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Short Communication

Industrial smart product-service system development for lifecycle sustainability concerns

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Abstract: Industrial smart product-service system (ISPSS), as an emerging industrial digital servitisation paradigm, has attracted ever-increasing attentions from both industries and academics recently. The prevailing adoption of cutting-edge information and communication technologies, digital technologies and artificial intelligence has enabled the engineering lifecycle management in an ever-smarter manner with context awareness. Nevertheless, little study has provided any systematic process to prescribe its sustainable development throughout the engineering lifecycle, let alone any to consider sustainability in the cyber space other than the physical components. Aiming to fill the gap, this work outlines the definition, key features and social, economic and environmental concerns of the proposed sustainable ISPSS, and further proposes a systematic four-phase cyber-physical development framework by referring to the ISO14001:2015 standards. As a short communication, it is hoped this research can attract more open discussion and in-depth investigation towards sustainable ISPSS development in the near future.

1 Introduction

Sustainable development is the utmost, recognised concern for today's industrial companies, of which rethink and revolutionise current design, production and usage pattern are of paramount importance. Owing to the prevailing implementation of smart, connected products in the operations, and empowered by the advanced information and communication technologies information and communication technology (ICT) and artificial intelligence (AI), industrial companies are ever-increasingly adopting the emerging smart product-service system paradigm, to offer smart solution (product-service) bundles in a digital servitisation business model [1]. Meanwhile, by collecting and analysing the meaningful product-sensed and user-generated data, industrial companies can better perform their sustainable use/maintenance, reuse, remanufacturing and recycling processes throughout the engineering lifecycle in the so-called smart circular system manner [2]. By nature, the convergence of industrial product-service system, sustainable strategies and smart enabling technologies derives an emerging sustainable industrial smart product-service system (sustainable ISPSS) paradigm, which provides a promising manner to enable the sustainable development of smart industrial solutions.

Nevertheless, to the authors' best knowledge, there is no systematic process for its sustainable development throughout the engineering lifecycle, let alone any to consider sustainability in the cyber space other than the physical components. Aiming to fill these gaps, this short communication provides the fundamental basis in Section 2 and a novel four-phase cyber-physical framework to prescribe the sustainable ISPSS development process in Section 3, respectively. Conclusions and future directions are highlighted in Section 4 to attract more open discussion and in-depth investigation in this promising research field.

2 Fundamentals of sustainable ISPSS

This section outlines the definition and key features of Sustainable ISPSS, summarises the state-of-the-art works related and discusses about its social, economic and environmental aspects towards sustainable development.

2.1 Definition

As shown in Fig. 1, the sustainable ISPSS can be regarded as a combination of industrial PSS, sustainable strategies and smart, enabling technologies. The industrial PSS denotes the following circumstances, namely: (i) *internal operations*, representing the inner-/inter-organisational operations inside the industrial companies, such as remote monitoring and diagnostics of computer numerical control machine tools; (ii) *external operations*, denoting the inter-activities among different stakeholders, including manufacturers, customers/users, suppliers and service providers, for example: order tracking by 'smart box'. Hence, not only end-solutions delivered to the users should be considered, but also the engineering solutions to make them should also be included. Meanwhile, smart enabling technologies, also known as digitalisation capabilities in literature, mainly include the connect capability (communication technology), intelligence capability (IT) and analytic capability (AI and big data analytics). Lastly, the three core sustainable strategies are: closed lifecycle loop, better resource efficiency (RE) and extended lifespan, respectively.

Hence, the formal definition of sustainable ISPSS can be given as: 'a type of industrial product-service systems, consisting of smart, connected products and their generated services as the solution bundle, to meet individual stakeholder's need in a sustainable manner, empowered by the cutting-edge operational technology, information and communication technologies and artificial intelligence'.

2.2 Key features

According to the above definition, the unique features of sustainable ISPSS can be extracted into three aspects, namely,

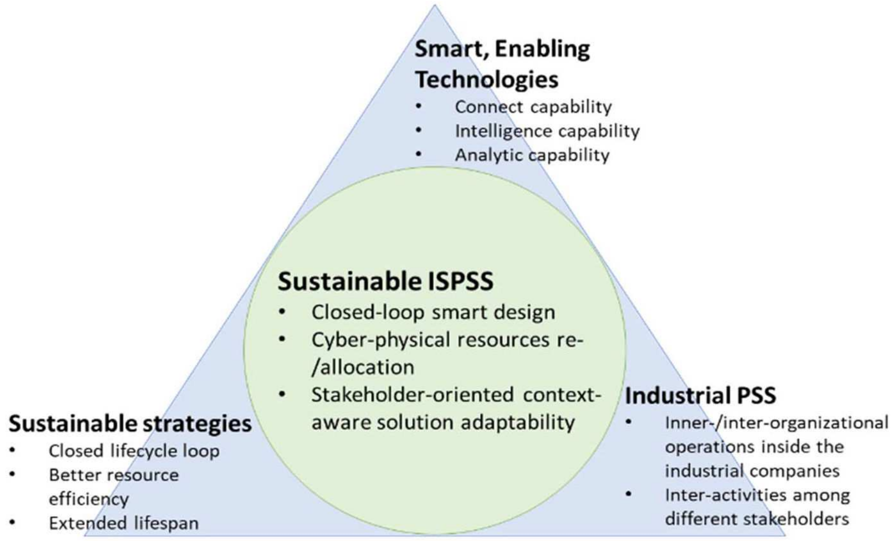

Fig. 1 *Composition of sustainable ISPSS*

closed-loop smart design for circulating the engineering lifecycle, *cyber-physical resource re-/allocation* for better RE and *stakeholder-oriented context-aware product-service adaptability* for extending the life span. All of these are conducted in a data-driven knowledge-intensive manner [3], which contributes to the sustainable development of smart solutions.

Closed-loop smart design underlines the fact that engineers should consider the reversibility of the whole engineering lifecycle from the very beginning design process. To achieve that, firstly, the function–behaviour–structure of the physical components (i.e. hardware) composing the product should be designed in a cradle-to-cradle manner [4], following specific design principles, such as design for reuse, design for disassembly and so on. Furthermore, smart functionalities as the decision-making services enabled by the embedded hardware and/or software should be properly designed to ease the reversibility, such as: self-reconfiguration, self-disassembly and self-degradation. Frankly, technology may not be available/effective yet, but there is a promising market upcoming especially in the industrial robotics and bio-engineering field.

Cyber-physical resource re-/allocation aims to achieve the better RE in both physical and cyber spaces. In the physical space, tangible resources of materials and components in sustainable ISPSS are either allocated during use (e.g. add-on modules) or reallocated in the circular production systems via 4R (reuse, repair, remanufacture, recycle) strategies (e.g. refurbishment of a wind turbine). More critically, in the cyber space, enabled by the advanced ICT and AI, the intangible resources of reliable dataset, annotated information and mined knowledge are also reallocated in the process of service innovation, where the valuable information/knowledge can be transferred to a new solution [5]. Furthermore, it also denotes the cyber-physical integrated situations, where smart services (software) can replace products (hardware) to some extent (e.g. software-defined manufacturing).

Stakeholder-oriented context-aware solution adaptability can effectively result in the extended lifecycle (EL) for sustainability. Similar to the smart PSS feature, context awareness and stakeholders' value co-creation play significant roles in realising solution sustainability. Cognitive/affective understanding of stakeholders from user-generated data (human intelligence) other than only sensory information from product-sensed data (machine intelligence) is of paramount importance to ensure better user experience and longer attachment [6]. To achieve it, the adaptable design principles should be followed with open-architecture product-service family established. Moreover, knowledge engineering approaches (e.g. knowledge graph) should also be adopted appropriately to represent and query the needs from the specific context [7].

2.3 Typical works

Following the definitions and key features, only a few representative sustainable ISPSS works are selected to date, which can be further summarised by its core strategies, as shown in Table 1. It can be found that industrial companies can readily implement the sustainable ISPSS starting from the very beginning by smart design for sustainability till the end of its lifecycle, by embracing the cutting-edge ICT, AI and digital technologies. Meanwhile, it is not surprising to discover that smart, connected products increasingly serve as the tool and media for *ad hoc* information processing and communication, while their generated digitalised services make the core values in the solution bundles offered. Furthermore, the concern of EL is normally conducted in the re-/design, use/operating/maintenance and reuse phases, while RE is considered mostly during re-/manufacturing, distribution and re-/use stages and closed-loop (CL) is primarily emphasised in the later phase of remanufacturing and recycle.

2.4 Social, environmental and economic concerns

To compliant with the United Nations' 2030 Agenda for Sustainable Development blueprint, especially the Goal 9 to 'build a Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation' [15], this work outlines the promising social, environmental and economic concerns of the proposed sustainable ISPSS.

Social aspect: Sustainable ISPSS is well in line with the Open Innovation 2.0 concept of a shared value vision, where various stakeholders contribute in the value co-creation process to meet their demands. Meanwhile, it aims to make a sustainable prosperity and improvements in human well-beings by leveraging the disruptive smart enabling technologies to provide product-service offerings.

Environmental aspect: Sustainable ISPSS follows the environmental management system strategies of 'reduce, reuse and recover', and the ultimate goal is to have less environmental impact so as to achieve sustainability in a circular economy. As listed in Table 1, the environmental concerns can be readily addressed by extended lifecycle, better resource use efficiency and the circulate lifecycle. However, appropriate WEEE treatment should be handled resulting from the ever-increasing smart products utilised.

Economical aspect: In sustainable ISPSS, digitalisation capabilities enable the value creation/capture, proposition and delivery in a context-aware and cost-effective manner. Value is created/captured in a data-driven manner from those massive stakeholders and their end smart, connected products in a co-creation process. Meanwhile, it reflects the sustainable, digital and servitised value proposition, by not only addressing the three big transformations among today's industrial companies internally, but also to meet personalised needs with sustainable, smart, on-demand solutions. Furthermore, value is delivered in a more software-defined manner via the Internet-of-Things (IoT) or Industrial Internet-of-Things (IIOT), where stakeholders have ubiquitous access to the cyber-physical resources shared, re-used, re-manufactured, recycled in a sustainable way.

3 Systematic framework for sustainable ISPSS development

To prescribe the sustainable ISPSS development, this section proposes a novel four-phase cyber-physical system framework, with its core procedures depicted below as well.

3.1 Overall system framework

Based on the above future perspectives, Fig. 2 depicts the overview of the ultimate goal of the sustainable ISPSS, as a CL lifecycle management system in today's circular economy.

The *vertical arrow* (in blue) represents a data-information-knowledge-wisdom flow in the digital servitisation process enabled by the advanced ICT infrastructure (e.g. cloud-edge computing), digital technologies [e.g. cyber-physical system (CPS)] and AI techniques (e.g. deep learning, knowledge graph). Firstly, industrial 5 V (velocity, veracity, value, volume, variety) data is collected via various sources in a heterogenous manner, including both user-generated data and product-sensed one. Secondly, unified information modelling should be established to manage the cleaned data with big data analytic methods. Thirdly, valuable knowledge should be extracted from the information models to construct the domain ontologies and specific knowledge graphs for knowledge representation and reasoning purposes in a cognitive (semantic) manner. Meanwhile, the interactions or digital twins (i.e. two-way arrow) of sustainable ISPSS development can be established in-between the physical and cyber space in a cost-efficient manner based on the analytics of massive user/manufacturer/product-generated data and the real-time communication between them (e.g. monitoring, control, optimisation and autonomous).

The *horizontal arrow* (in blue) presents the different implementation stages of ISPSS along the engineering lifecycle, of which the digital twin established can enable the design as ordered, manufacturing as built, distribution as located, usage as maintained/reconfigured/re-built, and end-of-life as recycled [16]. Each dark-blue box stands for a user involved stage, where different stakeholders engage in a value generation manner. The green arrow represents the key processes to be taken for reversibility, including smart reuse/redesign/reconfiguration (e.g. upgrade of product-service modules), smart remanufacturing (e.g. predictive maintenance) and smart recycling (e.g. smart WEEE management).

3.2 Systematic development process

Existing studies have emphasised much on the sustainable concerns of the physical products/components, while little reported on the cyber space. Aiming to bridge the gap, this section adopts the plan-do-check-adjust (act) (PDCA) model as regulated in the ISO14001:2015 to provide a stepwise approach for the holistic sustainable ISPSS development, especially in the cyber space. As shown in Fig. 3, the PDCA model is an iterative process that guides the stakeholders to achieve context-aware sustainable evolvement, including the following.

Core – context awareness: In sustainable ISPSS, all the procedures are undertaken in a data-driven knowledge-intensive manner, which are enabled by the massive product-sensed data and user-generated data in the context. Encoding these scenarios with multiple context features, the requirement-solution bundles proposed in the whole PDCA process can be diversified under different scenarios.

Plan – requirement elicitation: Detect and formulate the requirements of stakeholders in the digital servitisation platform. Meanwhile, based on the requirements, establish the sustainable development goals and processes in line with the organisation's environmental policies for product-service planning. For example, smart phone-sensed remaining lifecycle warning of the battery, as the waste management requirement generated in the cyber space, should be well-planned in compliant with the WEEE Directives.

Do – solution recommendation: Take actions by offering a practical solution to solve the elicited requirements in the plan step with sustainable concerns. As historical changing/upgrading/recycling cases accumulating in the cyber space, novel solutions can be generated by reusing/revising them under similar scenarios. Besides, for a complex ISPSS containing massive product/service components and hence triggering the ‘curse of dimensionality’ in decision making, clustering manners that partition the whole system into functional modules are also leveraged in this step to recommend the best solutions. For instance, based on the application scenarios, a context-aware decision making should be offered to guide the end-users to disassemble and dispose the battery in a proper manner.

Check – solution evaluation: Monitor and measure the cost efficiency of the proposed solutions against the sustainable policies. The evaluation indicators include (but not limited to) the quality of PSS, user satisfaction, cost, expected lifespan, RE and CL effectiveness. For instance, based on the historical battery

Table 1 Summary of smart sustainable/circularity strategies

Strategies	Representative studies	Specifications/applications	Enabling techniques	Major sustainability concerns
smart design	[3]	adaptable open architecture smart bicycle design to achieve better user experience with extended lifecycle considerations	DT, IoT, CPS	EL
smart manufacturing	[8]	cyber-physical machine tool to achieve on-demand cloud manufacturing services	DT, CPS, AR	RE
smart distribution	[9]	IoT-enabled smart box for cost-effective logistic service delivery	Big data analytics, IoT	RE
smart use/operating/ maintenance	[10]	predictive maintenance for extended lifecycle, and cost-effective machine prognostic and healthy management	Big data analytics, CPS	EL, RE
smart re-design / reconfiguration	[11]	adaptable automobile reconfiguration with context-aware modules to enlarge product timespan	IoT, smart embedded system	EL
smart reuse	[12]	reusable materials/components evaluating, tracking and tracing in a cost-effective manner	IoT, CPS	EL, RE
smart remanufacturing	[13]	virtual disassembly platform for cost-effective remanufacturing and recycling	AR/VR, CPS	CL, RE
smart recycle	[14]	DT-enabled industrial WEEE smart waste recycling	DT, CPS	CL

AR, augmented reality; VR, virtual reality; DT, digital twin.

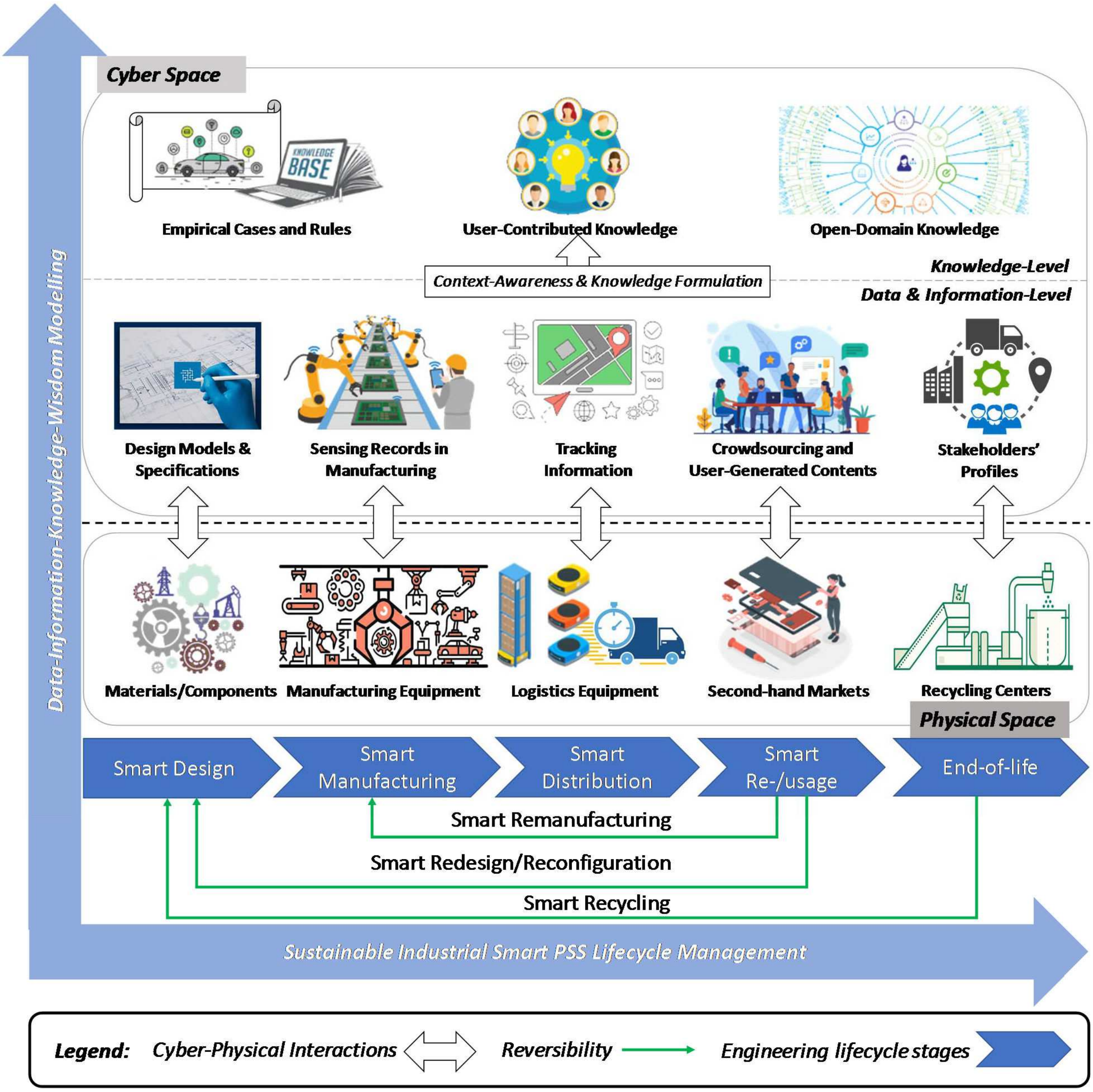

Fig. 2 *Proposed systematic framework for sustainable ISPSS development*

waste management cases, the cost effectiveness of the solutions should be compared and analysed properly in the service platform.

Adjust – knowledge evolvement: Update the knowledge resources continually in the cyber space to close an iteration. A knowledge management review should be conducted to add, delete and modify the concepts, constraints, empirical rules and cases stored along with the whole lifecycle stages. These modifications will impact the previous steps when a new iteration starts. Again, for example, with the adoption of new phones, enhanced waste management methods should be delivered in the solution bundle with context awareness.

4 Conclusion and future perspectives

Sustainable development has been a hot topic over the past few years, and ever-increasingly concerned by not only the government policy makers, but also modern companies to take proactive actions towards sustainability. Meanwhile, the rapid development of cutting-edge ICT and AI, as the smart enabling technologies, has ensured the digital servitisation transition, where ISPSS can be realised to meet individual customer needs readily. By nature, the 'smart' balance between sustainable development and high value-added solutions may not necessarily conflict with each other, but to make decision makings better. Motivated by that, this research aimed to discover the core relationship between sustainable and smart PSS in the industrial field, and further to prescribe the sustainable ISPSS development process. The main contributions can be summarised in two folds: (i) provided the formal definition, key features and sustainable concerns of the proposed sustainable ISPSS; and (ii) introduced a four-phase cyber-physical systematic development framework for sustainable ISPSS development. As a short communication, indeed more open discussions and in-depth research should be done in the near future to: (i) investigate the three key features of sustainable ISPSS with sociotechnical breakthrough, (ii) provide a systematic evaluation scheme for assessing the social/environmental/economic benefits of it and (iii) implement the proposed data-driven knowledge-intensive four-phase cyber-physical framework in a complicated industrial case study.

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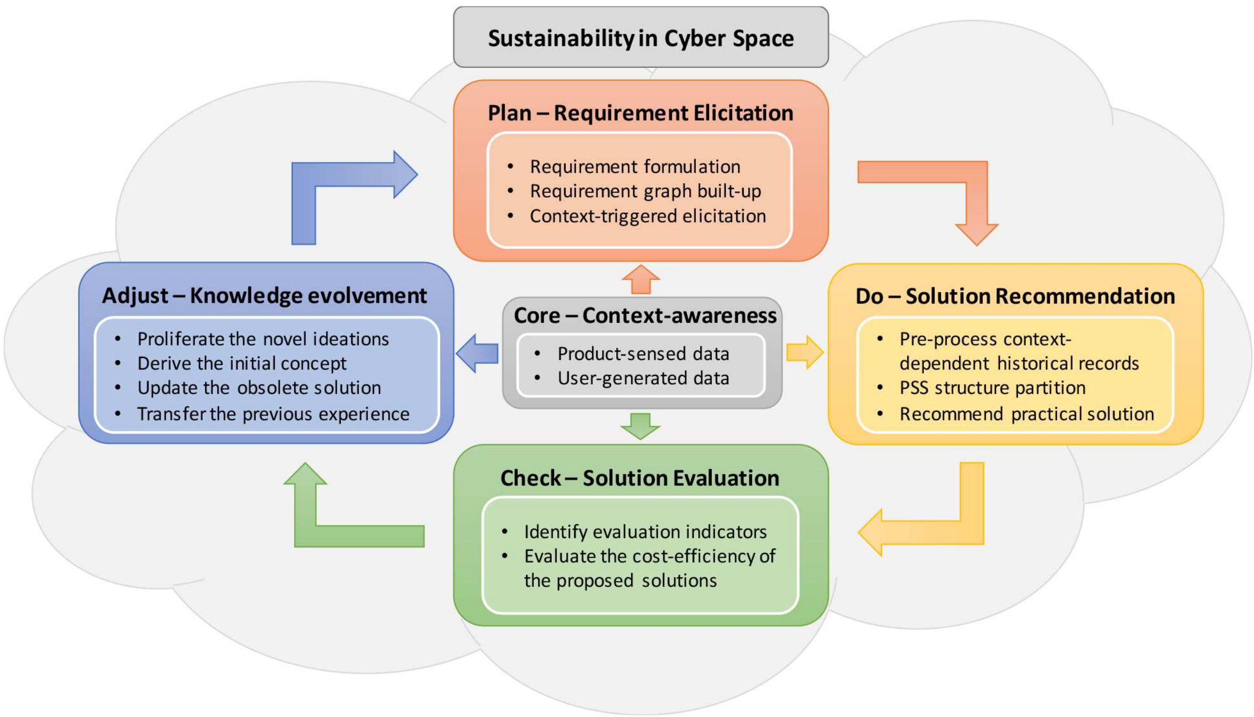

Fig. 3 *Four-phase procedures for sustainable ISPSS development in the cyber space*

6 References

[1] Zheng, P., Lin, T.-J., Chen, C.-H., *et al.*: 'A systematic design approach for service innovation of smart product-service systems', *J. Clean. Prod.*, 2018, **201**, pp. 657–667

[2] Alcayaga, A., Hansen, E.G., Wiener, M.: 'Towards a framework of smart-circular systems: an integrative literature review', *J. Clean. Prod.*, 2019, **221**, pp. 622–634

[3] Zheng, P., Lin, Y., Chen, C.H., *et al.*: 'Smart, connected open architecture product: an IT-driven co-creation paradigm with lifecycle personalization concerns', *Int. J. Prod. Res.*, 2019, **57**, (8), pp. 2571–2584

[4] McDonough, W., Braungart, M., Anastas, P.T., *et al.*: 'Applying the principles of green engineering to cradle-to-cradle design', *Environ. Sci. Technol.*, 2003, **37**, (23), p. 101403

[5] Li, X., Chen, C., Zheng, P., *et al.*: 'A knowledge graph-aided concept-knowledge approach for evolutionary smart product-service system development', *ASME J. Mech. D.*, 2020, **142**, pp. 101403–1

[6] Zheng, P., Liu, Y., Tao, F., *et al.*: 'Smart product-service systems solution design via hybrid crowd sensing approach'. *IEEE Access*, 2019, **7**, pp. 128463–128473

[7] Wang, Z., Chen, C.H., Zheng, P., *et al.*: 'A novel data-driven graph-based requirement elicitation framework in the smart product-service system context', *Adv. Eng. Inf.*, 2019, **42**, p. 100983

[8] Liu, C., Vengayil, H., Lu, Y., *et al.*: 'A cyber-physical machine tools platform using OPC UA and MTConnect', *J. Manuf. Syst.*, 2019, **51**, pp. 61–74

[9] Pan, S., Zhong, R.Y., Qu, T.: 'Smart product-service systems in interoperable logistics: design and implementation prospects', *Adv. Eng. Inf.*, 2019, **42**, p. 100996

[10] Lee, J., Ardakani, H.D., Yang, S., *et al.*: 'Industrial big data analytics and cyber-physical systems for future maintenance & service innovation', *Proc. CIRP*, 2015, **38**, pp. 3–7

[11] Abramovici, M., Göbel, J.C., Dang, H.B.: 'Semantic data management for the development and continuous reconfiguration of smart products and systems', *CIRP Ann. – Manuf. Technol.*, 2016, **65**, (1), pp. 185–188

[12] Iacovidou, E., Purnell, P., Lim, M.K.: 'The use of smart technologies in enabling construction components reuse: a viable method or a problem creating solution?', *J. Environ. Manage.*, 2018, **216**, pp. 214–223

[13] Chang, M.M.L., Ong, S.K., Nee, A.Y.C.: 'AR-guided product disassembly for maintenance and remanufacturing', *Proc. CIRP*, 2017, **61**, pp. 299–304

[14] Wang, X.V., Wang, L.: 'Digital twin-based WEEE recycling, recovery and remanufacturing in the background of industry 4.0', *Int. J. Prod. Res.*, 2019, **57**, (12), pp. 3892–3902

[15] United Nations Sustainable Development Goals: Available at https://www.un.org/sustainabledevelopment/sustainable-development-goals/, (accessed on 15 May 2020)

[16] Zheng, P., Wang, Z., Chen, C.-H., *et al.*: 'A survey of smart product-service systems: key aspects, challenges and future perspectives', *Adv. Eng. Inf.*, 2019, **42**, p. 100973