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Environment interaction model-driven smart products through-life design framework

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Abstract

With the advent of Industry 4.0, design of a smart product to work in a smart factory, or home or city over its lifecycle has to consider its intelligent interaction with its external environment (physical, human and cyberspace environments). Thus, environment interaction driven design of smart products becomes an important design research field, facing a huge challenge of integrating a smart product and its environment interaction design crossing all its life phases. The challenge questions are threefold: (1) how to model environment interactions through a product life cycle, (2) how to design a smart product with its environment interaction model, and (3) what design strategy to be taken in the design practice or implementation. In this paper, a high-profile design framework is proposed for guiding environment interaction model-driven smart products through-life design. It has three core elements: (1) a generic environment interaction model of a smart product through-life phases, which can help map out the interaction requirements between the smart product and other interaction elements through-life phases, (2) a smart product design process model for guiding product and its interaction design at each phase and (3) a design strategy of smart products through-life design. Its implementation feasibility is demonstrated with an industrial case study, showing that it is helpful to implement design solutions of a smart product for satisfying intelligent interactions with its external environments through-life phases.

Keywords: smart products; environment interaction; product modelling; life cycle design

1. Introduction

With the beginning and rising of Information and Communication Technology (ICT), such as RFID, sensors, Internet of Things (IoT) and other advanced electronics, more and more smart products as the core enabling technologies will be incorporated in smart production/manufacturing(Kiritsis 2011), such as smart devices, smart cars, smart trains and smart home appliances. These new types of product are reshaping industry boundaries and requiring enterprises to establish and support an entirely new technology infrastructure(Porter and Heppelmann 2014). An intelligent/smart product is defined as a physical and information-based representation of a product in intelligent manufacturing field(McFarlane *et al.* 2003) or a cyber-physical system (CPS) using the Industry 4.0 term(Nunes *et al.* 2017), which can operate autonomously, respond to their environments, or communicate with other products(Rijsdijk and Hultink 2009). The definition indicates that smart products tend to focus on connectivity and information exchange through-life (all phases), that is, how to interact with their external environments, such as physical environment (natural environment and other products/physical facilities/robots), human environment (through-life stakeholders such as users/operators), and cyberspace environment (distributed system)(Meyer *et al.* 2009, Poslad 2011). The interaction can create meaningful experiences and added value during the use phase of the smart products(Valencia Cardona *et al.* 2015). Smart products tends to be more active physically and/or socially in responses to its environment changes in the future(Wuest *et al.* 2018). Therefore, development of an interaction framework that supports the product's interactions with other products and multiple environments across multiple lifecycle phases is a necessary but a challenging task for smart product design in an efficient and scalable manner(McFarlane *et al.* 2013).

Current smart product design is primarily focused on one or a few product life phases such as product in service (use) (Barbosa *et al.* 2016), which is less likely to think through all life phases and most likely to fail to a systematic design solution to address all design requirements, users' needs and inter-phase conflicts in design goals/targets(Gutiérrez *et al.* 2013). Additionally, interactions are major demands/requirements and essential contexts in smart product through-life design(Poslad 2011), different with the conventional product or service design, the research on smart product design is much needed to comprehensively concern through-life interactions to realize all benefits from both global and local markets(Valencia Cardona *et al.* 2015, Duffy *et al.* 2016). The understanding of the environment interaction information is a key to designing powerful and successful smart products. Therefore, in order to achieve smart product design by taking into consideration of all its life phases, there is need for a smart product design framework to systematically guide smart product through-life design.

The motivation of this study is to explore and develop a design framework to bridge the gap between the real needs of designing a smart product through its lifecycle and current design methods mainly addressing a few product life phases as discussed in the prior section, which can guide smart product through-life design. The aims of the study is to (1) develop a generic environment interaction model for smart products through-life design, (2) develop a broad design roadmap/process for guiding the proposed smart products design practice from a through-life system design point of view, and (3) develop a design strategy for supporting interaction design with iterations and enabling technologies.

This paper proposes a novel environment interaction model-driven smart products through-life design framework (or methodology). It can support smart product design by systematically analyzing its interaction requirements with their external environments, synthesizing smart design solutions by exploring smart product design spaces (or dimensions), and integrating enabling smart technologies for implementing design solutions throughout all the life phases of the smart product for satisfying all environment needs. The main contributions of this paper are:

(1) A generic smart product environment interaction model for a life phase to help map out the interaction requirements between the smart product (SP), accompanying physical environments (PEs), human environments (HEs) and cyberspace environments (CEs) concerned in the phase. This information model can then help identify interaction requirements between SP and the triplet (PEs, CEs, HEs). This model is a generic model, thus can be applied to all life phases to support smart product design through-life.

(2) A smart product design process model for guiding the product and its interaction design at each phase. This model provides a guiding design process for smart product development at operational level.

(3) A design strategy of smart product through-life design by systematically integrating design at each lifecycle phase into the system design from a feed-forwards mechanism.

The smart product through-life design framework (or method) is demonstrated with a case study of smart high-speed train, which shows the implementation feasibility of the framework for guiding and supporting smart products design under the complex interaction information.

The rest of this paper is structured as follows. In Section 2, a brief literature review of design methods and interaction behaviours for smart products are presented. The proposed framework is described in Section 3. The case study with a high-speed train design as a smart product is presented in the Section 4. Section 5 discusses the application results and implications. The conclusions and future works are drawn in Section 6.

2. Related work

A smart product here can be either referred to a single machine, device or tool, or broadly referred to a product service system and an engineered system(Mühlhäuser 2007). Smart products have sensing, memory, communication, identity, self-reasoning and decision making capabilities all along their lifecycles(Kiritsis 2011). The definition of smart product is not unique when focusing on different aspects of smart products and different life cycle phases. Meyer *et al.* (2009) proposed a three dimensional classification model of smart products based on the information architectures, namely level of intelligence(e.g. passive, active, intelligent), location of intelligence(e.g. intelligence at object, intelligence through network) and aggregation level of intelligence(e.g. intelligent item, intelligent container). Leitão *et al.* (2015)considered the product life cycle as the fourth dimension to show the varying of roles and functionalities of smart products along its life cycle. Wuest *et al.* (2018) regarded smartness (pro-active/social) as a higher level of intelligence. These definitions on smart products form a core foundation for guiding the design of smart products.

The other related work of this paper can be classified into two categories: through-life design approaches and interaction behaviors of smart products.

2.1 Through-life design approaches to smart products

To enable profit creation through-life, life phases of a smart product are considered in the early design stage. The intelligence of a smart product is not unique and static, which is evolving depending on the smart product in its different phases of lifecycle(Sallez *et al.* 2010). Barbosa *et al.* (2016) and Duffy *et al.* (2016) have given the contexts of smart products through-life: for a smart product, in its design phase, its intelligence can reflect on smart acquirement of user needs, interaction and design requirements, smart conceptualization and design evaluation. While, in its production phase, its intelligence can reflect on automatic reconfiguration (or adaptation) of itself and dynamically defining the allocation of resources. Next, in the delivery phase, the intelligence of smart product may enable its intelligent interactions with a smart logistic system for efficient delivery. Moving on to its use and maintenance phases, the product intelligence is demanded to autonomously interact with its ambient environments (end users and other smart products), monitor and diagnose itself. Finally, in its recycling phase, product intelligence may require to analyze and present its own life manner to determine the way (remanufacturing, reuse and recycling) of value re-creation at the end of its life.

A lean and smart product development process is proposed based on Industry 4.0 concept(Rauch *et al.* 2016). A smart ship design technique is demonstrated with regard to the smart product through-life under an industry 4.0 environment (Ang *et al.* 2016). A co-creation platform of intelligent products is reported to help integration of human actors throughout the lifecycle into the design process of intelligent products(Hribernik *et al.* 2011). And a framework is proposed by Jiang *et al.* (2018) to improve the recovery rate based on the cloud-based recycling service of smart products.

2.2 Interaction behaviours of smart products

Smart products usually exist internal interactions with physical products and external interactions with informational environment(Borangiu et al. 2014). A concept of interaction flows including context awareness, product orchestration and interaction with the user is proposed to support smart products development(Ständer 2010). Emerging social-economics has transformed manufacturing paradigm to social manufacturing, thus social interactions are proposed to establish and maintain prosumer relationships(Jiang et al. 2016). Ding and Jiang (2017) clarified the operational logicality of production interaction and coordination among different participants based on social sensors of human-to-human, human-to-machine and machine-to-machine in social manufacturing environment. Smart product-service systems (PSS) are regarded as a sustainable strategy through cooperation and interaction of heterogeneous stakeholders to satisfy the demands of individual consumers(Valencia Cardona et al. 2015).The interaction between providers and consumers is an important characteristic of smart PSS. Zheng *et al.* (2018) proposed a platform-based, data-driven and digital twin-enabled systematic approach for smart PSS service innovation, and advised to integrate human factors with technical requirements into a comprehensive consideration in the smart PSS. The interactions between product lifecycle management (PLM) and service lifecycle management (SLM) is a foundation for collaborative design of integrated PSS so that an integral interaction model is proposed to support PSS development (Wiesner et al. 2015).

As for interaction design methods, four typical design approaches are used for interaction design, including user-centered design (focusing on user needs and goals), activity-centered design (focusing on the tasks and activities that need to be accomplished), systems design (emphasizing on components of a system) and genius design (considering skill and wisdom of designers involved to make products), which have been used to create successful products(Saffer 2010). User-centered design is currently the most popular method and plays an important role in smart products within the context of Industry 4.0, which focuses on the identification of interactions and services to fully reflect users' demands and preferences(Luetzenberger *et al.* 2013). Such a design method not only enables the control of the risks(Pacaux-Lemoine *et al.* 2017) and understanding of the relationships between system features and human actions and reactions(Nemeth 2004), but also leads to more useful and usable products(Buurman 1997).

While interaction technologies support the user to realize the role of flexible problem-solvers and strategic decision-makers in the cyber-physical system(Gorecky *et al.* 2014). The interaction/interface between human beings and machine is more and more complex and its ways are changing to meet individual requirements and support subject conditions, in addition, it needs to handle a huge quantity of information also being connected to servers in cyber-ends(Peruzzini and Pellicciari 2017). Many stakeholders involved in through-life of smart products have diverse interests and expectations. Therefore, it is essential to analyse the impact of stakeholder interactions on smart products design and identify the features of interactions among different stakeholders at different life-cycle phases of smart products(Song 2017).

When a smart product moves into a different environment, it may require very different behavioral strategies, facing unknown and/or dynamic environments. The environment-based design shares a common foundation: design coming from the environment, serving the environment, and changing the environment(Zeng 2004). Product environments (e.g. natural, social, technological) are not only identified as the sources of product requirements relating to structural requirements and performance requirements, but also classified as the events in the product life cycle. The communication and interaction with their environments are the key features of smart products(Nunes *et al.* 2017). Physical products with embedded information devices allow them to communicate to each other and interact with their environment(Kiritsis 2011).

Smart products are not only involved in human-product-interactions but can be part of social interactions. Now the role of designers in innovation shifts towards a sustainable society, thus the mutual relationship between PSS and social change processes should be taken into account in the development of new products or product service systems(Joore and Brezet 2015). The complex and dynamic interactions of socio-cyber-physical systems with their surrounding environment are important for logistic operations in production networks(Frazzon *et al.* 2013).

To sum up, existing studies on smart products in terms of the through-life design, environment-based design and user-centered design are limited to a specific smart product under a multidimensional hierarchy interaction space, and existing framework for smart products focuses on making individual products smart without addressing the need for communication with external environments including physical, cyberspace and human environments. Smart products often need to be designed to encompass a range of interactions with different objects and subjects throughout the lifecycle, such as other intelligent products, their environment, and human beings. It is well-known that the creation of high-quality interactions can positively influence the experience of consumers. However, how to build the high-quality interaction relationship between external environments and a smart product is a challenging problem in the new product developments in a holistic way of sustaining production profit and growth.

Here, this paper proposes a new environment interaction model-driven framework for achieving a smart product through-life design and demonstrates its effectiveness with typical application scenarios, illustrating the new environment interaction model. This method not only facilitates the solution to the above problems but also helps smart products to become more competitive.

3. Framework overview

According to definitions and descriptions of intelligent/smart products (Kärkkäinen *et al.* 2003, McFarlane *et al.* 2003, Mühlhäuser 2007, Ventä 2007, Yang *et al.* 2009, Leitão *et al.* 2015), a smart product should contain the following properties: physical system (including hardware and software), cyber system, data, information, knowledge, and interaction/interfacing(Lee *et al.* 2015). These properties are varying along the product through-life phases (including design, production, delivery, service, maintenance and recycling) driven by its external environment interaction model.

This paper proposes a high-profile framework, which can utilize environment interaction information in a system in which a smart product is embedded to inform smart product through-life design as shown in Figure 1. It has three parts. In Part 1, the external environments including physical, human and cyberspace are grouped in a pie wheel, and changed when the product runs through different life phases such as the Beginning of life - BOL (design and production), Middle of life-MOL (delivery, service and maintenance) and End of life-EOL(recycling), as represented in Part 3. Between the Part 1 and Part 3 is the Part 2—environment interaction through-life phases enabled by phase-specific environment interaction models (EIMs) and integral through-life design strategies. The part 1 is also concerned about how to define the generic environment interaction model, which mainly focuses on the interaction behaviors of smart product by identifying interaction requirements in each lifecycle phase. The part 2 is focused on what design process (model) is suitable for a smart product design based on environment interaction model in a single phase and part 3 is concerned about how to systematically integrate design at each life phase into the system design. The framework aims to resolve these three core problems.

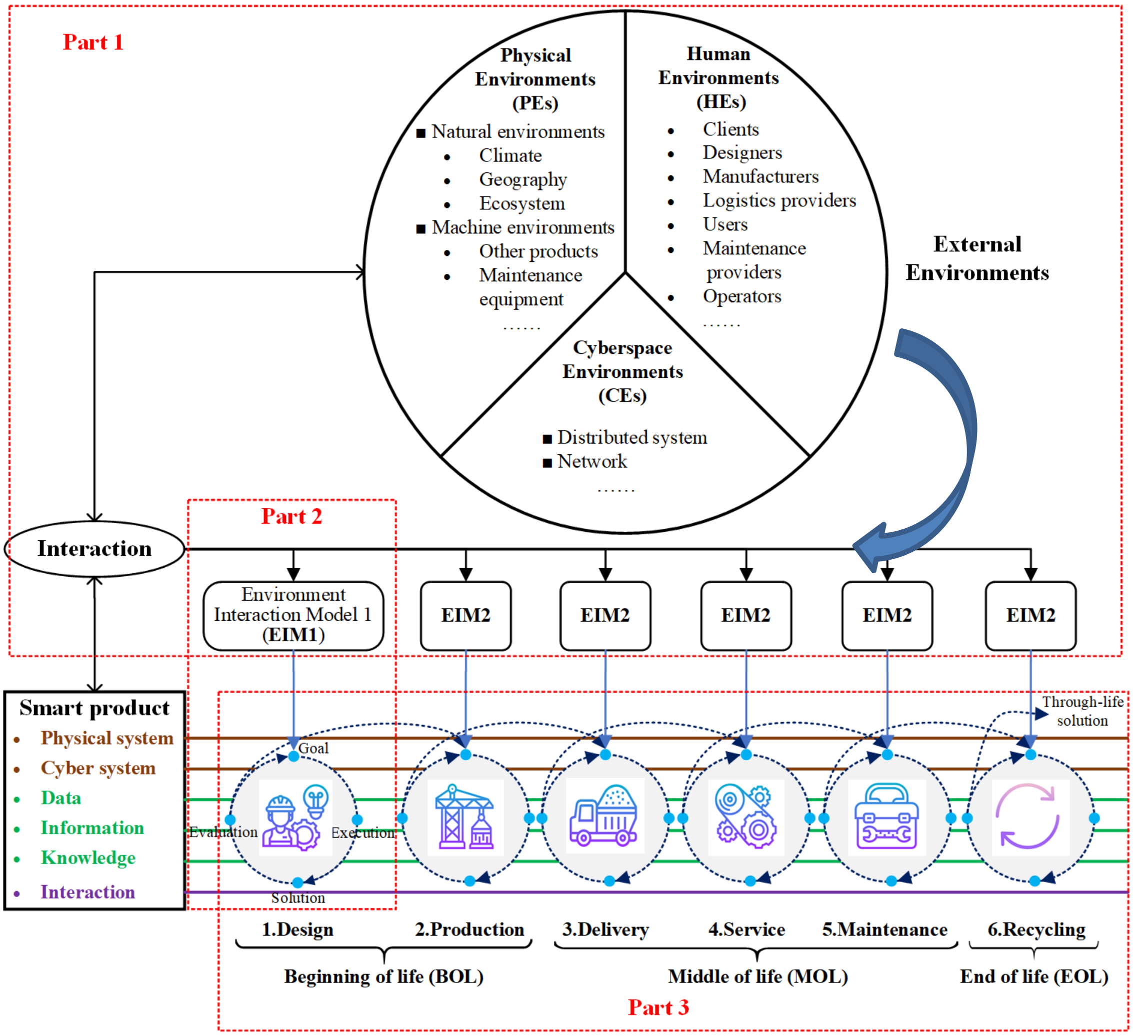

Figure 1. A generic overview framework for smart products through-life design

For example, in order to represent the external environment interactions involved in design processes, this paper adopts an environment interaction model driven design approach. It defines the interaction behaviours as a set of design requirements to meet. Similarly, the environment interaction model driven smart product design can be carried out through each lifecycle phase. In order to obtain a systematically integrated design solution in whole lifecycle, the framework provides a systematic and integral through-life design strategy. Figure 1 provides a generic overview framework for smart products through-life design.

The three key parts are detailed in next three sections.

3.1. Generic environment interaction model of smart products

A smart product often involves external environments that influence it through input effects (operating, controlling, etc.) and disturbing effects (e.g. excess temperatures), which returns feedback effects or side-effects(Pahl and Beitz 2013). As shown in Figure 1, from a physical environment point of view, environment is a multi-dimensional concept comprised of factors relating to the natural environments (e.g., climate, geography, ecosystem) and machine environments (e.g., other products, infrastructure, maintenance equipment) (Anand and Ward 2004, Zeng 2004, Tao *et al.* 2018). The typical natural environments have important influences on the safety and reliability of product, such as temperature, humidity, sand, rain/ice, snow, air pressure, salt spray, etc. At the same time, natural environments faced by smart products is more complicated and harsher with the extension of scope of use, such as alpine, plateau, desert, humidity, and complex environment, etc. The machine environments are regarded as constraint factors on the manufacturability and transportability of product. From a human environment point of view, experience requirements from multi-stakeholders (e.g. clients, designers, manufacturers, logistics providers, users, maintenance providers) need to be considered in the context of smart products through-life(Duffy *et al.* 2016). From a cyberspace environments point of view, the infrastructure of other ICT systems need to be taken into account (e.g. distributed system, network)(Poslad 2011). Therefore, environment interaction is a multidimensional, dynamical and hierarchical space, it is challenging to systematically take interaction information through all life phases into account a smart product design and development.

An interaction is a transaction (an exchange of information, goods or services) between two entities(Saffer 2010). While environment interaction, as a general term referring to ways of interfacing through-life activities within smart products and environments, is a composite and superimposed of various individual interactions. From a through-life point of view, each specific interaction activity in the lifecycle has corresponding interaction demands. Therefore, environment interaction model is divided into six submodules in different phases of lifecycle (See Figure 1).

Smart products are composed of physical systems (including sensors, mechanisms, control systems, and connectivity components) and cyber systems (including through-life dependency systems), which are so called the system of systems. The design for each phase should consider different required interactions with both physical systems and cyber systems (e.g. design system, production system, logistics system). This paper proposes a generic smart product interaction information model for a life phase to help map out the interaction requirements between the smart product (SP), accompanying physical environments (PEs), human environments (HEs) and cyberspace environments (CEs) concerned in the phase, which is smart product centred in a classic feedback loop, as shown in Figure 2. This model can then help identify interaction requirements between SP and the triplet (PEs, CEs, HEs).

This model is a generic model, thus can be applied to all life phases to support smart product design through-life. Different external environmental conditions along with their individual requirements towards interaction capabilities throughout the lifecycle of the smart product need to be identified in order to gauge the scope of different interactions that need to be looked at(Hribernik *et al.* 2011), as follows:

Smart products in design- the translation of smart requirements into smart components that possess knowledge of their physical systems (e.g. sensors, control, mechanisms, connectively) and cyber systems (e.g. design systems). Beginning in the design phase of the smart product's lifecycle, customers (users) and designers, are among the actors required to interact with the mock-up of smart product, which bridges the gap between designers and users/stakeholders. Smart products should also interact with the cyberspace environments (e.g. market analysis).

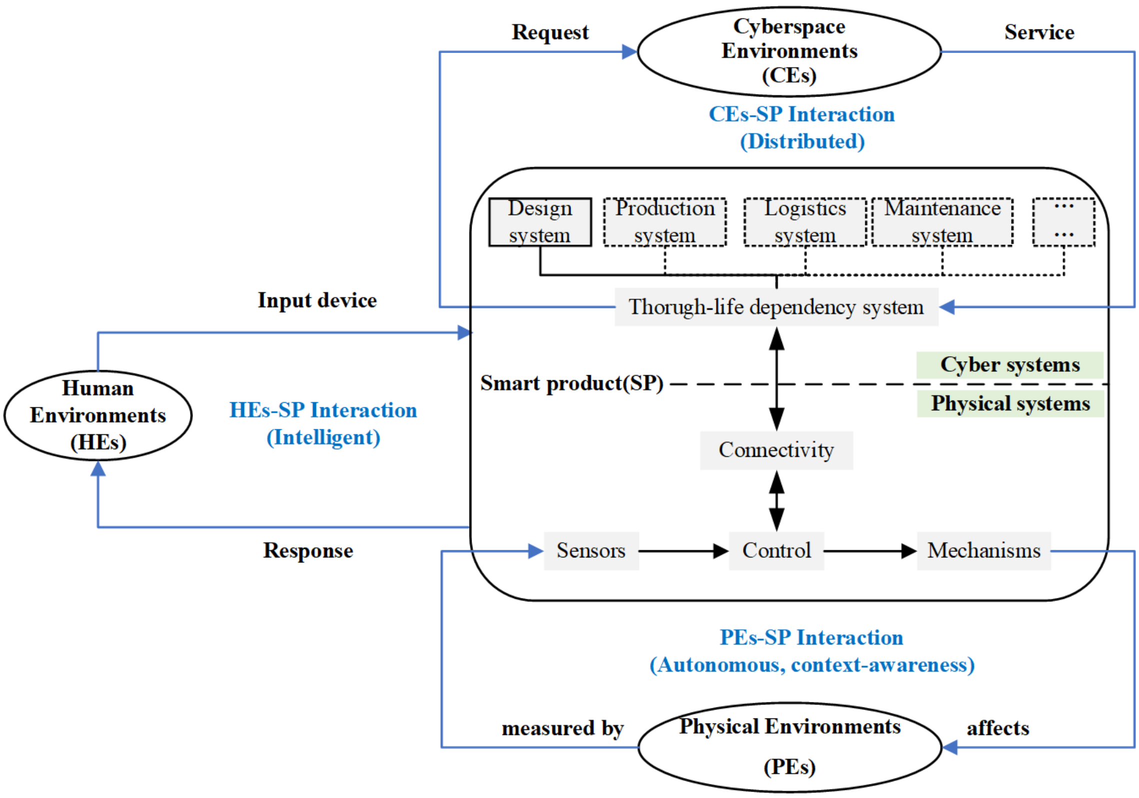

Figure 2. The generic interaction information model of smart products

Smart products in production-smart production lines and assembly will automatically reconfigure themselves in response to customized smart requirements and interact with production engineers based on smart manufacturing technology, which seek the production time, quality and cost in the physical end, and achieve the manufacturing process monitoring and production quality control in the cyber end for smart products. It is necessary to be considered that interactions between manufacturers, designers and a smart product, interactions between smart factory environments (e.g. smart manufacturing devices/tools) and physical systems in a smart product, and interactions between core enterprise business systems (such as ERP, SAP) and cyber systems in a smart product.

Smart products in delivery- The interaction with a smart logistical system in a cyberspace environment should be considered to ensure the efficient delivery of smart products, which seeks delivery time and distribution plan for smart products. The interactions between designers, transporters, distributors and smart products also need to be taken into consideration. The delivery of smart products has mutual influenced with laws, ways of transportation, climate and geography environment factors.

Smart products in service-smart products will autonomously interact with end users and other smart products to achieve value creation with respect to performance, resource utilization, and safety, which also use the interaction between the cyber systems such as service system and other business systems in cyberspace environment, and adaptation management system to seek economic and user-friendliness of physical systems. The use and status of smart products have mutual influenced with climate, geography, infrastructure and social (e.g. laws, cultures) environments factors.

Smart products in maintenance- health monitoring systems interaction with other data platforms in the cyberspace environments will allow smart products to adapt their maintenance regime and present themselves in a timely manner to minimize downtime, which seek maintenance procedures, time and cost in the physical systems. Customers, designers, suppliers, manufacturers and maintainers are among the actors required to interact with the smart product. The maintenances of smart products have mutual influences with maintenance devices and natural environments.

Smart products in recycling-the smart product will interact with smart remanufacturing and recycling systems in the cyberspace environments and present itself in a manner of recycling (e.g. product recycling, used material recycling, production waste recycling) in the physical systems based on design, manufacturing and usage information. The main task of designers includes design for recycling and design for remanufacturing, which adjust the structures/materials to facilitate the recyclers do recycling. The recycling of smart products has mutual influences on ecosystem and social environments.

For example, it is essential to smart high-speed trains that ensure the safe, reliable and stable operation of high-speed trains in complex external environments. Its through-life design process involves a series of users (including driver, passengers, maintainer, etc.) and other stakeholders (including manufacturing, supplier, etc.), natural environments (including temperature, humidity, sand, rain/ice, snow, air pressure, salt spray, ecosystem, etc.), machine environments (including track, line, platform, standards, organization, devices, etc.), cyberspace environments (including train dispatching command system, earthquake early warning system, etc.). A variety of different types of interaction requirements generated in the smart high-speed train's through-design process drive the high-speed train design.

Therefore, the smart products through-life environment interaction model is able to analyse the rationality and effectiveness of smart interactions in all lifecycle phases. In the next section, this paper will explain how the smart product design is expressed and implemented based on the environment interaction model.

3.2. Smart products design process model

In each lifecycle phase, the smart product design involves three main sets of activities, which are (1) how to identify and specify the environment interaction requirements based on environment interaction model, (2) how to position the level, location and aggregation of intelligence, and (3) how to explore the alternative solution. Therefore, the design process model aims to resolve these three core problems. A new generic smart products design process model as shown in Figure 3, which is detailed as follows:

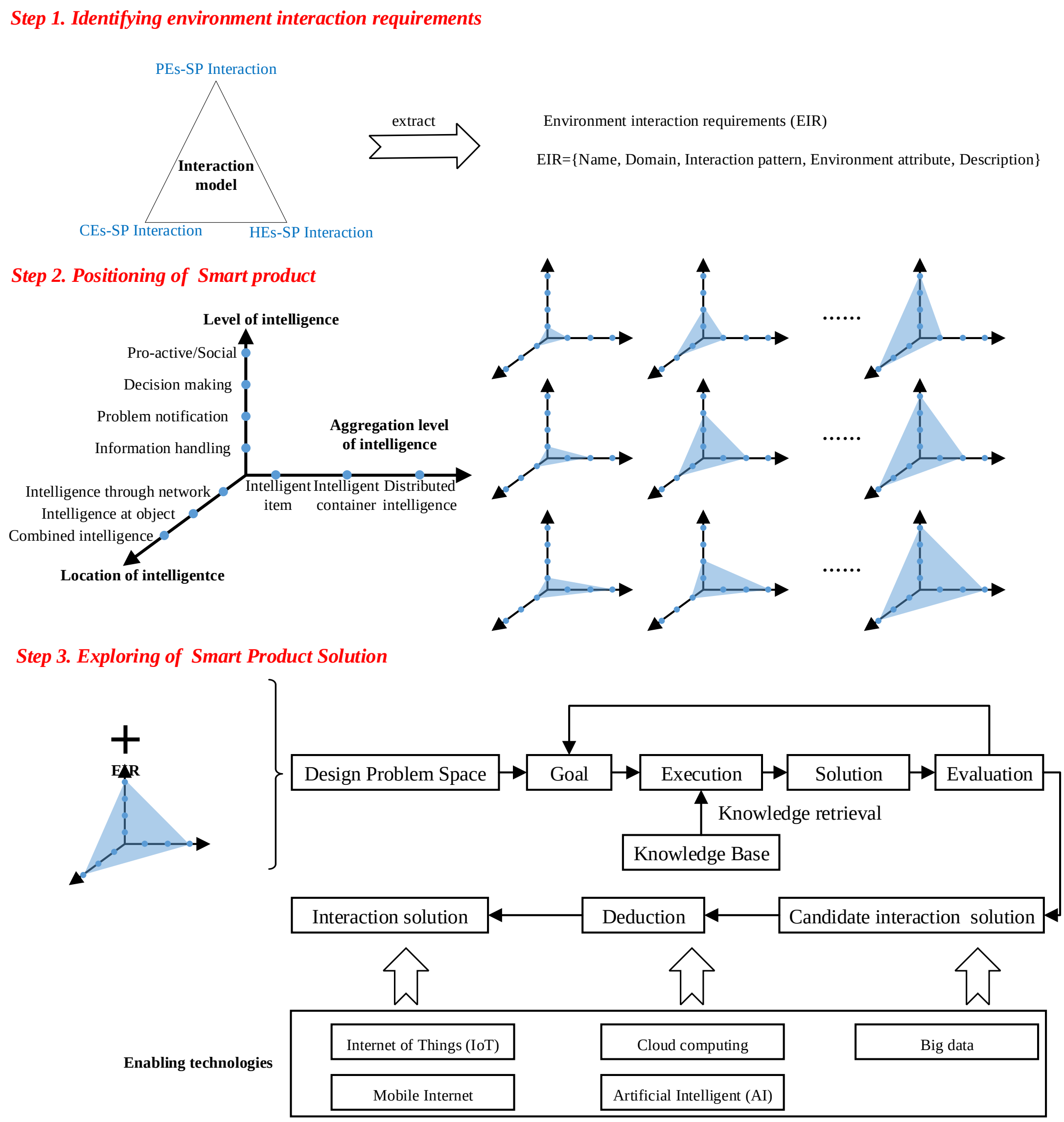

Figure 3. The generic smart products design process model

Step 1: Identifying environment interaction requirements

According to the various environment context and the generic environment interaction model, interaction requirements between SP and the triplet (PEs, CEs, HEs) can be identified and specified. The environment interaction model (EIM) is described as follows:

$$EIM_i = (SP \otimes PEs) \cup (SP \otimes CEs) \cup (SP \otimes HEs) \quad (1)$$

Where *i* is the phase of through-life design state; the interaction (⊗) between SP and the triplet (PEs, CEs, HEs). It should be noted that decisions on how many smart components and what environment components should be considered depending on designers' experience and other factors relevant to the concerned design requirements.

The environment interaction requirement (EIR) is expressed by five-tuple description including Name (*N*), Domain (*Do*), Interaction Pattern (*IP*), Environment Attribute (*EA*), Description (*De*):

$$EIR_i = \{N, Do, IP, EA, De\} \tag{2}$$

N represents the name of an environment interaction requirement such as real-time perception, real-time visualization etc., *Do* describes different classifications of interaction requirements such as SP-PEs, SP-CEs and SP-HEs. *IP* describes the interaction without taking into account technological details (Valverde *et al.* 2007), such as service, feedback, order criteria, etc. *EA* is the attribute description of the interaction requirement such as temperature value, device state etc. *De* is the detailed description of EIR.

Step 2: Positioning of smart product intelligence

The aim of positioning of smart product intelligence is to make sure that a number of practical goals for the application of smart products is achievable. According to the framework established by Meyer(Meyer *et al.* 2009), the positioning of the smart products is illustrated in Step 2 as a three dimensional intelligence distribution model. The options concerning the location, level and aggregation of the intelligence are explored by taking into consideration external environments. The level of intelligence includes information handling, problem notification, decision making and pro-active (social); the location of intelligence includes intelligence at object, intelligence through network and combined intelligence; and the aggregation level of intelligence includes intelligent item, intelligent container and distributed intelligence. The classification of smart products is not unique and static in different phases of lifecycle applications. Based on the environment interaction requirements, this three-dimensional intelligence distribution model can be used to guide positioning of smart products intelligence for constructing information architectures.

For example， the positioning of a high-speed train as smart product in its maintenance application is illustrated in Fig 4. The level of intelligence of the high-speed train could be able to apply self-diagnosis mechanisms using the gathered production data, while along the aggregation dimension; intelligence of the smart train could be considered as a distributed intelligence system. Finally, in terms of location of the intelligence, a combined intelligence could be distributed through the vehicle monitoring system and the remote big data health monitoring in the ground platform.

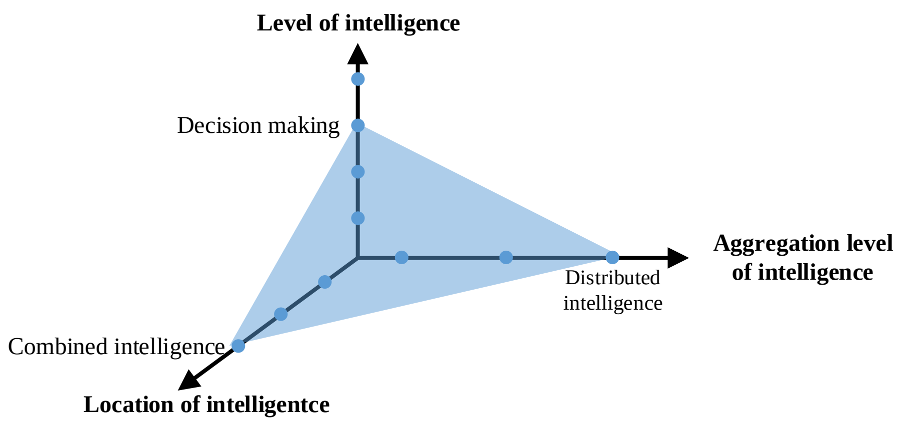

Figure 4. Positioning of intelligence of a smart high-speed train in maintenance

In formulating these propositions, the goals of an application of smart products are explicated, particular solution requirements are identified, and the circumstances where the goals can be achieved are discussed based on identified environment interaction requirements. There is a need for such propositions when searching for new solutions and applications. The positioning of smart products intelligence is a foundation for guiding the design of smart products.

Step 3: Exploring of smart product solution

According to environment interaction requirements and position of smart product intelligence, the design process in general follows the Norman's interaction design process(Norman 2016). First, the design problem space will be explored and then the goals of a design will be defined. After that, designers can execute the design with acquired design knowledge from the knowledge base to help explore potential solutions and identify better alternatives from evaluation. Interaction solutions can finally be generated through deduction through looking at similar products for inspiration. This process is shown in Step 3 of Fig 3.

This is an evolutional design process, which can be enabled by enabling technologies such as internet of things (IoT), cloud computing, big data. It must be noted, however, that the methods developed so far are all heuristic. One advantage of the environment interaction model driven design is to guide designers to rapidly explore design problem spaces and determine the focus areas or design goals, and in turn to lead to effective solution exploration and deliver the solution with evaluation and enabling technologies.

3.3. Systematic integral through-life design strategy

In different lifecycle phases of a smart product, the intelligence levels of smart product are not unique and static, which are evolving. On the one hand, design focuses are on different aspects such as perception abilities and interaction abilities in different phases. On the other hand, a smart product is typically modular-designed, some intelligent modules are upgradable over the lifetime when new interaction technology becomes available. Thus, the enabling technologies of a smart product are affecting its level of intelligence. A feed-forwards design strategy should be adopted based on the level and trend of key enabling technologies.

According to the generic environment interaction model and design process model of smart products, a systematic integral through-life design strategy of smart products is proposed based on the Donald Norman's interaction model(Norman 2016), as shown in Figure 4.

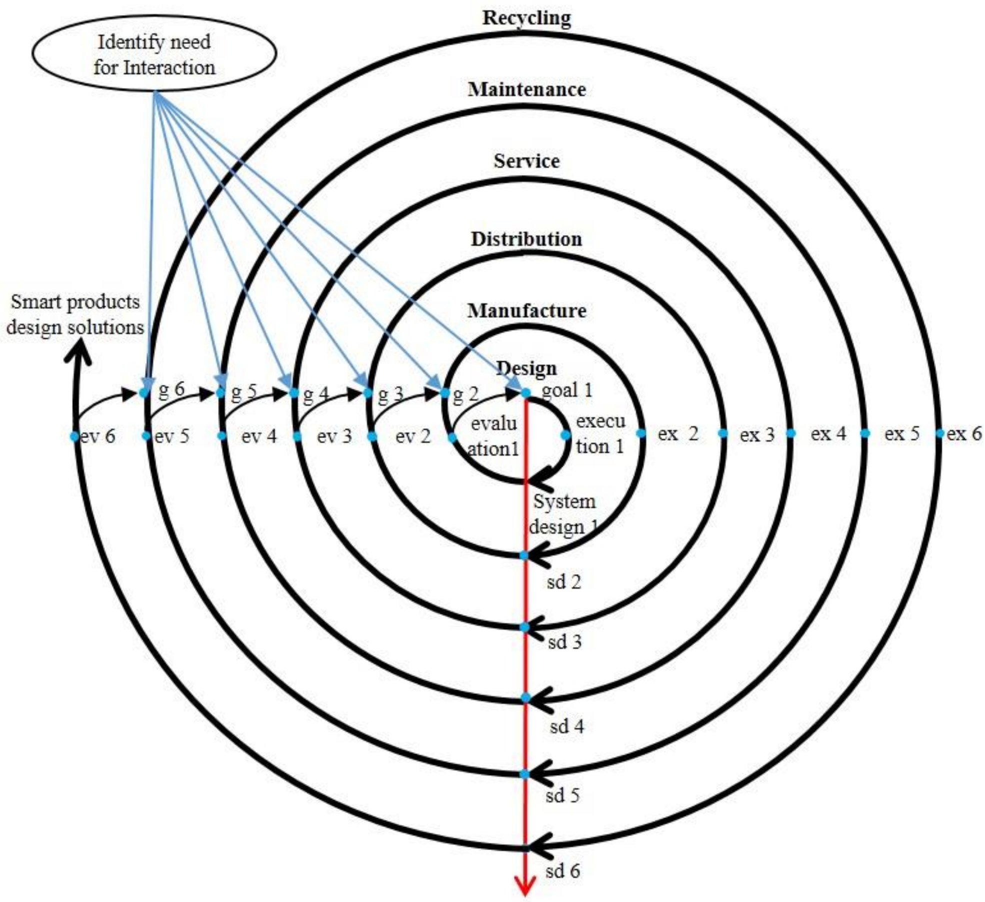

Figure 5. The design strategy of integral smart products through-life design

Smart products through-life design is a spiral and feed-forwards process throughout all phases, which is driven by identified interaction requirements and enabling technology. In each phase, the design process is iterative which follows the Norman's interaction design model (including goal, execution, system design and evaluation). At the end of each phase, the system design solution of smart products will be obtained and feed-forwarded to its next phase design until it reaches the final phase. A powerful and successful design solution of smart products will be obtained in the last phase, which can satisfy all environment interaction needs.

In this way, the model of interaction design provides a clear roadmap for designers to achieve the interaction design in different lifecycle phases. In the next section, this paper will introduce a specific interaction design case to demonstrate its application.

4. Case study

In this section, a case study is presented to illustrate some practical aspects of the proposed framework. The case describes a smart high-speed train design. The manufacturing enterprises of railway transportation equipment such as Bombardier and CRRC are now paying attention to the concept of smart product and its potential benefit by considering the train as an active CPS through its life-cycle(Barbosa *et al.* 2016). High-speed trains are complex transportation systems that must meet the requirements of external environments, train operators, passengers and agencies. This paper firstly constructs high-speed train's through-life environment interaction model, as shown in Figure 6.

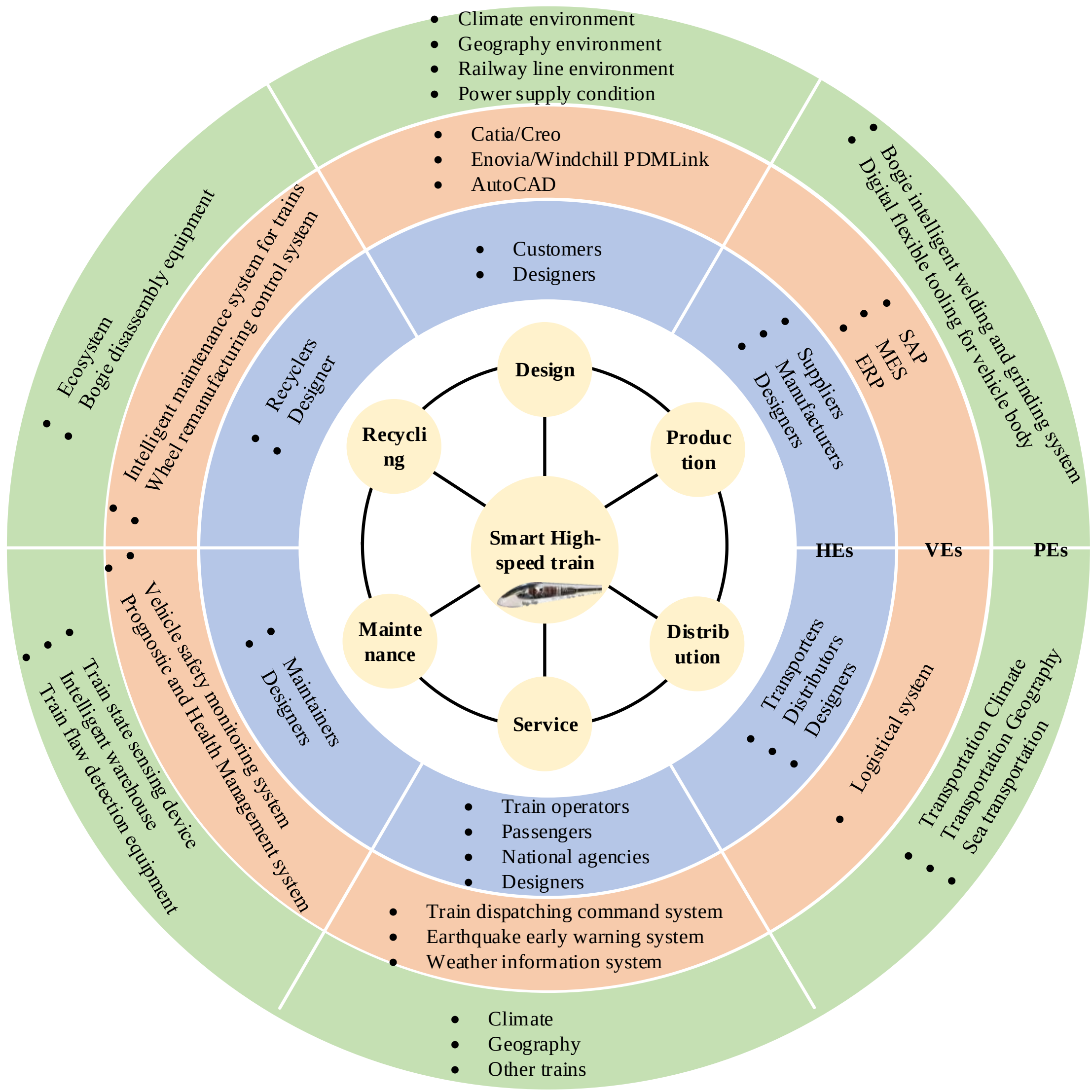

Figure 6. High speed train's through-life environment interaction model

In the design phase of smart high-speed train, the cyber system is totally virtual and supported by integrated software containing two commercial PLM solutions. Smart products take the progress of the mock up into account and automatically trigger in sequence the activities of the other design functions and record the different design modifications in a design history.

In the production phase of smart high-speed train, each major component and production resource that process them are active and intelligent products in a smart factory. Each smart component interacts with its external production environment (manufacturers and smart factory environments) and belongs to a CPS, which behaves in a reactive manner and adapt itself when facing unexpected events during manufacturing and tests. Specific manufacturing and design history of each IP component is stored and embedded in the train.

In the delivery phase of smart high-speed train, the information conveyed by the smart product may be used by logistics chains to facilitate inventory management. The interactive capacity of a smart product to sense its state and the characteristics of its external environment improves its safety in storage or its shipping efficiency. For example, random vibration excited by the vehicle is very important factor to choose the best transportation way from many options, such as sea transportation is with low frequency vibration while air transportation is with high frequency vibration.

In the recycling phase of smart high-speed train, smart products capitalized knowledge and history from their use and maintenance. The embedded product intelligence can help specify the physical parts to be recycled from the ones to be remanufactured or the ones reused as spared parts.

This case study, mainly takes the service and maintenance phase as an example to show the design process model, and other phases are similar. In the service and maintenance phase of smart high-speed train, involved stakeholders include designer, passengers, train operators, maintainers and national agencies. The physical environments have an important impact on the safe, reliable and stable operation of high-speed trains, such as climate (including temperature, ramp, etc.), geography, other trains and maintenance devices. The cyberspace environments provide environment information such as train dispatching command system, earthquake early warning system, weather information system and big data health monitoring platform. In reverse, the running of high-speed trains also has effects on the ecosystem environment, such as noise, energy consumption, radiation, etc. Therefore, according to the design process model for smart products, a design model for smart high-speed train in the service and maintenance phase is established as shown in Figure 7.

With the support of cyber-physical, intelligent and information handling technologies, smart high-speed train would achieve the function of smart monitoring, smart drive, smart service and smart maintenance.

Firstly, interaction information is acquired between a smart high-speed train and its service and maintenance environment including factors: climate, geography, train operators, maintainers, passengers, and national agencies. The train operators and national agencies want to visualize the status of smart high-speed trains in real time and its surrounding environments in terms of the dynamic status of high-speed trains and its operating environments and performance parameters. They also need it to be controllable remotely (automatic driving and operation safety monitoring of vehicles); The maintainers hope that smart high-speed trains can achieve operation fault self-diagnosis and intelligent maintenance (repairable); The passengers hope that smart high-speed trains can provide a variety of information and service (information active). According to equation (2), the environment interaction requirement (EIR) is obtained in service and maintenance (4, 5) phase, including $EIR_{4,5}(1)$, $EIR_{4,5}(2)$, $EIR_{4,5}(3)$, $EIR_{4,5}(4)$ and $EIR_{4,5}(1)$ as shown in Figure 7.

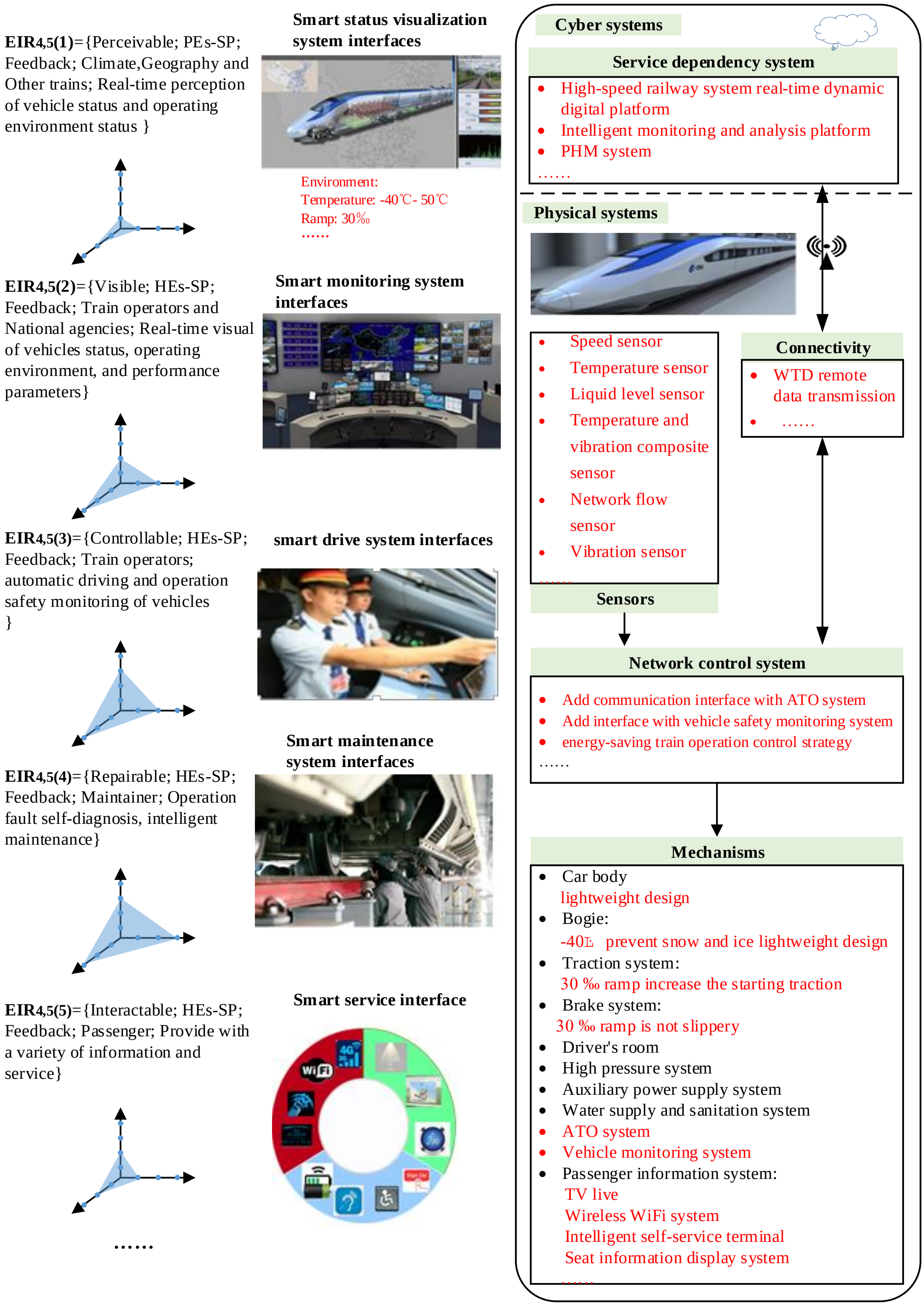

Figure 7. Smart high-speed train in the service and maintenance phase

Secondly, based on a three-dimensional intelligence framework model in Step 2 of Figure 3, designers need to position intelligence along the level, location and aggregation dimensions for each EIR of the smart train. Their position is shown in Figure 7.

Thirdly, according to Step 3 in Figure 3, designers need to explore a solution space and find a solution with system interaction interfaces to meet the goal based on combining environment interaction requirement and intelligence position of smart high-speed train.

Smart high-speed train should have system interaction interfaces including smart status visualization system interface, smart monitoring system interface, smart drive system interface, smart maintenance system interface and smart service interface. These interaction information drives smart high-speed train’s components design. The classification of smart high-speed train’s components includes sensors, mechanism, network control systems, connectors and cyber components (See Figure 7).

Smart status visualization system interface information drives the components design of sensors and cloud service. The sensors are not only needed to acquire the status data of high-speed trains and operating environments data. According to statistics, more than 1,500 sensors need to be installed and covering more than 2,500 monitoring points in eight coaches of a train. The types of sensors include speed sensor, temperature sensor, liquid level sensor, temperature and vibration composite sensor, network flow sensor, and vibration sensor, etc. In cyber system, it needs to provide the cloud service to support the smart status visualization system through a digital visualization platform.

Smart monitoring system interface information drives the components design of network control system, mechanism and cyber. The network control system needs to add the network topology interface, which is a communication interface with vehicle safety monitoring system. The mechanism needs to be added to the safety monitoring system. The intelligent monitoring and analysis platform should be built in the cyber system.

Smart driving system interface information drives the components design of network control system and mechanism to communicate with Automatic Train Operation (ATO) system, and the mechanism to implement the ATO system.

Smart maintenance system interface information drives the components design of the cloud service. The Prognostic and Health Management (PHM) system should be built in the cyber system.

Smart service interface information drives the components design of passenger information system and mechanism. The passenger information system needs to provide live TV channels, wireless Wi-Fi system, intelligent self-service stations, seat information display system, etc.

The components design of mechanism is influenced by a variety of environments. Take temperature and ramp as examples to show the influence relationships. Bogies need to prevent from snowing and icing at -40°C, and at 30 ‰ ramp, its traction system needs to increase the starting traction while the brake systems need to prevent from slippery. At the same time, the components operations of mechanism have influences on environments. For example, energy consumption can show the influence relationships. In order to decrease the energy consumption, the mechanism needs to be lightweight designed so as to reduce the weight of the car body and bogie, etc. Additionally, the economical and energy-saving train operation control strategy should be applied in the network control system.

Finally, after the incremental interaction design in each phase, the final system solution is obtained through the integral smart products through-life design strategy.

5. Discussions

As demonstrated in the case study, a whole design solution of a smart train can be obtained with the proposed environment interaction model, design process model and systematically integrate design strategy. According to the development of smart high-speed train in China, the result indicates that it is a feasible system design method. It is worth noting that the accuracy of interaction relationships among the smart products and external environments are important because they affect the design solutions, but it is difficult to guarantee. A comprehensive interaction model should contain all stakeholders and related environments (including physical environments and cyberspace environments). In addition, design knowledge and experience are import in the design process. In the case study, the through-life design of a high-speed train is realised on the basis of known and interactive design knowledge and experience.

Existing studies on smart product design including through-life design (Barbosa *et al.* 2016), environment-based design(Zeng 2004) and user-centered design (Luetzenberger *et al.* 2013) , can only focus on one or a few product life phases and making individual products smart without addressing the need for communication with external environments including physical, cyberspace and human environments. In contrast, this paper proposed a generic overview framework for smart products through-life design, which can support comprehensive design through all life phases to obtain a systematic design solution under a multidimensional hierarchy interaction space. Therefore, the advantage of applying the framework into practice is to realize the smart product design by taking into consideration of all its life phases and satisfy all environment requirements. Smart products tend to be more active physically and/or socially in responses to its environment changes in the future(Wuest *et al.* 2018). It is important to create meaningful experiences and added value (Valencia Cardona *et al.* 2015) and realize all benefits from both global and local markets (Duffy et al. 2016).

The limitation of this environment interaction model driven design method is its ability to achieve the computerization of the design framework. As demonstrated in the case study, the implementation of the proposed design method requires some disciplinary design knowledge support. This limitation in the future could be overcome by using a smart product design knowledge base and Digital-Twin modelling and simulation technologies, which are able to support the computerization of the design framework.

6. Conclusions and future works

In this paper, a new environment interaction model driven smart product through-life design method has been proposed, which is significant for meeting all environmental needs in the field of engineering design. Based on the proposed environment interaction model, the design framework for designing smart products throughout all lifecycle phases are presented to gain the design solutions. Then, the design strategy of smart products through-life is built as a guiding roadmap of smart products through-life design. A new generic design process model of smart products is proposed to guide each phase design. This method can be used in engineering design of smart products with some domain knowledge support. Our case study of designing a smart high-speed train shows that the proposed environment interaction model and design method are feasible and applicable in through-life design of smart products.

The implementation of the proposed design method associated with the design framework requires more verified product instances and accordingly the model can be refined gradually. The design of a smart product is a multi-disciplinary engineering problem, which also needs the cooperation of multi-domain experts. Thus, in addition to smart product-environment interaction, human-human interactions at each phase are also an important aspect. Therefore, in the future, the interaction information model and the design framework could be improved and an environment interaction design knowledge base could be established to support the development of new smart products.

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