those SCOAPs have the ability to self-adjust to variations or self-configuration for better performance. The driverless car with optimal route selection function based on the real time on-road and cloud-based data can be a good example of products in this level.

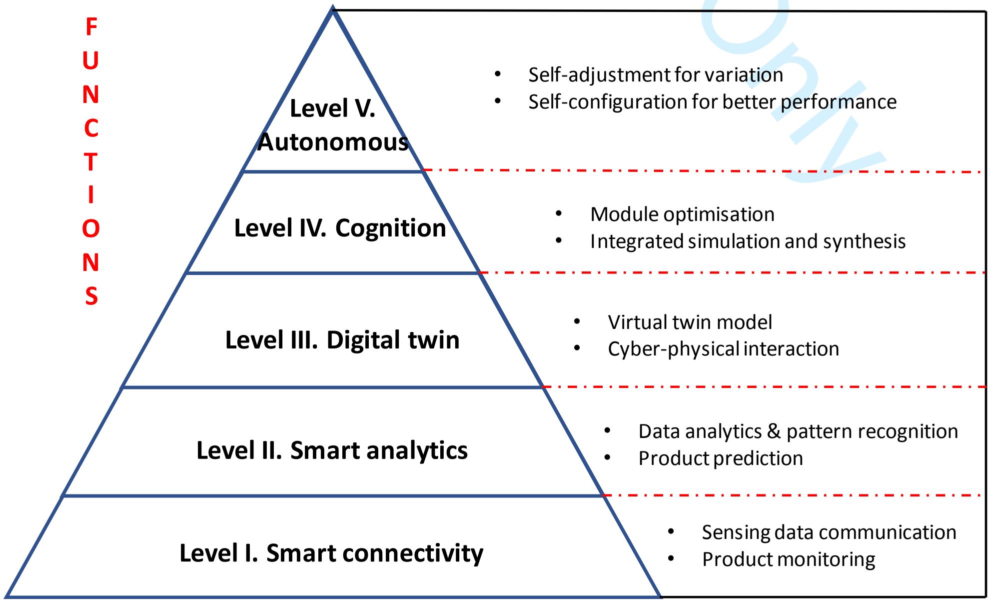


Figure 2. Evaluation criteria of SCOAP based on smartness and connectedness (derived from (Lee, Bagheri, and Kao 2015)).

On the other hand, the openness of SCOAP has two folds in such paradigm, i.e. software openness (e.g. software upgrade/add-on) and hardware openness (e.g. change of physical modules). Both are determined by the open interfaces (e.g. API or holes) provided and various vendors/suppliers integrated in the co-creation context. Moreover, the overall performance of openness is not a simple linear combination of hardware and software, but an integral consideration including all the dimensions. For example, the openness of a personalised Tesla car is realised by the integration of various Apps and different physical components into the product, while enabled/constrained by the overall performance of its embedded smart components (e.g. micro-processing system) and connectivity components (e.g. Wifi module) as well. Nevertheless, for SCOAP, software can replace some hardware components or allow a single physical device to perform well at multi-levels. For example, an Apple iOS system upgrade without change hardware component to realise new functionalities (e.g. smart home).

One should be aware that the levels aforementioned are only utilised to benchmark the proposed evaluation criteria, and companies should take overall consideration (e.g. cost, performance, positioning) to make value-added products in a more profitable manner.

4. SCOAP development methodology

As discussed in Section 2.3, none of the existing strategies alone can fit well for the IT-driven SCOAP development. Nevertheless, SCOAP adopts the basic principles of adaptable design for co-creation product changeability and lifecycle concerns.

Meanwhile, the innovative design process can be modelled by product configuration process to narrow down the user requirements. Due to the smartness and connectedness of SCP, the built-in-flexibility can be achieved with various software and hardware functionalities in the usage domain. Instead of investigating from the product design theory perspective, this research emphasises the IT-driven product development for SCOAP personalisation by exploiting the state-of-the-art ICT. Hence, the uniqueness of SCOAP development lies in its *intelligent platform-based approach* and *data-driven operation manner* in both cyber and physical world interactively. To realise it, a cloud-based IoT-enabled product development framework is proposed in Figure 3, which depicts the high-level user-manufacturer interactions.

Intelligent platform-based approach. Cloud computing provides a service-oriented architecture with different functional layers (i.e. infrastructure-as-a-service, platform-as-a-service and software-as-a-service) that enables ubiquitous access to a shared pool of configurable system resources and higher-level services of end users in a “pay-per-use” business model (Armbrust et al. 2010). It has the advantages of agility, scalability, high-performance computing, social media support, ubiquitous access multi-tenant and etcetera, where manufacturers companies can achieve abundant design information without a capital investment in the IT infrastructure (Zheng et al. 2017b). Moreover, with the co-work of CPS and digital twin (Grieves 2014), sensed data (e.g. user behaviour) can be collected, analysed and finally reflect to SCP in order to provide the best product/service to users. Hence, design and manufacturing resources are virtualised in the cyber space as services upon request in a service-oriented manner. Unlike the conventional product family design and platform development, which are conducted either in the physical space (e.g. changeable physical modules), or the cyber space (e.g. CAD models). With the embedded smart and connected functionalities, the SCOAP are capable of real-time interactions between its physical and cyber models coherently.

In the cyber space, cloud-service demander requests a personalised product by interacting with the SCOAP platform through graphical user interfaces (GUIs). The cloud-users can either conduct a product configuration process to select a customised product attribute existed on the product platform or submit a new design request to the cloud platform. Meanwhile, the SCOAP platform, hosted by the cloud-platform provider (i.e. OEM), should capture meaningful user information either through embedded ICT components, or from user's online input information. Moreover, the SCOAP platform provides adaptable interfaces for various third-party cloud-service providers (i.e. SMEs), to upload add-on modules or upgrade their resources under specific constraints. Reversely, the cloud-service providers can monitor real-time product information with the embedded components in the SCOAP platform (e.g. location information, and usage status).

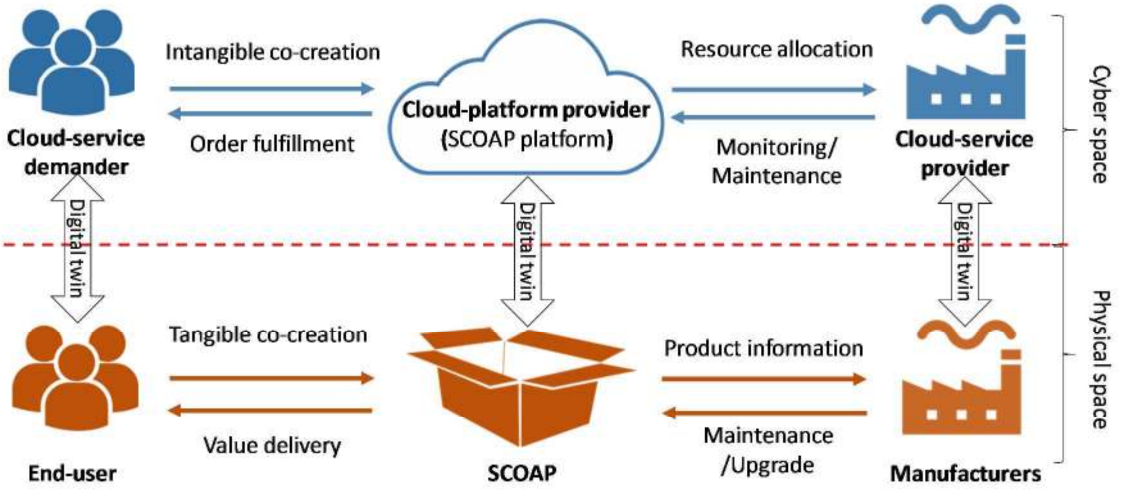


Figure 3. A conceptual framework of cloud-based IoT-enabled product development.

In the physical space, users have the tangible experience of the end-products and can make adaptable changes with the built-in-flexibility by following pre-defined constraints (e.g. the height range of a bicycle saddle). The SCOAP, delivers meaningful values to achieve user satisfaction, and also tracks important information from the user under certain privacy (e.g. location information, heart rate). Manufacturers can offer periodical product maintenance/ upgrade services to the customer based on their offline feedback in a face-to-face manner or tracked online information from the cloud.

Data-driven operation manner. Owing to the smartness and connectedness of SCOAP, massive user/product-generated/sensed data can be captured and transmitted in both the cyber and physical space, so that a synchronously interconnected digital twin can be established for each role, i.e. cloud-service demander and user, SCOAP platform and its product, and cloud service provider and manufacturer. The digital twin is enabled by a set of predefined communication protocols and standard interfaces for access control and adaptability of various ICT components. For example, body sensor network can capture real-time personal condition data (e.g. heart rate) and conduct information fusion to derive useful user behavioural knowledge in the cloud (e.g. daily exercise index) which well depicts the persona. Reversely, the online knowledge (e.g. health advice) in the cloud can be downloaded to the local mobile phone in the physical space to assist users to maintain good exercise habit. Moreover, another key benefit is that, with massive explicit (e.g. product features) and implicit data (e.g. user cognitive behaviour) elicited passively (e.g. breathing data during usage) or actively (e.g. online comments), product development tasks, such as design optimisation, manufacturing resources allocation, and etc., can be effectively modelled and analysed to create enormous personalised values.

5. Co-creation context in the SCOAP lifecycle

Active user participation in the product co-creation process can result in an improved user experience with individual customer satisfaction (Kujala 2003). As mentioned in previous sections, SCOAP takes the overall product lifecycle into consideration in a co-creation context to achieve personalisation, extended lifecycle and sustainability. Generally, an engineering product lifecycle can be classified into five sequential stages (Stark 2015), i.e. design stage, manufacturing stage, distribution stage, usage stage and end-of-life stage. For the proposed SCOAP, the ideal co-creation context is conducted in a cyber-physical manner, as shown in Figure 4.

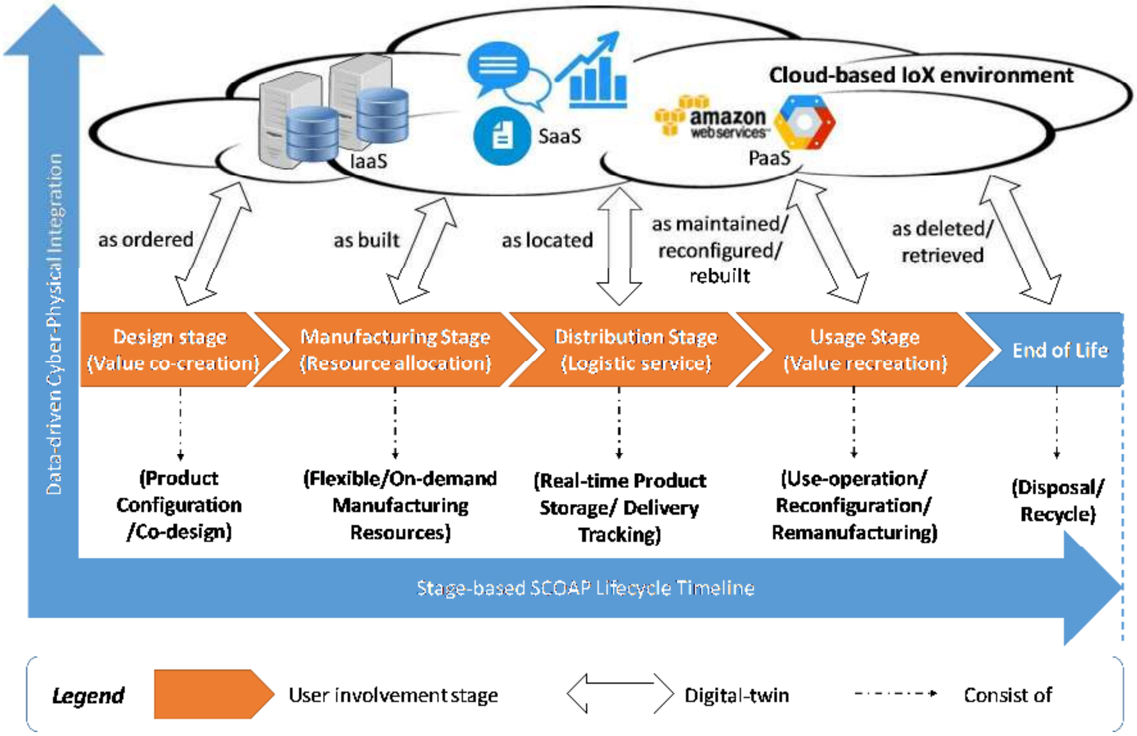


Figure 4. Co-creation context in the SCOAP lifecycle

The *horizontal arrow (in blue)* presents the lifecycle evolvement with time elapsed. Each *orange block* stands for a user involved stage, while each *dashed arrow* represents the ‘consist of’ relationship between the stage and its activities. For example, the design stage consists of co-design or product configuration activities for co-creation process. Meanwhile, the *vertical arrow (in blue)* represents the data-driven cyber-physical integration based on the content of Section 4. By exploiting the techniques of cloud, IoT and CPS, a digital twin of SCOAP development (i.e. *two-way arrow*) in each stage of lifecycle can be established in-between the specific physical and cyber models. User/manufacturer/product-generated/sensed data are recorded and analysed in the cloud-based Internet-of-X (IoX) (i.e. IoT, Internet-of-People and Internet-of-Services) environment, to enable real-time communication (e.g. monitoring, control) between the digital twin. The details of its co-creation context and interaction process of subsystems in each stage of SCOAP lifecycle are described below from the user's perspectives.

5.1 Design stage - value co-creation

The SCOAP design stage, as the value co-creation stage, is critical to enable the final success of the product. In this stage, two isssues are significant: 1) product family design to meet individualised changeability/upgrade demand; 2) co-creation toolkits to enable the user's own design request. Correspondingly, the co-design process for SCOAP can be conducted in two ways:

1) Online configuration. Due to the uniqueness of SCOAP, the modularity and scalability of its components should be extended to embedded hardware modules and also software system modules with open interfaces defined. Therefore, a three-layer based product architecture should be established, i.e. *physical product layer, embedded hardware layer,* and *embedded software layer* (Zheng, Xu, and Chen 2018). Each latter layer can be regarded as the extension of the prior one, and the scalable design of each layer is enabled by the optimisation of its parameters.

2) Cyber-physical interaction. This method often comes with a physical design prototype and its virtual twin in the cyber space. Key design components are equipped with built-in sensors to detect parameters highly related to the product design, and connectivity modules are pre-defined to enable the communication and data transmission. Lead users are asked to try on the prototype and hence, in-context data can be collected in the cyber space (input) to trigger the virtual model or analysed for design innovation (output). The PTC bicycle demo (2015) is a good example of such mode, where the change of physical components can be monitored in the virtual space in real time.

Following such manner, both active (i.e. user actively generated design data) and passive (i.e. designer pre-defined design data) user invovlement can be leveraged to enable value co-creation.

5.2 Manufacturing stage - resource allocation

In the SCOAP manufacturing stage, the key activity in this co-creation context lies in the on-demand manufacturing resource allocation. Only expert users with capable manufacturing knowledge are involved, mainly to select the prospective manufacturing resources, e.g. selection of 3D printing process. This cyber-physical manner requires a distributed control architecture capable of enabling resource sharing in dynamic environments (Nayak et al. 2016). From user's perspective, the distributed manufacturing resources and capabilities are *servitised* (Li et al. 2010), i.e. virtualised into a shared resource pool, so that each user can obtain customised services in the cloud platform upon request, i.e. on-demand manufacturing resources. Meanwhile, for the manufacturers, flexible/reconfigurable manufacturing systems with certain manufacturing capabilities (Koren, Gu, and Guo 2017) enable the rapid adaption to the user's dynamic changing orders. Hence, the main cyber-physical interactions in this stage can be summarised as:

1) Machine selection. Optimised manufacturing solution (output) should be provided to users based on their requests and capability/availability of existing machines in the cloud resource pool (input).

2) Manufacturing progress monitoring. The work-in-process can be read by RFID tags in the manufacturing shop floor or progress of NC code in real-time and visualised in the cloud to users.

5.3 Distribution stage- logistic service

Logistic service is the key solution provided to the users in the SCOAP distribution stage, where the digital twin is established mainly based on the real-time location information of the parcel. It consists of two types of services: storage/delivery service selection, and real-time product location information tracking. For the prior one, in the cloud-based IoT-enabled environment, various approved third-party logistic service providers are connected to offer personalised storage/delivery solutions. Users can make selection online based on their quality-of-service (QoS) and other criteria, e.g. cost, delivery time, etc. For the latter one, a unique identity, e.g. a QR code or barcode, is generated with a GPS sensor module already been embedded in each SCOAP, where the location information can be traced in real-time (e.g. Domino’s online pizza delivery system). Moreover, after service accomplishment, the users can provide their comments in the cloud as historical data for service provider’s evaluation.

5.4 Usage stage- value recreation

In the SCOAP usage stage, value can be re-created in a cyclic manner (Abramovici, Göbel, and Savarino 2017), through *use/operation, reconfiguration* or *remanufacturing* processes. The digital twin between the end SCOAP and its virtual model serve as the medium and tool for value recreation by introducing add-on e-services and capturing massive user generated/sensed data for product innovation.

Use/operation stands for the phase of daily usage and maintenance of the product. On one hand, owing to the embedded open toolkits, users can generate their own product/service based on the pre-defined adaptable hardware interface or API, following a set of constraints. For instance, users can adjust different modes of the smart watch based on the embedded system inherent. On the other hand, owing to the advanced ICT, companies can have real time access to the massive user generated data, e.g. location information by GPS module, which enables the maintenance, data-driven continuous design improvement (or "evergreen design") and next-generation product prediction.

Reconfiguration refers to the change or upgrade of configurable components of an existing product to meet new requirements. It follows the rules of product adaptability for an extended product lifecycle. For SCOAP, the reconfiguration is enabled by the digital twin established between the physical instance and the cyber one, where configurable components, their adaptable interfaces and a set of constraints have been pre-defined in the knowledge base. Therefore, the possible alternatives can be easily derived in the cloud platform based on user's request actively (e.g. willingness to upgrade system), or product's self-awareness passively (e.g. a warning to change battery).

Remanufacturing represents *"the rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired and new parts"*

(Johnson and McCarthy 2014). It requires the repair or replacement of obsolete components or parts to meet user's satisfaction. For SCOAP, the prediction and detection of a possible failure can be achieved based on the real-time monitoring and data-driven manner of the usage status (e.g. cutting tool wear). Moreover, with the open environment, expert users can provide novel re-design request in the cloud so that multiple potential vendors can offer customised solutions upon request.

5.5 End-of-life stage – reversed logistic

The reverse logistics (Govindan and Soleimani 2017) aims to reduce negative impacts on human and environment, in the end-of-life stage by properly reusing, recycling and disposing the wastes. For SCOAP, the cyber-physical interactions mainly contain three folds based on the data-driven manner:

1) Predicting remaining lifetime. Since the key components of SCOAP are interconnected in the cyber space, the remaining lifetime of them can be predicted based on its current condition, historical data and expert knowledge (input) in the cloud platform. Hence, proper end-of-life actions (output) can be performed beforehand. For example, the wearing of cutting tools based on the vibration signal, average use time, etc.

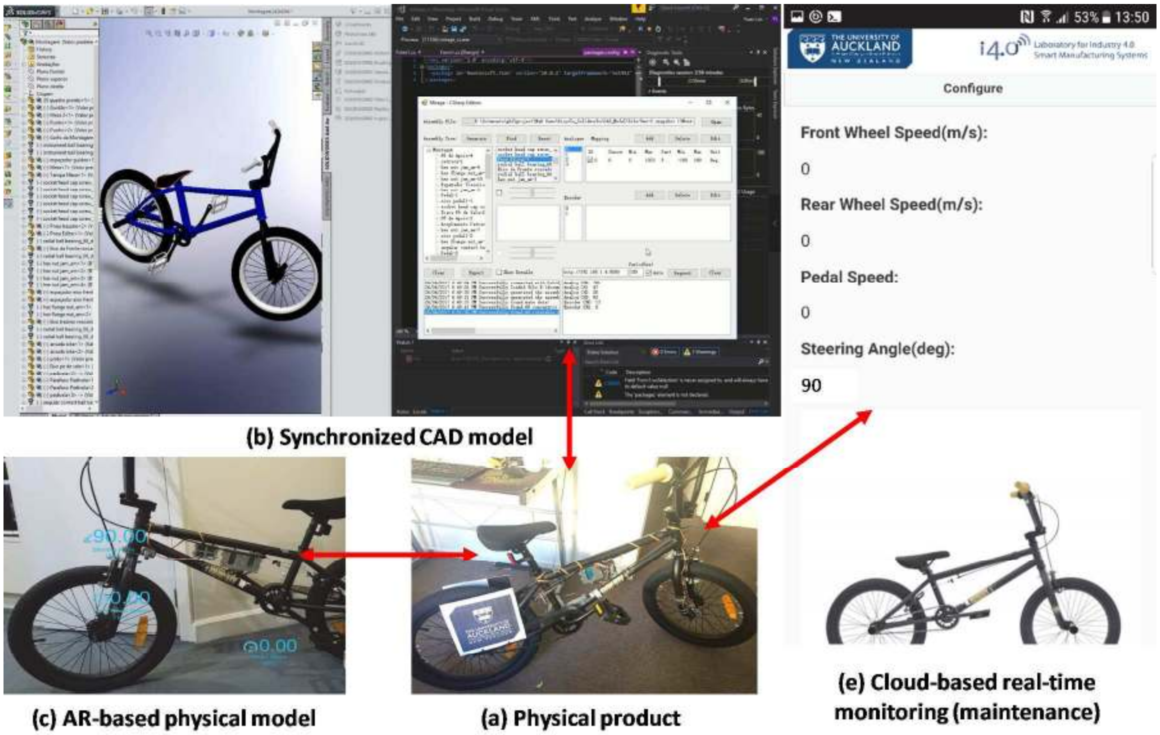
2) Smart recycling/recovering (retrieval). With the prediction results of first step, several ways can be performed: a) choosing recovery/recycling options; b) consumer return incentive mechanisms; c) assigning the flows between entities, etc. A recommended solution should be provided the users in a visualised manner.

3) Disposal. Once the SCOAP is decided to be disposed, smart warning should be given to the users with suggested ways of disposal (e.g. batteries to be disposed in specific containers with certain rewards). Also, product digital twin should be deleted

accordingly in the cloud. Nevertheless, all the historical data should be stored for other usage scenarios.

6. An illustrative example

To make the proposed concepts and methodologies more concrete, a Level III cyber-physical smart open architecture bicycle prototype, named MIRAGE, is developed at the University of Auckland, as shown in Figure 5. One can find demo video via YouTube link https://www.youtube.com/channel/UCNmCU0YFPrwvSZFAsV3LPvw?view_as=subscriber. Due to the complexity of realizing every aspect along its lifecycle, this illustrative example only showcases the execution of interactive performance analysis for value re-creation in the product usage stage, as well as a cost-effective solution for realizing a SCOAP in daily life. Hence, the main task is to facilitate a synchronisation between the physical product (Figure 5(a)) and its digital twin (Figure 5(b)) for value recreation. Specifically, the original bicycle's virtual model is driven by sensing data retrieved from the physical product, so as to perform high fidelity simulation and analysis in the virtual environment. Meanwhile, the user's riding status is visualised via Augmented Reality (AR) (Figure 5(c)), where manufacturers can achieve in-context user experience more readily. Moreover, real-time monitoring can be conducted in the Mobile App or cloud-based platform (Figure 5(d)), and hence, prospective design improvement (e.g. parametric design) or predictive maintenance (e.g. change of wheel) can be derived in the proposed data-driven IoT-enabled platform-based approach. The technical details for its realization and value recreation process are presented below.



(b) Synchronized CAD model

(c) AR-based physical model

(a) Physical product

(e) Cloud-based real-time monitoring (maintenance)

Figure 5. An illustrative example of a cyber-physical smart, connected bicycle

Open architecture of MIRAGE. In this work, the physical bicycle is decomposed (modularized) into different modules with adaptable interfaces for personalization concerns (e.g. wheel and saddle). Moreover, both its embedded smart components (e.g. *Intel Edison*, *Arduino UNO*) and connectivity components (e.g. Bluetooth 4.0 or Wifi) are also defined as the changeable embedded hardware modules with open interfaces (e.g. API). For instance, different sensors can be exploited as add-on modules to the Intel Edison board to perform various functionalities (e.g. rotation speed, angular change).

IoT-enabled platform establishment. Figure 6 presents the system architecture of MIRAGE, a web server runs on the main controller (i.e. an *Intel Edison* board) of the product. The main controller runs a light weight distribution of Debian which hosts a light-weight webpage using Express. The Web UI was written in jQuery mobile. The real-time dual-way data transfer of Web UI was powered by *Socket.io*. The I2C module of main controller was driven by the JavaScript wrapper of Intel's *mraa*, which is a low level skeleton library for communication on Linux platforms. Meanwhile, in order to quickly capture the electric level change of sensor signals (i.e. encoder signals) without corrupting the Web UI, particularly for a single-threaded processor, it is necessary to have a separated processing unit to simultaneously pre-process or buffer the raw sensor data. Hence, an *Arduino UNO* broad is responsible to pre-process the raw sensor data and keep the main controller updated.

To avoid the battery of sensing module drained out quickly, this project used Bluetooth Low Energy as communication method to reduce the power consumption of data transmission. The Bluetooth function on Edison was based on BlueZ protocol stack. Major data analysis is performed on Mobile APP instead of main controller in the sensing module. The mobile APP is developed using ionic framework v1, which uses Angular.js for UI design and Apache Cordova to get access to native hardware resources (i.e. Bluetooth module of smartphone). Users can visit the webserver (i.e. Apache MESOS, DC/OS) hosted by the main controller (see Figure 6), to perform configuration and acquire sensor data. Both AR App and desktop software (i.e. Solidworks) use HTTP request to retrieve sensor data from web server (see Figure 6). The software that interfacing CAD system is only compatible with SolidWorks, since the APIs of SolidWorks is well documented and open to the public. C# as programming language was chosen for plugin development. Its main functions contain three aspects: 1) capable of manipulating CAD model using provided APIs; 2) retrieving sensor data through HTTP request; 3) analysing the DoF of each individual part and helping designer to establish a profile for each product, which defines the mapping between sensor data and design model.

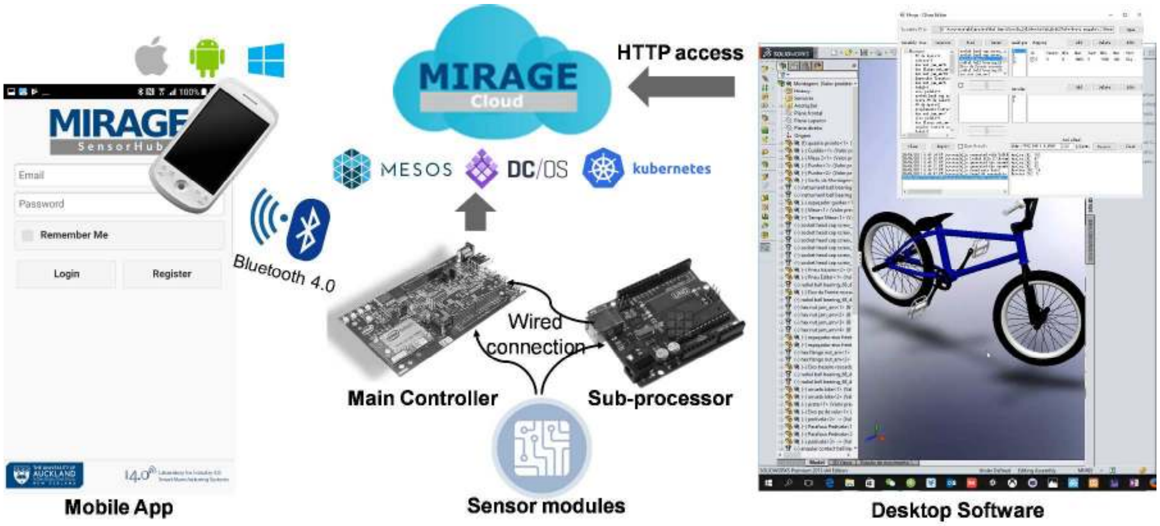


Figure 6. System architecture of MIRAGE

Data-driven value recreation process. In the MIRAGE usage stage, this work emphasizes the real-time monitoring of parts movement (e.g. wheel, headset). Hence, encoders are utilized where each encoder is connected to 2 pins of sub-processor for 2 phases of signals, namely A and B. By judging the level of Signal A at each rising edge of Signal B, sub-processor could differentiate the direction, then increase or reduce pulse count in data buffer. When main controller has spare processing power and enquires data from sub-processor, the sub-processor would pack the total pulse count value for each encoder and transfer the data package to main controller through I2C bus. Meanwhile, the sub-processor would clear the pulse counter for a new cycle. For example, the steeling angle is captured by Hall sensor embedded in a customised rotation sensing block. Its output is an analogue signal, after ADC, the result value is associated with a specific angle. Following such manner, user's real-time riding status can be monitored (Figure 5(d)). Meanwhile, the digital twin established between the physical product and its CAD models can drive design optimisation (i.e. maintenance/reconfiguration) by undertaking simulation process in the virtual environment. Moreover, all the real-time massive user/product generated data is captured into a cloud-based IoT platform and can be virtualised as a service (e.g. daily training status, or energy consumption analysis) in a data-driven manner.

7. Conclusions and future perspectives

The rapid development of ICT enables a promising market of IT-driven product, i.e. SCP, and also changes the way of user-manufacturer interaction in the product development process. This paper proposed a novel IT-driven co-creation paradigm of product open innovation for lifecycle personalisation concerns, i.e. SCOAP. The definitions, key characteristics, evaluation criteria, product development methodology and co-creation context of SCOAP are presented in this research. A demo product was given to provide a real implementation case in the usage stage. The main scientific contributions of this work can be summarised in three aspects below:

1) Provided useful guidance for companies to develop their SCPs with lifecycle concerns. The proposed new paradigm together with the evaluation criteria enlarge the scope of existing OAP concept by integrating both hardware and software open innovation in an IT-driven manner.

2) Introduced a novel way to undertake product development from IT-driven perspectives. Unlike most of the existing prescriptive methodologies, a platform-based data-driven design approach was proposed for SCOAP development by leveraging ICT and artificial intelligence in the era of smart manufacturing.

3) Proposed a cost-effective manner to realise co-creation. This work showed the capabilities of developing personalised, sustainable and evergreen SCPs by actively involving users/manufacturers/vendors into the co-creation context along the lifecycle.

Apart from these achievements, as an explorative study, this research still exists some limitations. One claim given by the authors is that, due to many factors, e.g. intellectual properties, user privacy, etc., the extreme case of SCOAP fulfilling every aspect in the product lifecycle may not even exist or ideal at all to realise personalisation. Therefore, manufacturers need to adapt or modify the general concept to real world applications so as to be flourished. Nevertheless, this work presents a real-life case of the proposed SCOAP and welcomes more open discussions and comments in this research field.

Meanwhile, the authors would like to point out several potential research directions in the near future, namely: 1) novel business model (e.g. smart services for sharing) and lifecycle management tools (e.g. smart recycling mechanism) to support SCOAP development; 2) modelling of user/product/manufacturer-generated massive data in such co-creation context by adopting artificial intelligence techniques (e.g. graph embedding approaches) with lifecycle concerns, to support product maintenance, prediction or recreation; 3) establishment of a SCOAP ecosystem by considering not merely single product family, but a series of interconnected ones and their generated e-services as a smart open product-service systems.

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