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A Knowledge Graph-aided C-K Approach for Evolutionary Smart Product-Service System Development

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Abstract: In order to meet user expectations and to optimize user experience with a higher degree of flexibility and sustainability, smart product and service system (Smart PSS), as a novel value proposition paradigm considering both online and offline smartness was proposed. However, conventional manners for developing PSS require many professional consultations, and still cannot meet with the new features of Smart PSS, such as user context-awareness and ever-evolving knowledge management. Therefore, aiming to assist Smart PSS development cost-effectively, this paper adopted Knowledge Graph (KG) technique and Concept-knowledge (C-K) model to propose an evolutionary design approach. Two knowledge graphs are firstly established with open-source knowledge, prototype specifications, and user-generated textual data. Then, triggered by personalized requirements, four KG-aided C-K operators are conducted based on graph-based query patterns and computational linguistics algorithms, thus generating innovative solutions for evolving Smart PSS. To validate the performance of the proposed approach, a case study of a smart nursing bed fulfilling multiple personalized requirements is conducted, and the evaluation result of its knowledge evolution is acceptable. It hopes that this work can offer insightful guidance to industrial organizations in their development of Smart PSS.

Keywords: knowledge graph; concept-knowledge model; smart product-service system; knowledge evolution; conceptual design

1. Introduction

Going through the eras of mass customization, lean production and agile manufacturing in the past decades, the industrial companies widely adopt co-creation business strategy and deeply embrace information & communication technology (ICT), to meet the higher user expectations from social and cultural aspects [1]. Smart product-service system (Smart PSS), a new paradigm that bundles smart, connected products (SCPs) and their generated e-service, triggers a revolution of product design from function realization to continuous optimization of user experience [2-3]. Possessing both the *offline smartness* which can react to a specific user context as a service with built-in-flexibility and self-learning mechanism [4-5], and the *online smartness* which is implemented by intelligent algorithms and customized analytic tools [6-7], Smart PSS offers more choices for multiple groups of users in design, manufacturing and usage stage (like modify product modules or install third-party APPs), and hence brings a higher degree of user flexibility in its sustainable development [8-9].

However, it is still challenging in practice to conduct personalized customization and co-develop the prototype of Smart PSS to fulfill a specific user requirement [10]. Two fatal issues, the lack of cost-effective knowledge supply manner in solution innovation [11], and the subjectivity and capriciousness of solution generation in the developing process [12], are recognized as the root-causes lead to the failure. For the first issue, omnifarious but rare-repetitive needs for expert knowledge and experience are triggered by various personalized requirements (*PRs*) under different using contexts, which is unfruitful to adopt some conventional knowledge reuse manners and also uneconomic to consult various experts [13]. For the second issue, since the goal of Smart PSS development is set beyond just delivering a single product that realize a personalized function, but also providing a series of customized value-added services [14], the generation and integration of novel solutions, especially in the stage of conceptual design, are mainly accomplished by the knowledge-intensive interactions among different stakeholders (e.g. customers, manufacturers, and suppliers), whose performances and results are significantly impacted by their available experience, personal preference, and fixed thinking-set [15].

Supporting a wide range of applications and enhancing multiple search engines, knowledge graph (KG) has shown its promising prospects in gathering and merging multi-source information about numerous entities and relationships, as well as offering extendable representation and explainable reasoning of multi-disciplinary experience and knowledge [16]. Hence, this paper seeks to establish KGs to exploit the multi-domain open-source knowledge, the specifications of the prototype, and the user-generated textual data, thus supplying expert knowledge with convenience and solving the first issue with cost-effectiveness.

Moreover, for the second issue, concept-knowledge model (C-K model) [17], a generative model illustrating the process of innovative product design with two spaces (Concept space **C** and Knowledge space **K**) and four operators (**C→K**, **C→C**, **K→K** and **K→C** operator) [18], is further enhanced to be more practical and productive with knowledge graph. A KG-aided C-K approach (KG-CK) to assist Smart PSS development process is hence proposed to automatically fetch, selectively integrate, and heuristically evolve the novel concept and knowledge in product/service design, without many experts' interventions.

The rest of this study is organized as follows. Section 2 briefly introduces previous works related to Smart PSS development, KG-aided innovation, C-K model and design knowledge evolution. In Section 3, the overall framework of KG-CK for evolutionary Smart PSS development is proposed. Section 4 presents the details in the construction of two KGs, and Section 5 illustrates the process for evolving design knowledge of Smart PSS with four KG-aided C-K operators. A case study of smart nursing bed is reported and discussed in Section 6, in order to make the theoretical concepts and methods more concrete. At last, conclusions and future works are summarized in Section 7.

2. Related works

2.1 Smart PSS and development approaches

Smart PSS, was formally defined as "*an IT-driven value co-creation business strategy consisting of various stakeholders as the players, intelligent systems as the infrastructure, smart, connected products as the media and tools, and their generated e-services as the key values delivered that continuously strives to meet individual customer needs in a sustainable manner*" [1]. From this definition, new features for Smart PSS were concluded, such as, *IT-driven, multi-stakeholder co-creation, context-awareness, self-adaptable*, and *ever-evolving* [19]. Accordingly, multiple design tools and methodologies supporting the development of creative products and services were proposed. Existing approaches could be categorized into three kinds, *platform-based approach*, *data-driven approach* and *hybrid approach*, respectively.

Platform-based approach, adopting the classical theory of product family design [20], enabled users to configure components and add-on services in Smart PSS in the early stage of product design by leveraging a product configuration system (PCS) built in the platform. PCS offered several options for upgrading/ changing to meet customers' requirements [21-22], which also benefited the manufacturers by reusing existing components with higher product flexibility [23]. Moreover, in recent years, with the combination of Digital Twin (DT) in these platforms, the interactions between physical products and cyber models, as well as users and manufactures, were strongly enhanced [24-25], which allowed a late differentiation in postponed manufacturing and meets individual needs even before the final delivery of Smart PSS [26].

Data-driven approach concentrated on the huge amounts of sensor-data and user-generated data, and then accomplished decision-making works in Smart PSS development with advanced data-mining algorithms and knowledge-based systems [10, 27-28]. Such approaches were satisfactorily applied to develop prognostic and health management (PHM) services to critical components [29-30], energy-saving and fault diagnosis systems [31], and user experience optimizations [10, 32]. Besides, based on natural language processing (NLP) techniques and semantic-web, text records like online reviews and user feedbacks were also leveraged for eliciting potential requirements [33-34]. With annotated usage patterns and semantical function-behavior-structure (FBS) relations, several tentative Smart PSSs were hence developed for ambient assisted living [35] and healthcare for the aging people [36-37].

Hybrid approach indicated a combination of *hybrid intelligence*, *hybrid design* and *hybrid value* in Smart PSS development, which tackled all the features of Smart PSS with comprehensive considerations [38]. *Hybrid intelligence* required a practice of crowdsourcing/crowdsensing to extract and generate valuable solution design concepts [39], *hybrid design* took both design and inverse design to be capable to change/upgrade with context-awareness [19], and *hybrid value* covered the considerations of open innovation, sustainability, intelligence and servitization in technical and business aspects [1]. However, as a newly proposed approach, only theoretical foundations for hybrid approach were established, instead of more practical in-depth implementations.

Apart from the existing studies summarized, most works still regarded Smart PSS development as a conventional design process, which was one-direction, manufacturer-centric, and product-dominant [40]. Therefore, an appropriate Smart PSS development approach enabling continuous evolving, user context-awareness and hybrid concerns should be provided. Besides, all the existing approaches for Smart PSS development relied much on the domain-specific knowledge supplied by the in-group experts. If an abnormal context occurs and knowledge outside the current domains was urgently demanded in explaining and reasoning, none of the previous development approaches could offer a solution without many professional consultations. Hence, Smart PSS development approach should also be able to leverage open-source knowledge and hence cost-effectively fill the knowledge gap.

2.2 Knowledge graph and its applications in innovation

Storing knowledge with a directed graph *G*= (*V*, *E*), Knowledge Graph (KG) was firstly proposed by *Google* in 2012. KG contained two components, viz., an ontology-based schema defining its vocabulary, and a graph database storing the triples of knowledge, viz., (*head*, *rel* (relation), *tail*) [41]. This idea was not completely new, which could be dated back to *Semantic Network* proposed in 1960s, and *Resource Description Frameworks* (*RDF*) published in 2004 [16]. However, in contrast to previous tools, KG possessed higher flexibility and extensiveness in knowledge management. The schema of KG didn't need to be established completely in advance and could be created evolutionarily, thus triggering a transfer from top-down manners to bottom-up manners in KG establishment, and preventing the proliferation of heterogeneous schemas for the same entities [42]. Besides, because of the huge amounts of interconnected typed entities and their attributes, deeper and broader searches were feasible in the searching algorithms. Therefore, KG was capable to provide more valuable and insightful knowledge management services for end-users (like multi-hop reasoning, knowledge-based question answering) in multiple domains and scenarios [43].

KG also facilitated innovation in a corporate knowledge management environment (so-called *Open innovation*), and several tentative KG-enabled innovation platforms were successfully established and well-operated in several sectors like banking, energy and telecommunication [44-46]. Specifically, KGs supported a collaboration of ideas created by thousands of employees, clients and other stakeholders using multiple languages [47], enabled a knowledge-based searching for related ideas, collaborative partners, potential users and involved knowledge areas [48], and hence provided high-valuable solutions for multiple categories of issues raised in the process of innovation [49].

However, since KG's momentum was led by IT companies like *Google*, *IBM*, *Baidu*, *Alibaba* and other academic institutions of computer science, developing online knowledge-based services was still dominant in most KG applications (like medical Q&A in *Watson*, business consulting in *Alipay Chatbot*). In this situation, KG just played a mediate role of an information provider, but stopped before further utilizing fetched knowledge to improve the product/service itself. Under the scenario of Smart PSS, components/ modules were the fundamental carriers for achieving the desired functions and bundled add-on services, which should be ever-evolving to meet uprising user requirements [3]. Therefore, novel applying manners further exploiting KGs to generate innovative solutions should be investigated for Smart PSS development.

2.3 Concept-Knowledge model and design knowledge evolution

To express knowledge evolution in innovative design process in detail, Concept-Knowledge (C-K) model, a generative model with a solid logical foundation, was proposed and gained considerable interest in the design community [50]. C-K model contained two spaces, concept space **C** and knowledge space **K**, portraying the understanding for an object x in the process of conceptual design. **C** was composed by a group of undecidable concepts $c_1, c_2, \ldots, c_m$ which represented the partially unknown or unusual properties in object x. While **K** contained all established propositions $k_1, k_2, \ldots, k_n$ for x, namely, the guaranteed knowledge and prior experience used in design process [17-18]. C-K model regarded knowledge evolution during the whole design process as a sequential transform between undecidable concepts in **C** and true propositions in **K**. Four operators, **C→K**, **C→C**, **K→C** and **K→K**, were proposed to describe the movement of elements in two spaces: for some undecidable concepts in **C**, they might be concatenated into propositions in **K** with logical reasoning (**C→K** operator), or be elaborated with additional unusual properties (**C→C** operator); the established propositions in **K** might be used to update a new property (**K→C** operator), or interconnected by deduction (**K→K** operator) [51]. Further elaborations and illustrative cases could be found in [18].

Although C-K logic warranted the innovativeness and consistency in the design process, C-K model didn't explicitly reveal the designer with what to do next at any moment in the design [52-53]. The final result of design appeared to be empirical, due to various levels of past experience of designers and different knowledge reuse manners [54-55]. Additional procedures and expertise for eliciting and analyzing designer's intentions and ideations were usually required when applying C-K model [15], which brought much inconvenience in the practice. Therefore, C-K model, especially its four C-K operators, should be enhanced to be more heuristic and automatic in assisting product/service design, rather than subjectively searching the whole solution space relying on plenty of designer's expertise. Revealing the promising directions for design knowledge evolution with logical consistency and abundant details, a practical approach based on C-K model would offer more insightful innovation guidance for Smart PSS development.

3. Conceptual framework of KG-aided design approach

In order to fill the abovementioned research gaps, this paper proposes a KG-aided C-K approach (KG-CK) for cost-effectively assisting the devolvement of Smart PSS. Figure 1 depicts the conceptual framework of this approach, whose two modules will be further elaborated in Section 4 and 5.

The first module is the *exploitation of knowledge graphs*, preparing for the generation of innovative solutions. Data from three sources are collected, viz. multi-domain open-source knowledge, the prototype of Smart PSS, and user-generated textual data. Based on these data, two extendable knowledge graphs, internal KG (IKG) and external KG (EKG), are first constructed. Here, *internal* means the nodes and relations in IKG reveal the principles and ideations inside the Smart PSS, as well as the interactions with the end-users; while *external* offers instructive thoughts from other disciplines and domains, thus indicating the possible directions where the Smart PSS can be evolved to. More specifically, based on function-behavior-structure (FBS) ontology, IKG stores the entities of product structures/service modules in Smart PSS, and their relations about how they process the context information and achieve the desired functions. Meanwhile, EKG is formed by conducting NLP techniques on the open-source, professional websites/databases of multiple domains. It is hence capable to provide novel concepts and probable relations, when solving an unusual requirement for Smart PSS innovation. Both KGs are stored in cloud (like *Neo4j*), which can be easily integrated with the knowledge-based systems and applications without many transplanting considerations.

The second module is the *requirement-oriented knowledge evolution* based on C-K model. Considering the concepts of *context*, *product*/*service*, and *movement*/*action* in the requirements, this stage leverages four C-K operators (**C→K**, **C→C**, **K→C** and **K→K**) to evolve Smart PSS design knowledge. Relying on the KG-based applications of multi-hop search and question answering, as well as the semantical and topological similarity calculation of entities and relations in two KGs, four C-K operators are enhanced to be more automatic, objective and heuristic, thus generating more context-aware innovative solutions and promoting value co-creation with few human interventions and shorter development cycle.

4. Exploiting two knowledge graphs

4.1 Construct EKG using open-source knowledge

As depicted in Figure 1, EKG is constructed with multi-domain open-source knowledge. Figure 2 presents a piece of disease introductions collected from a professional medical website as an example. Since the content from this website has been reviewed by professional physicians, the source data is reliable.

Note that the collected knowledge is mostly structured with rather fixed templates, it can be directly formalized with a pre-defined initial *Schema* = <*Concept*, *Property*, *Relation*> [16], where:

- *Concept* = $\{label_i\}$, and each $label_i$ is a class name, like the tags in section headings in figure 2. The concrete example under each label, viz., *instance*, appears as an entity in KG.
- *Property* = $\{<key_{ij}, property_{ij}>\}$, a key_{ij} is a shared sort of attribute in $label_i$, like the tags in sub-headings. The corresponding value, $property_{ij}$, is recorded in textual form and stored in KG.
- *Relation* = $\{<head\_label_i, rel\_type_{ij}, tail\_label_j>\}$, which shows relationships between concepts defined by the hyperlinked references in the webpage. *Relation* is directed, which means the first concept serves as the head and the second one serves as the tail.

Based on the structure of webpages or textual templates (like tags, tabulations char, line breaks and hyperlinks), the initial schema can be manually pre-defined by the domain experts, while all the concepts and relations in plentiful similar webpages are automatically discovered by web crawler tools (like *Octoparse*) and correspondingly added into EKG. However, plenty of long texts and unstructured hyperlinked texts still exist in the collected data, bringing much difficulty in entity recognition and relating. Therefore, assisted by NLP toolkits, a knowledge formulation manner is proposed to process these texts, extracting more entities and relations to evolve the pre-defined initial schema. Its six steps are listed in Figure 3.

Figure 4 shows an illustrative example for the webpages presented in Figure 2, where the expert-defined initial schema is shown in black. In the initial schema, the set of *Concept* is directly extracted from the hyperlinked section headings on the webpage, which contains *Disease*, *Symptom*, *Test*, *Drug*, *Food*. The instances for each concept, like *Rheumatoid Arthritis* (a disease), *NSAIDs* (a drug), and *Duck Liver* (a food), are automatically extracted, and they serve as the nodes in EKG. The set of *Property* for each concept is defined by the sub-section headings and the following tags and short texts, like *Incidence_rate* and *Infectivity* of *Disease*. *Relation* is linked by common sense, like *<Disease, Has_Symptom, Symptom*, *<Disease, Need_Test*, *Test>*, or by some reference links presented in the website, like *<Disease, Recommended_in_diet, Food>, <Disease, Accompanied_ with, Disease>*. Then, after processing the unstructured texts in the hyperlinked texts of *Doctors and Hospitals* and *Useful Drugs* with the NLP-based knowledge formulation manner proposed in figure 3, more concepts, properties and relations are added to the schema (as shown in red in figure 4). EKG is also automatically expanded using the triples organized by the recognized entities like *Dr. JZX* and the relations like *Good_at_diagnose*, *Usually_prescribe*.

4.2 Construct IKG using FBS ontology and user-generated textual data

As depicted in Figure 1, IKG is established to model the components/modules and their relations in a Smart PSS under multiple using contexts. We firstly initiate the schema of IKG with the function-behavior-structure (FBS) ontology of the prototype in the design stage. FBS ontology is a classical model for conceptualizing design objects with three categories of *Function* (goals of the design object), *Behavior* (attributes derived from the structure) and *Structure* (components and their relationships). Concerning the paradigm of PSS, *Behavior* and *Structure* are differentiated into both *Product* and *Service* aspects [56]. Establishing FBS ontology and defining the corresponding entities in IKG can be manually (like analyzing product specifications), or assisted by several mature ontology-based design tools like *MASON* and *EIViz* [57]. This paper will not elaborate on the detailed process.

Since FBS ontology is usually established before the usage stage and doesn't contain context information, user-generated data should be additionally considered. In this paper, texts in users' comments and complaints are collected, which report the efficiency and efficacy of product/service under various contexts. Inspired by *functional basis* [58], categories of contexts and operations on these contexts are pre-defined in table 1. Context information is categorized into four classes: *physical context* (surrounding environment), *social context* (the nearby products and services), *user context* (users and related user-PSS interactions), and *operational context* (operational status of Smart PSS). The operations on these contexts are also divided into four classes, viz., *perceive*, *process*, *learn* and *respond*. Examples in each category are listed in table 1.

To perceive the context information from user-generated text, the NLP-based formulation manner proposed in Figure 3 is adopted again but with minor modifications.

In Step 1, the sentences in the texts are additionally labelled with positive and negative attitudes, using the rates of product/service, or the counts of affect words (like *amazing*, *great*, *wonderful* in *pleasant feelings*, and *lousy*, *useless*, *unhappy* in *unpleasant feelings*, referring to [59]). Step 2 and 3 are still the same, which automatically parse each sentence into a syntax tree and fetch the *SVO pattern* with NLP toolkits. Then, two more restrictions are added to Step 4 and 5 for perceiving the context information and establishing the context-derived relations.

- In Step 4, *NP* in the *Subject*, NP_{sub}, should be an entity of product structure or service module defined by the existing FBS ontology. Meanwhile, *NP* in the *Object*, NP_{obj}, should contain words listed in the column of *Context Examples* in Table 1, or their *synonyms* and *hyper/hyponyms* suggested by *WordNet* (for English) or *HowNet* (for Chinese).
- In Step 5, *VP* should contain words listed in the column of *Operation Examples* in Table 1, or their *synonyms* and *hyper/hyponyms* suggested by *WordNet* or *HowNet*. If the SVO pattern is matched in the sentence labelled with a *negative attitude*, store a *negative annotation* to the extracted relations named by *VP*; otherwise, store a *positive annotation*.

Figure 5 shows an illustrative IKG for a PSS, a fire alarm enabling emergency evaluation, where the schema and entities in black define the FBS architecture. For example, based on the *Product Structure* of *Gas Sensor* and the *Service Module* of *Hazard Identification*, *Emergency information* containing the measured *Gas Concentration* and recognized *Hazard Pattern* is reported, which finally achieves the ultimate function of *Deciding Emergency Level*. To enrich the IKG with more semantic information, nodes of *Product Structure/Service Module* are linked to the context defined in table 1 (as shown in red in figure 5), for example, *Gas Sensor* can *monitor* (perceive context) *odor* (physical context) and *Hazard Identification* can diagnose (learn context) *Danger* (social context).

5. Evolving Smart PSS design knowledge with four KG-aided C-K operators

5.1 Overall process

Based on the principle of four operators in C-K model, figure 6 shows the flowchart for evolving Smart PSS design knowledge with the aid of EKG and IKG in conceptual design, which contains two phases.

Based on **C→K** and **C→C** operators, Phase I aims at proposing several innovative functions for Smart PSS in response to the elicited personalized requirements (*PRs*). As a preparation, *PRs* are manually solicited from investigations or questionnaires or automatically elicited from huge amounts of user-contributed data [60]. Key concepts illustrating the *context*, *product*/*service*, and *property/activity* are also elicited from *PRs*. Considering these concepts, structured queries are formed for the **C→K** operator, which lookup EKG for several pieces of innovative knowledge (K_{inno}) to propose *PR*-oriented, innovative functions. Otherwise, if no valid K_{inno} is reachable, **C→C** operator is then conducted, and multi-hop related concepts in EKG are fetched to further elaborate *PR*. Additional **C→K** queries will be formed accordingly, in order to propose more innovative functions.

Once all pieces of K_{inno} are found for innovating functions, the next phase is trying to achieve these functions and generate solutions with the evolved products/services. **K→K** operator is firstly conducted to map the relevant knowledge stored in IKG, and check whether a solution can be generated by reconfiguring the existing product structures and/or service modules. If low relevance is achieved, **K→C** operator will be adopted. By recommending probable product structures and service modules under similar contexts, Smart PSS can be evolved heuristically by changing or upgrading these structures and components.

Although the majority of steps in figure 6 are automated by graphical database queries and similarity calculations, few human censorships are introduced to guarantee the quality of the result and promote the procedure with high efficiency. Specifically, multi-domain experts are invited to evaluate the usability and reasonability of K_{inno} in function innovation, and the stakeholders inspect the feasibility of evolved solutions in implementation and potential application in response to the required *PRs*.

When all the solutions are generated after two phases, it can proceed to detailed design, manufacturing, and evaluation of the evolved Smart PSS. Concept and relations in EKG and IKG can be accordingly evolved, if key principles and ideations of the evolved Smart PSS are significantly changed. However, this paper will only concentrate on four C-K operators, and won't further elaborate on the subsequent works.

5.2 Implementation of four KG-aided C-K operators

*5.2.1 KG-aided **C→K** operator: KG-based question answering*

Corresponding to Rupp's boilerplate [61], requirements can be defined as "*Under what condition, the product/service shall/should/will do what process*". Under the context of Smart PSS and FBS structure, a personalized requirement can be translated with a formula *PR* = <*context* (given), *product/service* (unknown), *movement/action* (given, to solve an issue)> [60, 62]. Hence, the aim of **C→K** operator in this case is to fill the unknown slots with possible concepts and inter-relate these concepts into some valid propositions, under the given constraints of *context*.

Actually, this process belongs to the realm of KG-based question answering (KGQA) [43]. In KGQA, all possible entities and relations are firstly retrieved with a structured query (question). Then the answers are refined according to the constraints embedded in the query (context). Following this idea, the words in *movement* and *action* are firstly tagged by part-of-speech using the abovementioned NLP toolkits, viz., *movement* = $\{(VP_{mov\_1}, NP_{mov\_1}), (VP_{mov\_2}, NP_{mov\_2}), \ldots, (VP_{mov\_p}, NP_{mov\_p})\}$ and *action* = $\{(VP_{act\_1}, NP_{act\_1}), (VP_{act\_2}, NP_{act\_2}), \ldots, (VP_{act\_q}, NP_{act2\_q})\}$. Then, four structured query patterns are constructed as follows:

Pattern I

$$\text{MATCH Node}(prod) \in \text{EKG}$$
$$\text{IF keys}(prod) \in \{VP_{mov\_1}, VP_{mov\_2}, ..., VP_{mov\_p}\}$$
$$\quad \text{OR properties}(prod) \in \{NP_{mov\_1}, NP_{mov\_2}, ..., NP_{mov\_p}\}$$
$$\text{RETURN } ent = \text{Node}(prod)$$

Pattern II

$$\text{MATCH Node}(serv) \in \text{EKG}$$
$$\text{IF keys}(serv) \in \{VP_{act\_1}, VP_{act\_2}, ..., VP_{act\_q}\}$$
$$\quad \text{OR properties}(serv) \in \{NP_{act\_1}, NP_{act\_2}, ..., NP_{act\_q}\}$$
$$\text{RETURN } ent = \text{Node}(serv)$$

Pattern III

$$\text{MATCH Edge}(prod, mov_V, mov_N) \in \text{EKG}$$
$$\text{IF } mov_V\text{.name} \in \{VP_{mov\_1}, VP_{mov\_2}, ..., VP_{mov\_p}\}$$
$$\quad \text{OR } mov_N\text{.name} \in \{NP_{mov\_1}, NP_{mov\_2}, ..., NP_{mov\_p}\}$$
$$\text{RETURN } ent = \text{Edge.head}$$

Pattern IV

$$\text{MATCH Edge}(serv, act_V, act_N) \in \text{EKG}$$
$$\text{IF } act_V\text{.name} \in \{VP_{act\_1}, VP_{act\_2}, ..., VP_{act\_q}\}$$
$$\quad \text{OR } act_N\text{.name} \in \{NP_{act\_1}, NP_{act\_2}, ..., NP_{act\_q}\}$$
$$\text{RETURN } ent = \text{Edge.head}$$

Query patterns **I** and **II** search for the possible entities (a node in EKG) who own the corresponding pairs of *Key-Property*, while patterns **III** and **IV** retrieve the head entities in an edge (<*head*, *rel*, *tail*>) of EKG with the matched triples.

To refine the fetched entities of *prod* or *serv*, *context* = $\{con_1=val_1, con_2=val_2, \ldots, con_m=val_m\}$ listing m constrains is considered. For an entity with n keys, $ent = \{(key_1, prop_1), (key_2, prop_2), \ldots, (key_n, prop_n)\}$, its score under the context is computed by Eq. 1.

$$Score(ent \mid context) = \begin{cases} 1 & context = \varnothing \\ \frac{1}{m}\sum_{j=1}^{m} \max_{\forall i \in \{1,2,\ldots n\}} PhSim(prop_i, val_j) & context \neq \varnothing \end{cases} \quad \text{(Eq. 1)}$$

Semantic similarities between two phrases (or short texts) are calculated by Eq. 2 [15].

$$PhSim(ph_1, ph_2) = \begin{cases} 2^{L-1} & I \\ 1 & II \\ DictSim(ph_1, ph_2) & III \end{cases} \quad \text{(Eq. 2)}$$

I. When words in all the corresponding positions of ph_1 and ph_2 are synonyms, hyper/hyponyms or the same; L is the length of phrase;

II. When words tagged by NN or VB in two phrases are synonyms, hyper/hyponyms or the same;

III. When words in two phrases are literally different, their dictionary-based similarity is computed by *JCn Similarity* in *WordNet* (for English) or *HowNet* (for Chinese) [63] on all words contained in two phrases. Specifically, for $ph_1 = \left(w_1^1, w_2^1, ..., w_N^1\right)$ and $ph_2 = \left(w_1^2, w_2^2, ..., w_M^2\right)$, the similarity is computed by Eq. 3.

$$DictSim\left(ph_1, ph_2\right) = \frac{1}{2}\left(\frac{1}{N}\sum_{w_a^1 \in ph_1} \max_{\forall w_b^2 \in ph_2} JCn\left(w_a^1, w_b^2\right) + \frac{1}{M}\sum_{w_d^2 \in ph_2} \max_{\forall w_c^1 \in ph_1} JCn\left(w_c^1, w_d^2\right)\right) \quad \text{(Eq. 3)}$$

After the context-based refining on all the fetched entities, at most $k_{C\text{-}K}$ entities with the highest *Score* are remained. A set of innovative knowledge, {K_{inno}}, is hence formed, where each K_{inno} = <$head_{inno}$, rel_{inno}, $tail_{inno}$> = <*ent* (*prod*/*serv)*, VP_{mov}/VP_{act}, NP_{mov}/NP_{act}>. Multi-domain experts are also invited to double-check the reasonability of K_{inno} in responding to *PR*. In the following phase of solution generation (Phase II), {K_{inno}} will guide the upgrade of the functions of product structures and service modules.

*5.2.2 KG-aided **C→C** operator: multi-hop searching*

It is possible that no proper entities can be found during the **C→K** operator, for instance, few nodes retrieved by queries, low scores in the context-based refining, or unreasonableness recognized by the experts. In this situation, **C→C** operator is conducted. More highly-related entities (concepts) are fetched to further elaborate *PR* and expand the searching for K_{inno}.

Since EKG is a large but sparse graph (whose density $D = |E|/|V|^2$ is close to 0), multi-hop semantic search is recommended, which queries the EKG with a path consecutively composed by multiple relations. This searching method significantly enlarges the range of search and returns more insight results, but doesn't excessively burden the processing due to limited numbers of edges. Therefore, multi-hop semantic search is adopted in implementing **C→C** operator. Specifically, for a pair of (*VP*, *NP*) in the element of *movement* or *action* in requirement *PR*, we start with a node named by *NP*, and an edge typed by *VP*. Then, two *h*-hop query patterns are constructed as follows:

Pattern V

$$\text{MATCH Consecutive EdgeSet} = \{\text{Edge}_1, \text{Edge}_2, \ldots \text{Edge}_h\} \subseteq \text{EKG}$$
$$\text{IF Edge}_1.\text{head} = \text{Node}(NP)$$
$$\quad \text{AND labels}(\text{Node}(NP)) = \text{labels}(\text{Edge}_h.\text{tail})$$
$$\text{RETURN } ent = \text{Edge}_h.\text{tail}$$

Pattern VI

$$\text{MATCH Consecutive EdgeSet}_1 = \{\text{Edge}_1, \text{Edge}_2, \ldots \text{Edge}_k\} \subseteq \text{EKG}$$
$$\quad \text{AND EdgeSet}_2 = \{\text{Edge}_h, \text{Edge}_{h-1}, \ldots, \text{Edge}_{k+1}, \text{Edge}_k\} \subseteq \text{EKG}$$
$$\text{IF Edge}_1.\text{head} = \text{Node}(NP)$$
$$\quad \text{AND type}(\text{Edge}_1.\text{rel}) = \text{type}(\text{Edge}_h.\text{rel}) = VP$$
$$\text{RETURN } ent = \text{Edge}_h.\text{head},\ rel = \text{Edge}_h.\text{rel}$$

Pattern **V** aims at searching an *h*-hop directly linked entity that has the same label as the original one. The retrieved entity is chosen to replace *NP* when conducting **C→K** operator again. Pattern **VI** traces back to the ancestors and checks other siblings. In this situation, *NP* and *VP* can be simultaneously replaced by the retrieved *ent* and *rel*.

Traversing all the pairs of (*VP*, *NP*), we can get all the alternative choices for the replacement of *PR*. Note that when *h* enlarges, the relationships between the retrieved nodes and the original ones become weak. Hence, the retrieved alternative choices are further inspected with *GraphSim*(ent_0, ent_1), which is a graph-based topological similarity iteratively computed by *SimRank Algorithm* [64].

$$GraphSim^{EKG}(ent_1, ent_2) = \begin{cases} 1 & ent_1 = ent_2 \\ \dfrac{C}{2|I(ent_1)||I(ent_2)|} \displaystyle\sum_i^{|I(ent_1)|} \sum_j^{|I(ent_2)|} GraphSim^{EKG}(I_i(ent_1), I_j(ent_2)) + \\ \dfrac{C}{2|O(ent_1)||O(ent_2)|} \displaystyle\sum_i^{|O(ent_1)|} \sum_j^{|O(ent_2)|} GraphSim^{EKG}(O_i(ent_1), O_j(ent_2)) & ent_1 \neq ent_2 \end{cases} \quad \text{(Eq. 4)}$$

Where *I*(*ent*) denotes the set of in-neighbor nodes in EKG for the corresponding node of *ent*, while *O*(*ent*) denotes the set of out-neighbors. When $I(ent_1)$ or $I(ent_2)$ is empty, or $O(ent_1)$ or $O(ent_2)$ is empty, the corresponding part of the sum is set to 0. *C* is the decay factor, which is recommended to set to 0.8 [64]. After the calculation, top $k_{c\text{-}c}$ choices of replacement are remained. *PR* is hence extended to an alternative set {*PR*'}. Then, **C→K** operator is conducted again, trying to retrieve more K_{inno} for function innovation.

5.2.3 KG-aided ***K→K*** *operator: relevance evaluation*

Actually, in Phase I, the fetched entities in K_{inno} usually don't indicate real structures or modules, but some mediated concepts for achieving the innovative functions. Hence in **K→K** operator, we try to relate K_{inno} with the design knowledge K_{dsgn} stored in IKG, find an existing product structure *prod* or service module *serv*, and update the Smart PSS by reconfiguring *prod*/*serv*.

Relevance between two pieces of knowledge is firstly evaluated. For K_{inno} = <$head_{inno}$, rel_{inno}, $tail_{inno}$> in EKG and K_{dsgn} = <$head_{dsgn}$, rel_{dsgn}, $tail_{dsgn}$> in IKG, the knowledge relevance is quantified by Eq. 5.

$$KnowRel\left(K_{inno} \to K_{dsgn}\right) = \frac{1+RelSim\left(rel_{inno}, rel_{dsgn}\right)}{2} \times \max\left\{\begin{matrix} EntSim\left(head_{inno} \to head_{dsgn}\right) + EntSim\left(tail_{inno} \to tail_{dsgn}\right), \\ EntSim\left(head_{inno} \to tail_{dsgn}\right) + EntSim\left(tail_{inno} \to head_{dsgn}\right) \end{matrix}\right\} \quad \text{(Eq. 5)}$$

For a pair of entities in *head*/*tail*, $ent_{inno} = \{(key^{inno}_1, prop^{inno}_1), (key^{inno}_2, prop^{inno}_2), \ldots, (key^{inno}_m, prop^{inno}_m)\}$ and $ent_{dsgn} = \{(key^{dsgn}_1, prop^{dsgn}_1), (key^{dsgn}_2, prop^{dsgn}_2), \ldots, (key^{dsgn}_n, prop^{dsgn}_n)\}$, the similarity can be either computed with a topological similarity using Eq. 4 in IKG (*case I*) if ent_{inno} could be defined as nodes in IKG, or calculated with their semantic similarity with Eq. 2-3 (*case II*).

$$EntSim\left(ent_{inno} \to ent_{dsgn}\right) = \max\begin{cases} GraphSim^{IKG}(ent_{inno}, ent_{dsgn}) & I \\ \frac{1}{m}\sum_{j=1}^{m} \max_{\forall i \in \{1,2,\ldots,n\}} PhSim\left(key_i^{inno}, key_i^{dsgn}\right) PhSim\left(prop_i^{inno}, prop_i^{dsgn}\right) & II \end{cases} \quad \text{(Eq. 6)}$$

Considering the *negative attitude* may occur in the context-derived relations in rel_{dsgn}, the counts of the positive/negative annotations are leveraged, and negative value may occur in calculating *RelSim*.

$$RelSim\left(rel_{inno}, rel_{dsgn}\right) = \begin{cases} PhSim(rel_{inno}, rel_{dsgn}) & Pos=Neg=\varnothing \\ PhSim(rel_{inno}, rel_{dsgn}) \frac{Count\left(Pos\right) - Count\left(Neg\right)}{Count\left(Pos\right) + Count\left(Neg\right)} & \text{Else} \end{cases} \quad \text{(Eq. 7)}$$

Traversing all pieces of design knowledge in IKG, top $k_{k\text{-}k}$ pieces of knowledge with the highest *KnowRel*. Are remained. Then the nearest nodes of *prod* or *serv* for K_{dsgn} are traced in IKG. An evolved solution, *Solution* = <*PR*, K_{inno}, K_{dsgn}, *prod*/*serv*>, is hence generated by reconfiguring the existing product structures and service modules with the guidance of K_{inno}. Stakeholders are also invited to check the feasibility of the proposed solutions. They can also rapidly tailor the product/service and realize the evolved solution on the product configuration systems (PCS) [65], by reusing existing design elements in the product/service family.

5.2.4 KG-aided **K→C** operator: recommendation with K-nearest neighbors

Due to limited sorts and numbers of existing design knowledge stored in IKG and a large difference among domains and disciplines of IKG and EKG, it's sometimes hard to establish a direct mapping between K_{inno} and K_{dsgn}, thus impeding evolving Smart PSS by direct reconfiguration. Therefore, in this situation, with the guidance of K_{inno}, possible *prod*/*serv* in IKG is recommended by **K→C** operator for changing/ upgrading.

Heuristically, solution generation is guided with a coupling of ($head_{dsgn}$: *prod*/*serv*)-[rel_{dsgn}]->($tail_{dsgn}$) ⋈ ($head_{inno}$)-[rel_{inno}]->($tail_{inno}$: *mov*/*act* in *PR*), where $head_{inno}$ and $tail_{dsgn}$ serve as a bridge between K_{inno} in EKG and K_{dsgn} in IKG. To establish the coupling, *K*-nearest neighbors for two entities are retrieved from two separate KGs as references.

Step 1: For the given $head_{inno}$ in K_{inno}, *K*-nearest neighbors in EKG are retrieved by the nodes possessing top *K* highest $GraphSim^{EKG}$. The retrieved entities form the set of Ref_{inno}.

Step 2: For an entity $tail_{dsgn}$ labelled with *prod*, *serv*, *con*, *mov* and *act* in IKG, *K*-nearest neighbors in IKG are retrieved by the nodes possessing top *K* highest $GraphSim^{IKG}$, and form the set of Ref_{dsgn}.

Step 3: Evaluate the mapping possibility with two sets of neighbors.

$$P\left(head_{inno} \rightarrow tail_{dsgn}\right) = \frac{\sum_{\forall ent_i \in Ref_{inno}} \sum_{\forall ent_j \in Ref_{dsgn}} GraphSim^{EKG}\left(ent_i, head_{inno}\right) GraphSim^{IKG}\left(ent_j, tail_{dsgn}\right) EntSim\left(ent_i \rightarrow ent_j\right)}{\sum_{\forall ent_i \in Ref_{inno}} \sum_{\forall ent_j \in Ref_{dsgn}} GraphSim^{EKG}\left(ent_i, head_{inno}\right) GraphSim^{IKG}\left(ent_j, tail_{dsgn}\right)} \quad \text{(Eq. 8)}$$

Step 4: Traverse all the entities labelled with *prod*, *serv*, *con*, *mov* and *act* in IKG, and pick up the top k_{k-c} possible entities.

For the retrieved entities in the scope of *prod*, *serv*, *con*, *mov* and *act*, their directly related nodes of *prod*/*serv* are discovered in **K→C** operator: If the majority of annotations in the relation is *negative*, then this *prod*/*serv* is recommended to be changed during the evolution of Smart PSS; else, it could be updated to adapt to *PR*. However, entities beyond this scope in IKG are not considered in Step 2-4, since they often indicate system-level behaviors or functions for the Smart PSS, which is rather generic and hard to be re-decomposed without many experts' interventions.

6. A case study for the development of smart nursing bed

6.1 Backgrounds and user requirements

The aging population is a worldwide issue, and the situation becomes severe in China. According to the official survey report on the living conditions of China's urban and rural older persons published in 2018, more than 15% of total 240 million elderly population are empty nesters (no children accompanied), very elderly people (>80 ages), semi-or-totally disabled. Also, due to the declining birth rate, the number of elderly people who need professional nursing services will exceed 100 million by 2050. Hence, Smart PSS developed for elderly nursing are urgently demanding, and the potential markets are promising.

Nursing bed is the most primary product used in hospitals, pension agencies or communities, which is adopted in this paper for a case study. Available experts and reliable data sources are additional reasons for choosing this product. This case study is conducted under a project-based learning (PBL) scheme of Shanghai Jiao Tong University, by a group of 5 randomly selected engineering graduate students in 8 weeks.

As presented in figure 7, the existing nursing beds on the current market are largely equipped with the brushless motor and control system, improving the basic function of changing body postures with less manpower. Some advanced products also adopt multiple sensors and Bluetooth modules, achieving some degree of smartness and connectiveness. However, considering various user contexts like health condition and medical history, nursing bed should be empowered with more personalized functions and add-on services, thus benefiting the elderly as well as the nursing personnel one step further.

To evolve the nursing bed, an interview with 7 nursing personnel and 6 consumers purchasing nursing beds for their elderly relatives is conducted. Based on the results, top 3 personalized but mutual requirements are collected, as manually formatted in table 2.

However, the majority of *PRs* are referred to multiple medical fields, which is largely beyond the designers' expertise. Multiple sorts and pieces of medical knowledge are demanded in this case, before proceeding with the evolvement of the prototype. In the conventional PSS development manners, the knowledge gap is usually fulfilled by the frequent consultations to the professional physicians, which increases the cost of the product/service development and also much delayed its process. Hence, it's worthy to leverage the proposed KG-CK approach, and cost-effectively evolve the prototype with more context-awareness and heuristic guidance.

6.2 Constructing EKG and IKG for smart nursing bed

Two knowledge graphs are firstly established for KG-CK. For EKG, more than 18000 Chinese webpages introducing the diseases, therapies, symptoms, drugs, famous doctors and hospitals are downloaded from a professional medical website, *xywy.com*. Considering the tags and contents presented in these webpages and the hyperlinks among the pages, 9 labels in the *Concept* and 15 types in the *Relation*, as well as the *Property* for each concept, are selected and synthesized in the schema of EKG, with the assistance of two physicians. Then, leveraging *Stanford CoreNLP toolkits* and *Octoparse,* more than 35000 nodes and 161000 relations are automatically extracted from the webpages, and assigned to the corresponding labels and types. EKG is hence established as illustrated in figure 8, and stored in *Neo4j*, an online graph database. Table 3 reports the statistics of the nodes and relations in EKG.

As for the IKG, five experts in the design team of a prototype nursing bed are invited. Following the FBS structure shown in figure 5, the whole product of nursing bed and added-on services are firstly decomposed into 28 major *product structures* and 11 *service modules*. Then, according to the product specification and the recommendations of experts, the *movement/activity* for each structure/component is separately listed and synthesized into system-level *behaviors* and overall *functions*. Then, 286 pieces of online comments which have more than 30 words and mentioned at least one product structure or service module in the prototype are collected from *JD.com,* a famous e-commerce platform in China. Considering the rules listed in section 4.2, 21 contexts in table 1 are mentioned in these comments, and 91 relations are automatically extracted and manually checked. Figure 9 presents the IKG established for the prototype nursing bed in *Neo4j*, and table 4 reports the statistics of nodes and relations.

Due to different domains and structures of data set, the sizes and elements presented in table 3 and 4 varied much. It's difficult to conduct a direct fusion on the nodes and merge the corresponding relations in two knowledge graphs. Hence, *WordNet* and *HowNet* are adopted to evaluate the semantic similarity among words in the nodes and relations. *SimRank* algorithm is also executed with 5 iterations on two KGs, in order to measure the topological similarity between each pair of nodes. In the following procedure, these two similarities facilitate searching and matching nodes and relations belonged to different KGs.

6.3 Evolving nursing bed with four C-K operators

According to the flowchart shown in figure 6, in Phase I, **C→K** operator is firstly conducted for the *PRs* listed in table 2. Query patterns in section 5.2.1 are established and leveraged to fetch the possible entities, relations and properties. As listed in Table 5, the retrieved K_{inno} is judged by the physicians, considering its validity and effectiveness in responding to *PRs*.

Note that no K_{inno} is matched for PR_3. Also, as pointed out by the physicians, *Cardiovascular diseases* mentioned in PR_2 are a generic term including a huge set of heart-related diseases. Therefore, with the queries in section 5.2.2, **C→C** operator is conducted for the *movement/action* in PR_2 and PR_3. The highly-related entities and relations in 3-hop are discovered, as reported in table 6. Names of specific cardiovascular diseases are precisely found for PR_2 (*Sinus arrhythmia*, *Atrial fibrillation*, *Cardiac failure*), and the applications of rehabilitation are further elaborated for PR_3 (*an adjuvant cure for knee joint diseases*).

Then, more pieces of K_{inno} are retrieved by conducting **C→K** operator and validated by the physicians again, as listed in table 7. After that, useful pieces of K_{inno} in table 5 and 7 form the set of innovative functions and serve as the input for Phase II (generate evolutionary solutions with **K→K** and **K→C** operators).

In Phase II, with the relevance calculation functions of Eq. 5 - 7 in **K→K** operator, 7 reasonable solutions are firstly generated, as listed in table 8. With these solutions, the nursing bed can achieve the innovative functions and solve the personal requirements in conceptual design by reconfiguring the existing *prod/serv*: (1) To *prevent* the occurrence of *decubitus* (for PR_1), the nursing bed can equip *a medical air cushion* on the *bed board*, and/or drive the *back actuator* with a *regular pattern* for *periodic turning-over*; (2) To detect the *wet impregnation* (for PR_1), the nursing bed can leverage *humidity sensor* and/or *vital signs monitoring service*; (3) To facilitate *rehabilitation* for the very elderly (for PR_3), the nursing bed can coordinate *the leg actuator* for the recommended *joint exercise*. Besides, since the nodes in EKG and IKG offered abundant details in their properties, like *Description* in *joint exercise* (*double-side lying leg lift, 10~15 times per day*), this supplementary information could be served as a reference for the reconfiguration.

However, entities labelled as *Symptom* and *Drug* in table 5 and 7 cannot be mapped in **K→K** operator, due to the large difference between IKG and EKG. **K→C** operator is hence conducted on these entities to recommend some possible *prod*/*serv* for changing/upgrading. For each *Head* in K_{inno}, top 3 mapped entities are retrieved with 5 nearest neighbors, and the corresponding suggestions are listed in table 9.

With the results retrieved from **K→C** operator, several heuristic solutions are generated: (1) To *alarming emergency situations* (for PR_2), the current *vital signs monitoring service* is suggested to be upgraded to recognize *palpitation* (irregular heartbeat), *tachycardia* (>100 beats/min), and other *cardiac symptoms*; (2) To *remind medical advices* (for PR_2), *emergency call* and *remote consultation services* need to be enhanced to better support frequent communications between *nursing bed and nursing staff/doctors*. (3) To fulfill a higher demand in *storing, processing or communicating* (for PR_2), the current components of *microcomputer* is recommended to be replaced by a more powerful processor.

Validating and synthesizing these novel solutions in the stage of detailed design, a smart nursing bed with a mobile app (*WeChat Mini Program*) is eventually developed, as shown in figure 10 and 11. A brief interview is conducted again on the 7 nursing personnel and 6 consumers who proposed *PRs*. In conclusion, they are satisfied with the PSS (nursing bed with app), and regard their *PRs* are sufficiently solved.

6.4 Discussions and limitations

Nursing bed is a typical product enabling value-creation by bundling personalized smart services. However, it also requires full exploitation of multidisciplinary knowledge and user-generated data in product/service design. On the foundations laid by the graph-based design theory and computational linguistic methods in product design and system engineering [52, 66], this research work is the first attempt to propose a systematic approach for Smart PSS development, integrating C-K design theory with large-scale, multidisciplinary knowledge graphs. This section discusses how KG-CK can cost-effectively facilitate the design process of such Smart PSS with three benefits.

Firstly, based on NLP techniques and Knowledge graph, KG-CK enables exploiting the huge amount of open-source data for product/service design, and hence offer a cost-effective manner to supply domain-specific knowledge in innovation. For the showcase in this paper, a brief comparison of the performance among groups in the same PBL scheme is reported in Table 10, which proves the cost-effectiveness of KG-CK in this case. Unnecessary to frequently consult experts for professional guides, the cost, time, and manpower required for the development and customization process are reduced, while the project progress and final achievements are still promoted. In the fierce commercial competition in smart product market, this advance could achieve a first-mover advantage in creativity and adaptability [67].

Secondly, as several previous studies pointed out [15, 52-53], C-K model provides a highly expert-involved manner to generate an empirical design solution, and sometimes needs additional procedures and expertise to elicit and analyze designer's intention and ideation in practice. To tackle this issue, rules and algorithms are designed in KG-CK with the isomorphic principles of four C-K operators. With a specified flowchart constituted by KG-aided operators, KG-CK automatically searches two KGs and finally generates a heuristic and consistent solution, and thus operates more fluently with less intervention from designer's cognitive factors (like personal preference, available experience, fixed thinking-set [15]). Designer's workload is also reduced to focus on the implementation and evaluation of the generated solutions, thus improving the productivity in the design process.

At last, in establishing IKG and conducting four KG-aided C-K operators, positive/negative annotations in user-generated comments/complaints are considered in extracting and leveraging the context-derived relations, which brought better context-awareness and reasonableness to the results. In the validation and evaluation of the showcase, the generated solutions in Table 8 and 9, like *facilitating knee rehabilitation exercises* and *regularly changing body posture to prevent decubitus*, are highly regarded by the designers, users and nursing staff, and finally realized in the evolved smart nursing bed.

Nevertheless, there are still two limitations in KG-CK. Firstly, although KG construction manner and KG-aided C-K operators are rather domain-independent, their feasibility and effectiveness are fundamentally determined by the quality and quantity of the collected data. In this showcase, due to constrained medical data sources and common knowledge, limited sorts and types of properties and relations are established in EKG and IKG. It thus results in no evolutionary solution for the requirement of *Enable voice control* in PR_3, and several solutions generated for PR_1 and PR_2 are somehow generic and oversimplified. For this issue, some commercialized multilingual knowledge graphs covering more domains and possessing abundant labels, properties and relations, like *schema.org*, *WikiData* and *OpenKG*, can be leveraged and merged with the existing one. Professional databases of journal papers, patents, engineering standards, or other highly reputable and reliable data, can also serve as the heterogeneous knowledge sources by adopting multiple graph-based conceptual modelling and knowledge representation manners [52, 67]. Besides, to guarantee the reliability of the huge amount of data, a crowdsourcing manner to facilitate online-data mining in product innovation can be leveraged [69].

Another limitation lies in the efficiency of algorithms adopted in KG-CK. Taking the *SimRank algorithm* as an instance, for a graph $G = (V, E)$, the time complexity is $O(k|E|^2)$ and the space complexity is $O(|V|^2)$ in total k iterations [64]. When KG incrementally grows larger, plenty of time and space is required in conducting four C-K operators. For this issue, knowledge graph embedding methods based on machine learning, like *TransE*, *TransR*, and *DKRL* [70], could be adopted to represent the nodes and quantify their relations with a complexity of O(|E|).

7. Conclusions and future works

Continuously evolving the modules/components in products and services for better user experience is the core task in the development of Smart PSS. To conduct personalized customization and co-develop the prototype of Smart PSS with higher context-awareness but lower cost, this paper proposes a KG-aided C-K (KG-CK) approach to cost-effectively assist Smart PSS development on the foundation of Knowledge Graph techniques and Concept-Knowledge theory. The main contributions are summarized into three aspects.

1) *A straightforward manner for knowledge management in multidisciplinary product/service design*. Relying on open-source knowledge and deeper search in KGs, KG-CK possesses the ability of knowledge reasoning under multiple engineering contexts and multidisciplinary fields, while adequate experts who possess specialized knowledge are no longer a mandatory constraint for the design team. Therefore, emphasis on transferring experience and knowledge in the minds of multi-background team members in the previous works [15, 71], can be converted to synthesizing multi-domain knowledge and improving the utilization of the open-source data, which straightforwardly solves the multidisciplinary design problem.

2) *A practicality and productivity enhancement for C-K model via knowledge graph*. Expanding two spaces in C-K model with possible concepts and knowledge recommended by four isomorphic KG-aided C-K operators, KG-CK improves the automation and productiveness of design assistance via KG technique and the related computational linguistics algorithms, while still preserving the innate advantages of innovativeness and consistency from C-K model.

3) *An implementation of the hybrid approach in Smart PSS development*. Coordinating with three features in the novel idea of *hybrid approach* in Smart PSS development [40], *hybrid intelligence* is achieved by utilizing open-source and user-generated data collected from Wiki pages, e-commerce platforms and professional forums; *hybrid design* is realized by conducting four multidirectional C-K operators on the concept space and knowledge space; and *hybrid value* is obtained by enabling sustainable open innovation on products/services with cloud-based knowledge base.

Based on these contributions, future research directions will focus on two aspects. On one hand, a data-driven personalized requirement elicitation manner, as well as an incremental evolutionary manner for updating both IKG and EKG, can be integrated with KG-CK, thus forming a closed-loop for Smart PSS continuous evolvement. On the other hand, larger-scale and more informative KGs covering more multidisciplinary domains, as well as the KG embedding algorithms, will be exploited in KG-CK to improve cost-efficiency and domain-independency in developing more sorts of Smart PSS.

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Table caption list

Figure caption list

Figure 1 The conceptual framework of KG-CK for evolutionary Smart PSS development

Figure 2 A piece of disease introduction collected from a professional medical website

Figure 3 Six steps in the proposed NLP-based knowledge formulation manner

Figure 4 An illustrative schema and the corresponding EKG (*Translated from Chinese into English*)

Figure 5 An illustrative schema and the corresponding IKG (*Translated from Chinese into English*)

Figure 6 Flowchart for evolving Smart PSS design knowledge with four KG-aided C-K operators

Figure 7 The prototype of an electrical nursing bed equipped with sensors and Bluetooth modules

Figure 8 An illustration of EKG stored in the platform of *Neo4j* (*Translated from Chinese into English*)

Figure 9 An illustration of IKG stored in the platform of *Neo4j* (*Translated from Chinese into English*)

Figure 10 The evolved Smart Nursing Bed

Figure 11 User interface of the bundled *WeChat Mini Program*

Table 1 Categories of contexts and operations on the contexts

Contexts (*Obj*)	**Context Examples**	**Operations (*Verb*)**	**Operation Examples**
Physical Context	Time	**Perceive Context**	Detect
	Location		Confirm
	Weather		Display
	Temperature		Monitor
	Direction		Navigate
	Humidity		Search
	Odor		Request
	……		Recognize
Social Context	Peer agents		Measure
	Resource supply		……
	Complementary service	**Process Context**	Import/Export
	Danger/Abnormal		Translate
	……		Compare
User Context	Name/Age/Gender		Filter
	Nationality/Religion		Integrate
	Marriage/Family		Dismantle
	Mood/Health		……
	Medical history	**Learn Context**	Memorize
	Address/Contact		Track
	Preference/Habit		Diagnose
	……		Communicate
Operational Context	Power/Energy		Validate
	Hardware maintenance		……
	Software version	**Respond to Context**	Change
	Portability/Wearability		Escape
	Computing power		Alarm/Notify
	……		…...

Table 2 Top 3 personalized requirements (*PRs*) for smart nursing bed presented in Rupp's boilerplate

No.	Context	Movement/Action	Votes
PR_1	Health = Disabled; Medical history = Limb palsy; Address = Pension agency	Detect incontinence; Prevent decubitus	6
PR_2	Family = No children accompanied; Medical history = Heart disease, Hypertension; Address = Home	Alarm cardiac emergency symptom; Remind medication of cardiovascular disease	5
PR_3	Age = Very Elderly; Health = Semi-disabled; Preference = Need rehabilitation; Address = Pension agency	Support daily physical activity; Facilitate rehabilitation; Enable voice control	3

Notes: Words in table 2 are translated from Chinese into English

Table 3 The statistics of the nodes and relations in EKG

Label / Type	Definitions and explanations	Has Property / Relationship	Counts
Nodes			
Disease	A known disease	*Name, Definition, Incidence_rate, Infectivity*	8801
Test	A medical examination item	*Name, Introduction, Price*	3346
Drug	A commonly used drug	*Name, Medication_manner, Price*	3825
Food	A recommended or inhibited diet	*Name, Description*	2260
Symptom	An appearing illness in body	*Name, Description, Body_parts*	5998
Division	A department in hospital	*Name, Description*	54
Doctor	A famous doctor	*Name, Title, Hospital, Address*	2970
Therapy	A therapy to cure or prevent a disease	*Name, Description, Application*	6707
Cause	A possible cause for a disease	*Name, Description, Possibility*	1613
Total			**35574**
Relations			
Accompany_with	A complication for a disease	*<Disease, Accompany_with, Disease>*	11979
Has_medication	Use a drug to cure a disease	*<Disease, Has_medication, Drug>*	14600
Recommended_diet	Recommend a food for a disease	*<Disease, Recommended_diet, Food>*	20091
Inhibited_diet	Inhibit a food for a disease	*<Disease, Inhibited_diet, Food >*	14162
Has_symptom	An indicating symptom for a disease	*<Disease, Has_symptom, Symptom>*	5998
Need_test	A required test to diagnose a disease	*<Disease, Need_test, Test>*	39398
Cure_in	Disease is cured in a division of hospital	*<Disease, Cure_in, Division>*	8755
Diagnose	A doctor who is good at diagnose a disease	*<Doctor, Diagnose, Disease>*	13502
Prescribe	A usually-prescribed drug	*<Doctor, Prescribe, Drug>*	7305
Belongs_to	A doctor is belonged to a division	*<Doctor, Belongs_to, Division>*	3014
Relief	A drug can effectively relief a symptom	*<Drug, Relief, Symptom>*	10764
Reveal	Discover a symptom by a medical examination	*<Test, Reveal, Symptom>*	4713
Prevent	A therapy can prevent or postpone a disease	*<Therapy, Prevent, Disease>*	3050
Adjuvant_cure	A therapy can support or facilitate the cure	*<Therapy, Adjuvant_cure, Disease>*	1657
Trigger	A cause can trigger a disease	*<Cause, Trigger, Disease>*	2329
Total			**161317**

Table 4 The statistics of the nodes and relations in IKG

Label / Type	Definitions and explanations	Has Property / Relationship	Counts
Nodes			
Prod	A product structure in the prototype PSS	*Name, Description, Parameter*	28
Serv	A service module in the prototype PSS	*Name, Description, Parameter*	11
Mov	Movement, a physical object operated by a product structure	*Name, Description, Type*	19
Act	Activity, a virtual object or human served by a service module	*Name, Description, Type*	8
Beh	Behavior, a system-level object manipulated by the prototype PSS	*Name, Description, Type*	11
Fun	Function, a system-level function achieved by the prototype PSS	*Name, Description, Users*	7
Con	Context, a basic context interacting with a structure/module in product and service	*Name, Description, Category, Value_set*	21
Total			**105**
Relations			
Correlate	Two product structures have structural correlation	*<Prod, Correlate, Prod>*	37
Rely_on	A service module relies on a product structure	*<Serv, Rely_on, Prod>*	41
Prod_Int_Con	A product structure interacts on a context, according to the user-generated knowledge	*<Prod, Prod_Int_Con, Con>, Pos, Neg*	64
Serv_Int_Con	A service module interacts on a context, according to the user-generated knowledge	*<Serv, Serv_Int_Con, Con>, Pos, Neg*	27
Mov_VP	The operation of a product structure on a movement	*<Prod, Mov_VP, Mov>*	52
Act_VP	The service of a service module on an activity	*<Serv, Act_VP, Act>*	18
Mov_Compose	The physical movements in the system-level behavior	*<Mov, Mov_Compose, Beh>*	22
Act_Compose	The virtual or human-related activities in the system-level behavior	*<Act, Act_Compose, Beh>*	23
Achieve	A behavior achieves a system-level function	*<Beh, Achieve, Fun>*	38
Total			**322**

Table 5 K_{inno} retrieved from EKG in **C→K** operator

PRs	***Retrieved K_{inno} in C→K***			***Useful K_{inno}?***
	Head	***Rel***	***Tail***	
PR_1	*Therapy*: Medical air cushion	Effectively prevent	*Disease*: Elderly decubitus	√
PR_1	*Therapy*: Regular turning-over	Prevent	*Disease*: Decubitus	√
PR_1	*Cause*: Wet impregnation	Trigger	*Disease*: Decubitus	√
PR_1	*Therapy*: Sits bath	Adjuvant_Cure	*Disease*: Fecal incontinence	√
PR_2	*Drug*: Aspirin	Has_medication^{-1}	*Disease*: Cardiovascular diseases	
PR_2	*Drug*: Clopidogrel	Has_medication^{-1}	*Disease*: Cardiovascular diseases	
PR_2	*Symptom*: Palpitation	Has_symptom^{-1}	*Disease*: Cardiovascular diseases	
PR_2	*Symptom*: Angina pectoris	Has_symptom^{-1}	*Disease*: Cardiovascular diseases	
...	…	…	…	

Notes: Words in table 5-9 were translated from Chinese into English; -1 represented a reversed direction of the relation

Table 6 Related entities and relations discovered from EKG in **C→C** operator

PRs	**Top 5 pairs of (VP, NP)**	**Original *movement/action* in *PRs***
PR_2	(Has_symptom^{-1}, Sinus arrhythmia)	VP: Alarm symptom; NP: Cardiac emergency
	(Has_medication^{-1}, Sinus arrhythmia)	VP: Remind medication; NP: Cardiovascular disease
	(Has_symptom^{-1}, Atrial fibrillation)	VP: Alarm symptom; NP: Cardiac emergency
	(Has_medication^{-1}, Atrial fibrillation)	VP: Remind medication; NP: Cardiovascular disease
	(Has_symptom^{-1}, Cardiac failure)	VP: Alarm symptom; NP: Cardiac emergency
PR_3	(Cure in, Rehabilitation division)	VP: Facilitate; NP: Rehabilitation
	(Adjuvant_cure, Senile rheumatoid arthritis)	VP: Facilitate; NP: Rehabilitation
	(Adjuvant_cure, Osteoarthritis)	VP: Facilitate; NP: Rehabilitation
	(Cure in, Orthopedics division)	VP: Facilitate; NP: Rehabilitation
	(Adjuvant_cure, Knee joint degeneration)	VP: Facilitate; NP: Rehabilitation

Table 7 Added K_{inno} for the replacement concepts shown in table 6

PRs	***Retrieved K_{inno} after C→C***			***Useful K_{inno}?***
	Head	***Rel***	***Tail***	
PR_2	*Symptom*: Palpitation	Has_symptom^{-1}	*Disease*: Sinus arrythmia	√
PR_2	*Symptom*: Tachycardia	Has_symptom^{-1}	*Disease*: Sinus arrythmia	√
PR_2	*Drug*: PMAT	Has_medication^{-1}	*Disease*: Sinus arrythmia	√
PR_2	*Symptom*: Angina pectoris	Has_symptom^{-1}	*Disease*: Atrial fibrillation	√
PR_2	*Symptom*: Palpitation	Has_symptom^{-1}	*Disease*: Atrial fibrillation	√
PR_2	*Drug*: PHT	Has_medication^{-1}	*Disease*: Atrial fibrillation	√
PR_2	*Symptom*: Tachycardia	Has_symptom^{-1}	*Disease*: Cardiac failure	√
...	…	…	…	…
PR_3	*Disease*: Hepatorenal syndrome	Cure_in	*Division*: Rehabilitation division	
PR_3	*Disease*: Tenositis	Cure_in	*Division*: Rehabilitation division	
PR_3	*Therapy*: Joint exercise	Adjuvant_cure	*Disease*: Senile rheumatoid arthritis	√
PR_3	*Therapy*: Joint exercise	Adjuvant_cure	*Disease*: Osteoarthritis	√
PR_3	*Disease*: Senile osteoporosis	Cure_in	*Division*: Orthopedics division	
PR_3	*Cause*: Cartilage atrophy	Trigger	*Disease*: Knee joint degeneration	√
PR_3	*Therapy*: Cycle ergometer	Prevent	*Disease*: Knee joint degeneration	
...	...	…	...	…

Table 8 Solutions of reconfigured *prod*/*serv* generated by **K→K** operator

PRs	**Valid K_{inno} in EKG**			**Mapped K_{dsgn} in IKG**			**Nearest *prod/serv***
	$Head_{inno}$	Rel_{inno}	$Tail_{inno}$	$Head_{dsgn}$	Rel_{dsgn}	$Tail_{dsgn}$	
PR_1	*Therapy*: Medical air cushion	Effectively prevent	*Disease*: Elderly decubitus	*Prod*: Bed board	Correlate	*Prod*: Back supporter	*Prod*: Bed board
PR_1	*Therapy*: Regular turning-over	Prevent	*Disease*: Decubitus	*Mov*: Back posture	Compose	*Beh*: Abnormal posture	*Prod*: Back actuator
PR_1	*Therapy*: Regular turning-over	Prevent	*Disease*: Decubitus	*Prod*: Back actuator	Change	*Mov*: Back posture	*Prod*: Back actuator
PR_1	*Cause*: Wet impregnation	Trigger	*Disease*: Decubitus	*Prod*: Humidity sensor	Detect (+)	*Context*: Wetness	*Prod*: Humidity sensor
PR_1	*Cause*: Wet impregnation	Trigger	*Disease*: Decubitus	*Serv*: Vital signs monitoring	Monitor (+)	*Context*: Wetness	*Serv*: Vital signs monitoring
PR_3	*Therapy*: Joint exercise	Adjuvant_ cure	*Disease*: Senile rheumatoid arthritis	*Mov*: Leg posture	Compose	*Beh*: Abnormal posture	*Prod*: Leg actuator
PR_3	*Therapy*: Joint exercise	Adjuvant_ cure	*Disease*: Osteoarthritis	*Mov*: Leg posture	Compose	*Beh*: Abnormal posture	*Prod*: Leg actuator

Notes: (+)/(-) in table 8-9 indicated a majority of positive/negative annotations in the context-derived relations in Rel_{dsgn}

Table 9 Solutions of changing/upgrading possible *prod*/*serv* recommended by **K→C** operator

PRs	***Head* in K_{inno} ($head_{inno}$)**	**Possible K_{dsgn} in IKG**			**Improvement**
		$Head_{dsgn}$ ($prod_{dsgn}$/$serv_{dsgn}$)	Rel_{dsgn}	$Tail_{dsgn}$	
PR_2	*Symptom*: Palpitation	*Serv*: Vital signs monitoring	Report	*Act*: Physiological state	Upgrade
PR_2	*Symptom*: Palpitation	*Serv*: Vital signs monitoring	Feedback (+)	*Con*: Health	Upgrade
PR_2	*Symptom*: Palpitation	*Prod*: Microcomputer	Store (-)	*Con*: Health	Change
PR_2	*Symptom*: Palpitation	*Serv*: Vital signs monitoring	Report	*Act*: Nursing staff	Upgrade
PR_2	*Symptom*: Palpitation	*Serv*: Emergency call	Communicate	*Act*: Nursing staff	Upgrade
PR_2	*Symptom*: Tachycardia	*Serv*: Vital signs monitoring	Report	*Act*: Physiological state	Upgrade
...	...	...	…	...	…
PR_2	*Drug*: PMAT	*Serv*: Remote consultation	Communicate	*Act*: Doctor	Upgrade
PR_2	*Drug*: PMAT	*Serv*: Emergency call	Communicate	*Act*: Doctor	Upgrade
PR_2	*Drug*: PMAT	*Serv*: Vital signs monitoring	Feedback (+)	*Con*: Health	Upgrade
PR_2	*Drug*: PMAT	*Prod*: Microcomputer	Store (-)	*Con*: Health	Change
PR_2	*Drug*: PMAT	*Serv*: Vital signs monitoring	Require (+)	*Con*: Medical history	Upgrade
PR_2	*Drug*: PMAT	*Prod*: Microcomputer	Store (-)	*Con*: Medical history	Change
PR_2	*Drug*: PHT	*Serv*: Remote consultation	Communicate	*Act*: Doctor	Upgrade
...	...	...	…	...	…

Table 10 Comparison between the group using KG-CK and other groups in the same PBL scheme

Performance	**The group using KG-CK**	**Average of other 8 groups (Non-KG-CK designers)**
Manpower	5 graduate students (4 in Mechanical Engineering, 1 in Industrial Engineering, randomly selected in class)	5~6 graduate students (4~5 in Mechanical Engineering, 1 in Industrial Engineering, randomly selected in class)
Time allocated for requirement elicitation	~ 2 weeks	~ 2 weeks
Time allocated for conceptual design	~ 1 week	Usually > 4 weeks
Time rested for detail design and manufacturing	~ 5 weeks	Usually < 2 weeks
Accumulated time spent for consulting experts	~ 1 week (usually in the stage of conceptual design)	Nearly during the whole 8 weeks
Total cost in the project	RMB ¥6280	> Total budget of RMB ¥8000
User requirements	See Table 2	Similar with Table 2
Main functionalities	Regular body posture changing, Monitor/control via mobile app, Recommend useful knowledge, Knee rehabilitation exercises, Abnormal status alarm, and etc.	1 group fails to finish the project. The rest 7 groups are all able to change body postures and alarm warnings. 2 in them also develop monitoring app/software.
User satisfaction for solving their requirements	Satisfied, and the best award	Plain or unsatisfied

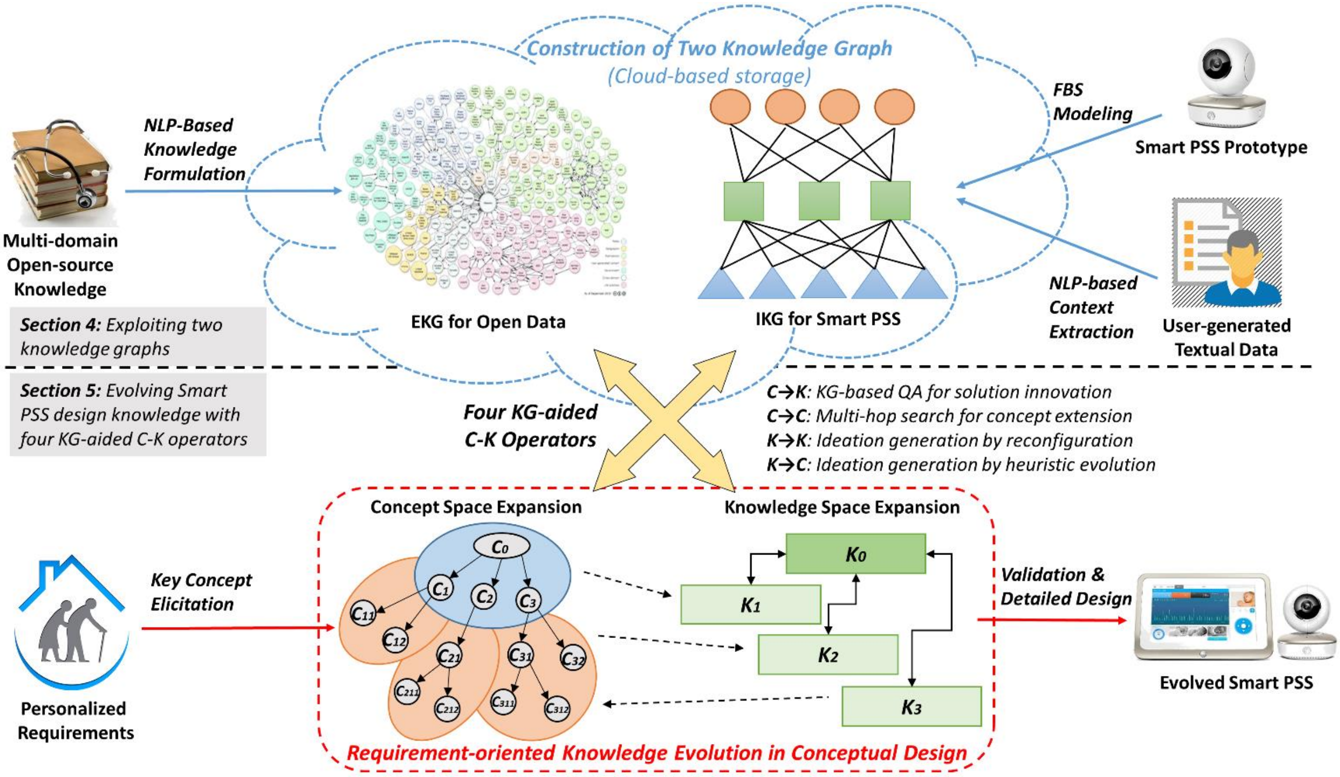

Figure 1 The conceptual framework of KG-CK for evolutionary Smart PSS development

Figure 2 A piece of disease introduction collected from a professional medical website

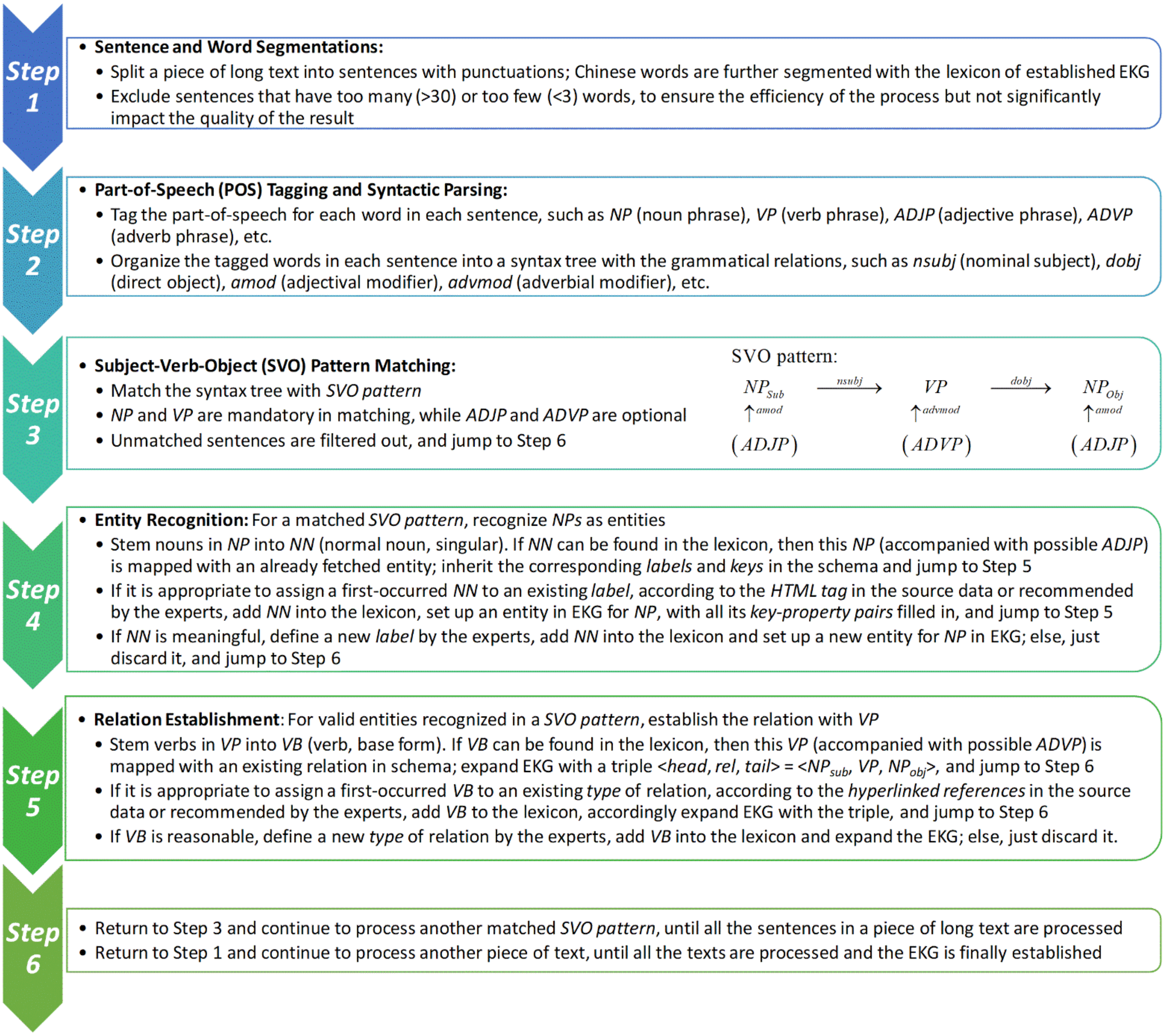

Figure 3 Six steps in the proposed NLP-based knowledge formulation manner

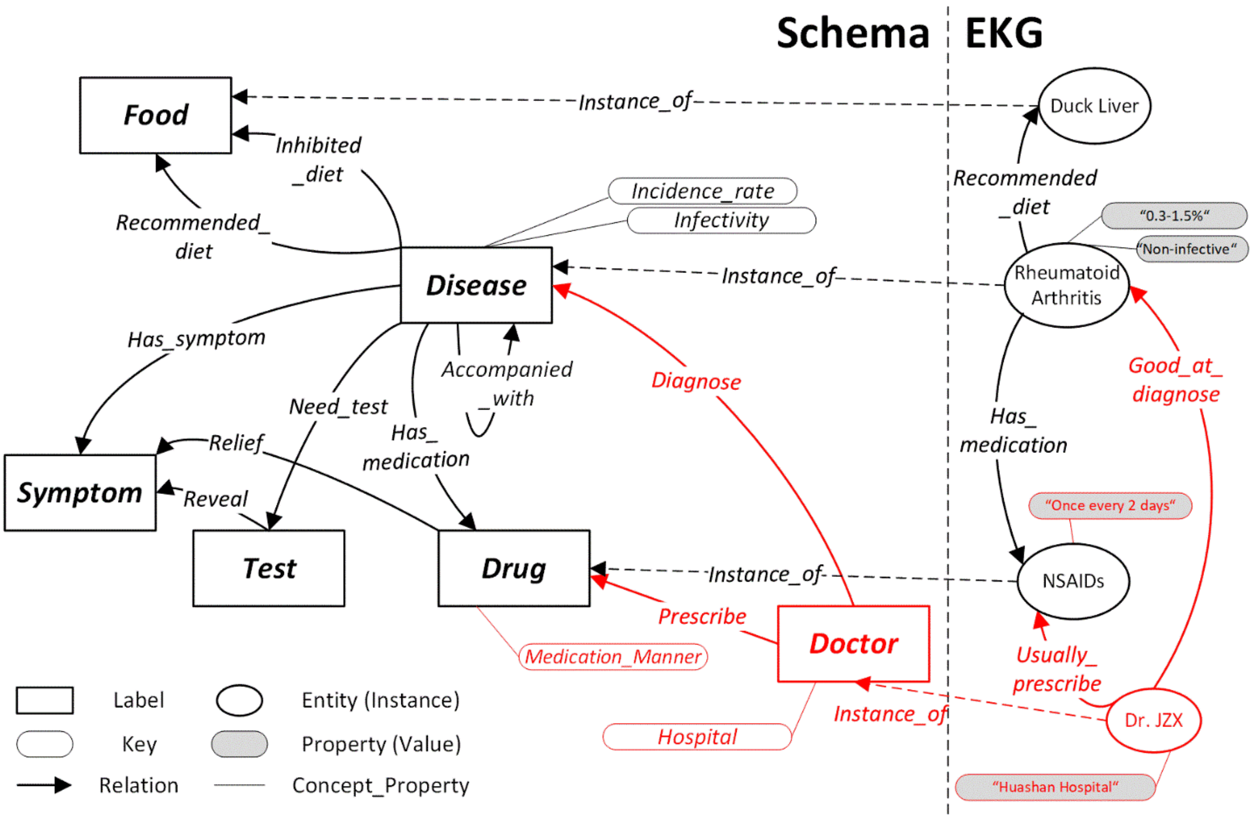

Figure 4 An illustrative schema and the corresponding EKG (*Translated from Chinese into English*)

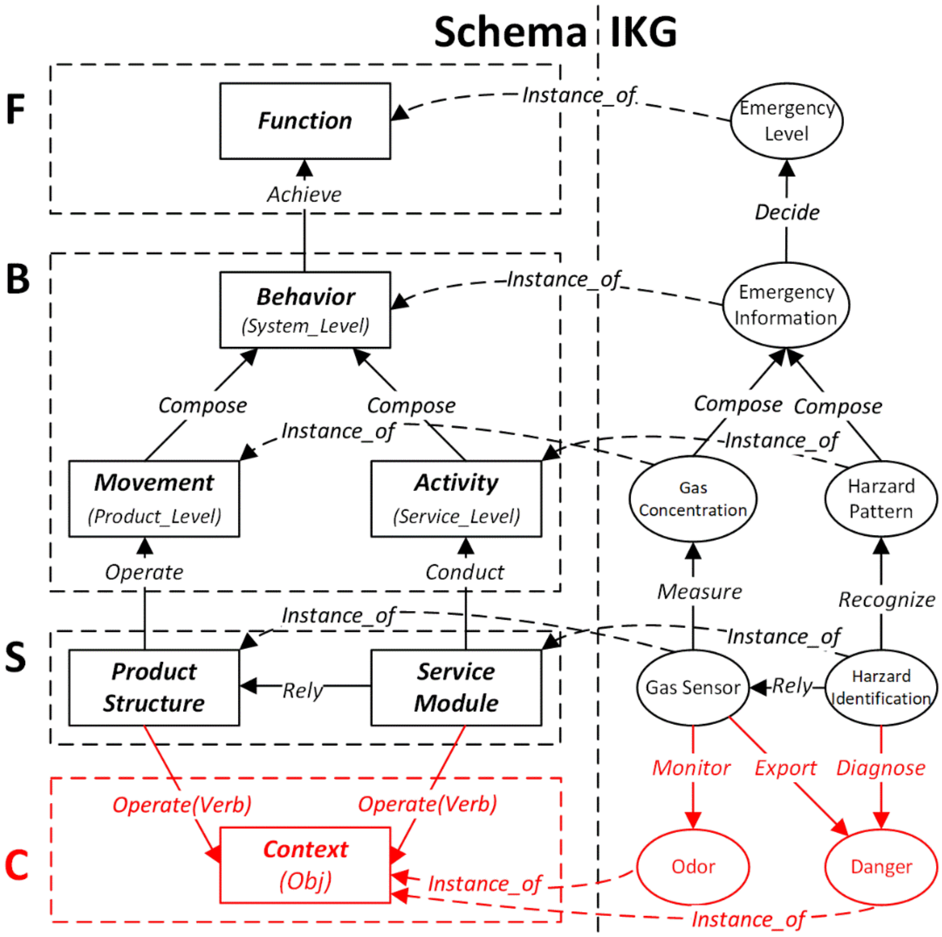

Figure 5 An illustrative schema and the corresponding IKG (*Translated from Chinese into English*)

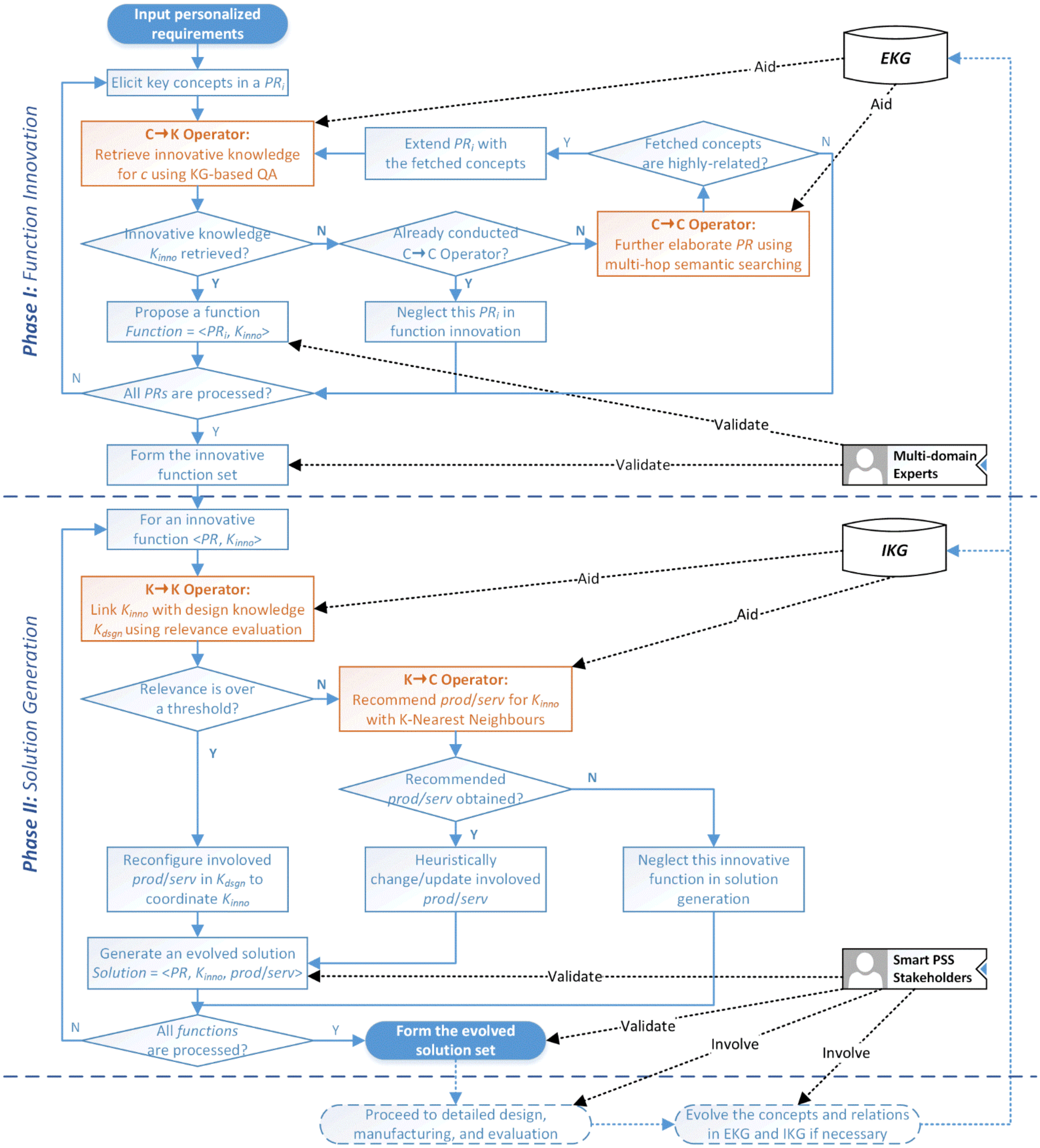

Figure 6 Flowchart for evolving Smart PSS design knowledge with four KG-aided C-K operators

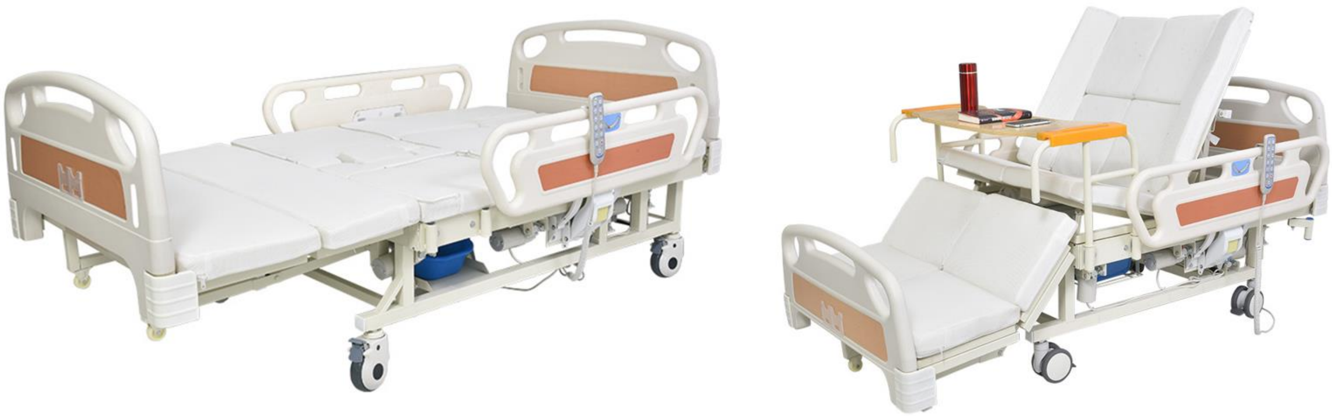

Figure 7 The prototype of an electrical nursing bed equipped with sensors and Bluetooth modules

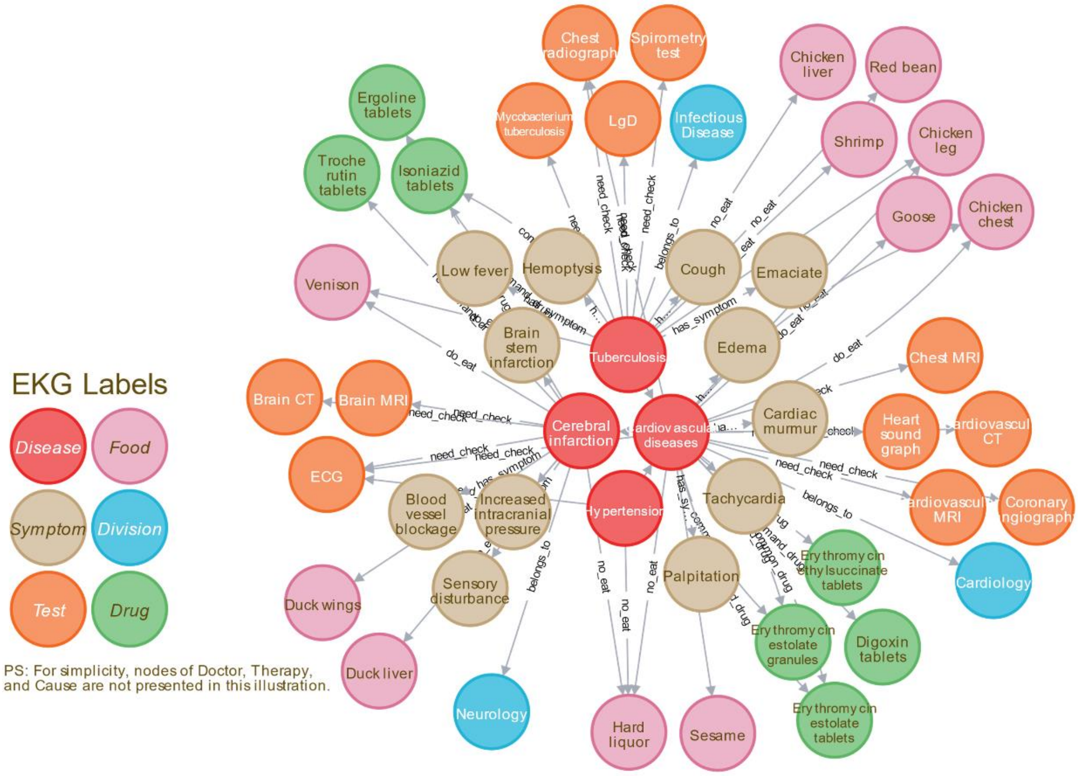

Figure 8 An illustration of EKG stored in the platform of *Neo4j* (*Translated from Chinese into English*)

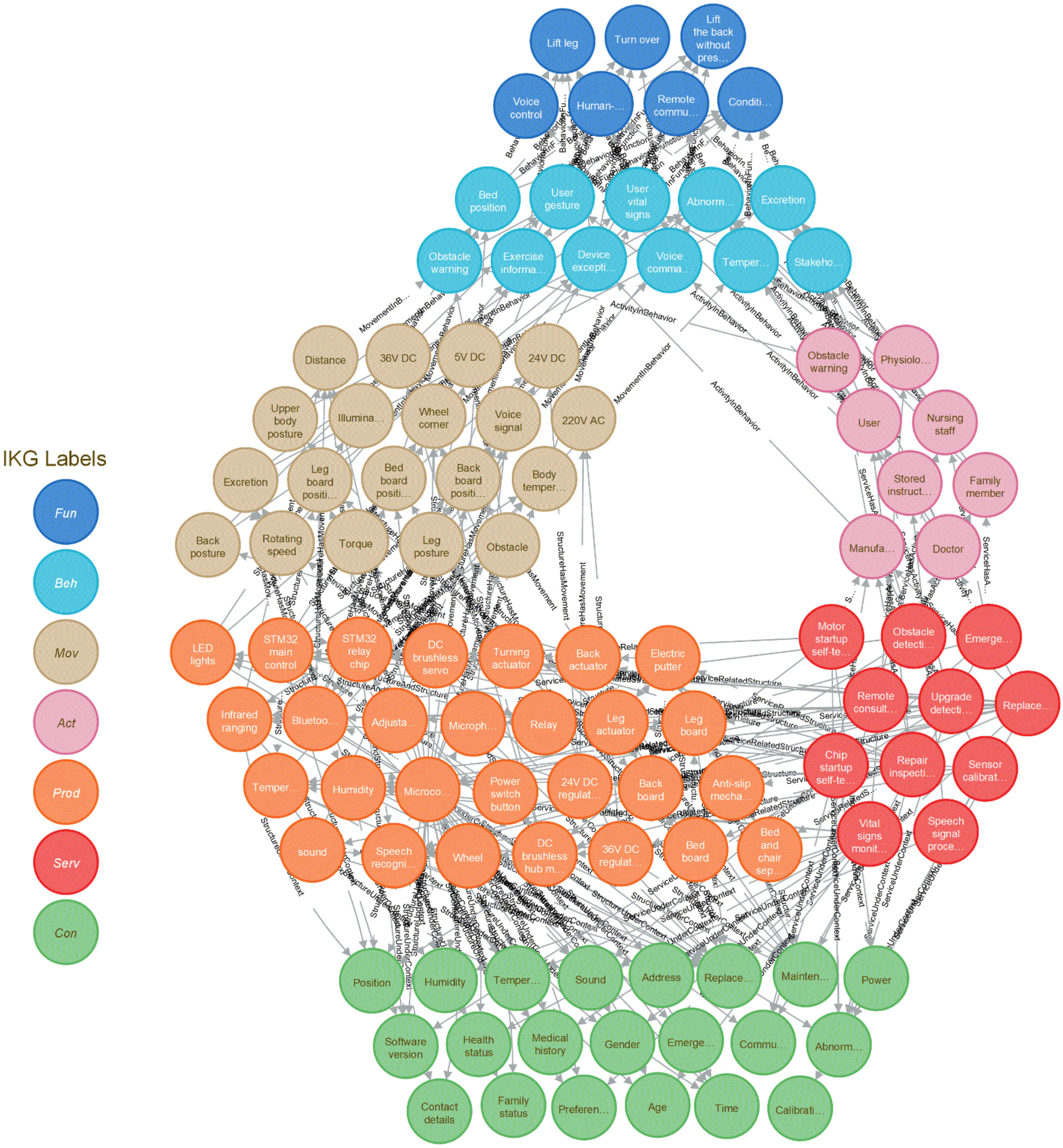

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Figure 10 The evolved Smart Nursing Bed

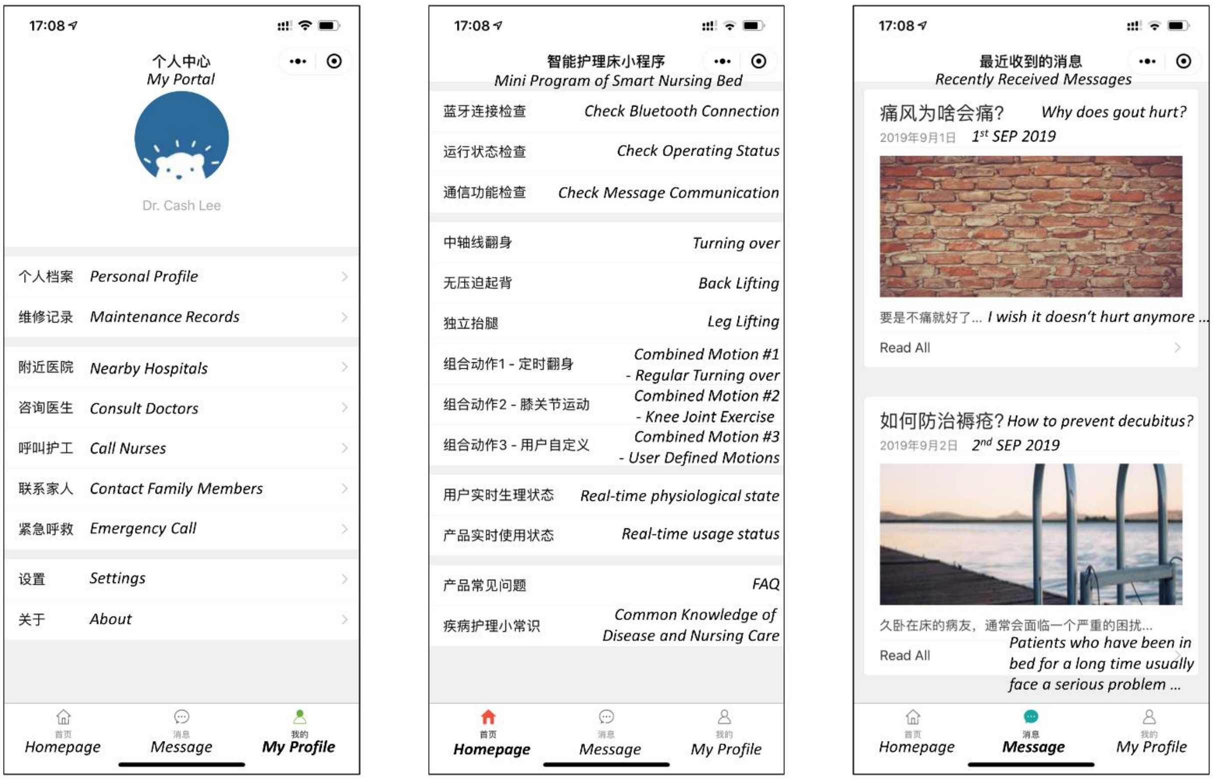

Figure 11 User interface of the bundled *WeChat Mini Program*