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An Integrated Open Approach to Capturing Systematic Knowledge for Manufacturing Process Innovation Based on Collective Intelligence

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Abstract: Process innovation plays a vital role in the manufacture realization of increasingly complex new products, especially in the context of sustainable development and cleaner production. Knowledge-based innovation design can inspire designers' creative thinking; however, the existing scattered knowledge has not yet been properly captured and organized according to Computer-Aided Process Innovation (CAPI). Therefore, this paper proposes an integrated approach to tackle this non-trivial issue. By analyzing the design process of CAPI and technical features of open innovation, a novel holistic paradigm of process innovation knowledge capture based on collective intelligence (PIKC-CI) is constructed from the perspective of the knowledge life cycle. Then, a multi-source innovation knowledge fusion algorithm based on semantic elements reconfiguration is applied to form new public knowledge. To ensure the credibility and orderliness of innovation knowledge refinement, a collaborative editing strategy based on knowledge lock and knowledge–social trust degree is explored. Finally, a knowledge management system *MPI-OKCS* integrating the proposed techniques is implemented into the pre-built CAPI general platform, and a welding process innovation example is provided to illustrate the feasibility of the proposed approach. It is expected that our work would lay the foundation for the future knowledge-inspired CAPI and smart process planning.

Keywords: manufacturing process innovation; computer-aided innovation; open innovation; collective intelligence; knowledge management; knowledge-based engineering

1. Introduction

In today's rapidly changing market landscape, regardless of any product industry, technological innovation has been regarded as an important factor for manufacturing enterprises to ensure future competitive advantage. As a basic form of technological innovation, manufacturing process innovation is the key guarantee for the R & D final realization of new products [1–3], especially in the field of complex equipment, such as aircraft, aerospace, automobile, construction machinery, and so on [4–7]. Because the structure of the world economy has undergone significant changes, with demand for energy saving and environmental protection becoming increasingly urgent [8–10], developing countries need to transform and upgrade their manufacturing industries with process innovation to reduce energy consumption and achieve sustainable development; developed countries, accordingly, are trying to guide and accelerate the global return of manufacturing industries by means of process innovation [11,12].

However, manufacturing enterprises have long encountered a variety of problems in the implementation of process innovation. These problems are mainly manifested in the difficulty of innovation, the poor effect, and the low success rate [13,14]. Generally speaking, the new manufacturing process technologies—especially sustainable process technologies—often entail long-term, complex, experimental, and higher-risk development efforts [15–17]. Industrial innovation survey data shows that the lack of technical staff and relevant innovation knowledge is one of the prime reasons for the termination or failure of innovation activities [3,13,18]. In fact, manufacturing process innovation is a cross-industry and interdisciplinary type of complex system engineering, which requires not only domain experts with multidisciplinary knowledge, but also technical or management personnel of manufacturing sites with process know-how [14,19]. Nevertheless, the empirical knowledge existing in these scattered owners has not yet been effectively organized according to innovation design procedure and cannot currently be applied to Computer-Aided Process Innovation (CAPI) [3,20].

It is recognized that reasonable and efficient innovation knowledge capture is the foundation for the effective innovation knowledge application, and it is regarded as one of the core requirements for smart innovation engineering of the Future Industry 4.0 [21–24]. Although several pre-research works exist in process innovation knowledge management and CAPI framework [2,3,25], there is still a lack of an integrated approach to effectively capturing systematic process innovation knowledge under the open innovation paradigm. The open process innovation knowledge capture is, essentially, a process of effective combination of knowledge owners' collective intelligence [20,26]. It will be able to match the characteristics of process innovation knowledge and make full use of the wisdom of multidisciplinary and multi-sectoral personnel, so as to meet the needs of CAPI-oriented knowledge organization.

Consequently, our goal in this research work is to construct an open knowledge capture approach, which can obtain structured, formalized, and systematic innovation knowledge from open environments and thus support manufacturing process problem-solving. By building an open knowledge–social community and considering multi-type knowledge organization and evolution in the process of knowledge-inspired innovation design, a novel holistic paradigm of process innovation knowledge capture based on collective intelligence (PIKC-CI) and the corresponding knowledge processing approach are explored. Accordingly, an open knowledge capture system for manufacturing process innovation (*MPI-OKCS*) is constructed in this paper, in order to implement the proposed method for practical application.

The remainder of this paper is organized as follows. In Section 2, some related works about innovation-oriented knowledge capture and CAPI are reviewed. Section 3 presents the overall paradigm of PIKC-CI. Section 4 shows the detailed procedure of the proposed PIKC-CI method, mainly including multi-source knowledge fusion and collaborative knowledge refinement. Then, a prototype system *MPI-OKCS* is implemented in Section 5 and further studied, with a case application of welding process innovation knowledge capture by using the mentioned method. The last section concludes this paper with some implications for future research.

2. Literature Review

2.1. Innovation-Oriented Knowledge Capture and Management

As is commonly recognized, knowledge is an essential asset for organizations and plays a crucial role in innovation; from another perspective, innovation can be regarded as the knowledge-based creation and the knowledge-based outcome [27,28]. To focus this study, related research has been conducted in previous contributions to innovation knowledge management and knowledge-based innovative design. Esterhuizen et al. [29] explored how knowledge conversion can grow innovation capability maturity, and provided a framework for the use of knowledge creation processes as a vehicle to improve innovation. By exploring the complex relationships between knowledge management and innovation, Xu et al. [30] proposed an integrated approach to knowledge management for innovation, and developed a corresponding distributed prototype system. Bosch-

Mauchand et al. [31] presented a novel approach to support the assessment of manufacturing process performance based on knowledge management integration. To effectively support systematic manufacturing process innovation, Wang et al. [32] presented an approach to principle innovation knowledge extraction from process patents.

In the knowledge-based economy, it is difficult for a single person or enterprise to have all the knowledge needed to achieve innovation. In the engineering field, open innovation is defined as the use of purposeful knowledge transfer in order to accelerate internal innovation and expand the application markets of external innovation [33,34]. Open innovation has recently become a new model of technological innovation because of its ability to combine internal and external collective intelligence [35,36]. Besides, the latest Web 2.0 technologies lay more emphasis on online collaboration and information sharing between users, and provide a technical basis for open knowledge capture and management. By combining open innovation strategy and Web 2.0 technologies, Hüsig and Kohn [37] introduced a new form of Computer-Aided Innovation (CAI)—"Open CAI 2.0".

2.2. Computer-Aided Process Innovation

Firstly proposed by J.A. Schumpeter from the perspective of economic development [38], process innovation received attention from both academic research and industry [19,20,39]. He believed that process innovation and product innovation constitute the technological innovation system of enterprises. The technological developments of information and communication technology (ICT) and innovation theory have provided a more structured knowledge-driven environment for technicians and market decision-makers [40–42]. Computer-based applications, such as CAD/CAE/CAPP/CAM, help users to achieve better solutions and hence to introduce better products, processes, and services to the diversified markets [17,43,44]. Meanwhile, the combination of innovation theory and ICT to support technological innovation has become a new research category known as CAI [40]. However, from a practical point of view, most of the current methods or tools of innovative design are more suited for product innovation than process innovation; sometimes they not only do not enhance the process innovation ability of manufacturing enterprises, but also even have some negative effects on production efficiency [39,45]. It is necessary for us to realize that process innovation and product innovation are quite different. In general, the process of process innovation covers a wider technical field, involves more participants, and suffers more realistic constraints. Actually, the traditional computer aided tools of the manufacturing process (e.g., CAPP/CAM) mainly focus on improving the efficiency and standardization of process design and management [23,43,46], rather than creating or improving process methods, and therefore cannot systematically enhance the development level of the manufacturing process in enterprises [2,3,15].

In recent years, some domain research endeavors have been carried out into specific types of manufacturing process innovation by using the Theory of Inventive Problem Solving (TRIZ) [42] and knowledge-based engineering [23]. Cakir and Cilsal [47] introduced a TRIZ-alike matrix-based access system and established a knowledge database for various contradictions of chip removal process. Duflou and D'hondt [48] applied TRIZ principles of physical conflict, resolving to improve the performance of single point incremental forming. By focusing on the semiconductor industry, Sheu et al. [49] developed a suitable contradiction matrix and corresponding inventive principles for that particular industry based on chemical–mechanical processing patents. With the development of CAI and the requirements of manufacturing process problem-solving, the basic concept and framework for CAPI were presented by Geng, Tian, and Wang [2,3,25,50], with some specific application cases being used to illustrate the feasibility of structured/systematic process innovation design [20,32,51].

2.3. Summary

In summary, much research has been done regarding aspects of innovation design theory and methods, and innovation knowledge modeling and management; however, very little work has addressed systematic knowledge-driven process innovation design and CAPI. It's gratifying that the existing research results have shown the feasibility of structured process innovation with the computer-aided method.

Currently, CAI is developing towards a knowledge-driven, open, and systematic direction. As a branch of CAI, CAPI is more focused on solving manufacturing process problems, improving process methodologies, fostering whole process innovation design cycles, and even enhancing the overall manufacturing innovation capability of enterprises. Manufacturing process innovation knowledge, which exists in the entire lifecycle of process innovation, is used to support the correct implementation of process innovation activities, and to produce new process knowledge [2]. Obviously, the formalized knowledge capture and management is crucial to systematic CAPI, especially under the open innovation paradigm. Thus, this paper will mainly explore CAPI-oriented open innovation knowledge capture based on collective intelligence.

3. An Overall Paradigm for Innovation Knowledge Capture Based on Collective Intelligence

From the systems thinking perspective, the innovation realization of CAPI is essentially the process of capturing and applying process innovation knowledge to solve specific process problems with the support of innovation theories, methods, and tools. Problem solving is a complex intellectual activity based on high-order cognition, and innovative problem solving is considered to be the process of overcoming at least one obstacle that impedes the achievement of the desired goal [52]. Thus the problem-solving of process innovation actually mainly includes analysis and formulation of process problems, process conflict extraction and resolution, detailed design of process innovation schemes, and evaluation and optimization of the scheme. The innovation design procedure can be basically divided into four stages, as illustrated in Figure 1, and each stage needs the support from the corresponding type of innovation knowledge. According to the role of knowledge in manufacturing process innovation design, we divide innovation knowledge into several types, such as Process Contradiction Matrix, Manufacturing Scientific Effect, Innovative Scheme Instance, and so on [25]. The above types of knowledge are required to be explicit, structured and formalized descriptions, so as to stimulate the creative thinking of the process designers and facilitate the implementation of knowledge-inspired innovative design in the computer support environment. Although the designers and experts in the manufacturing field have strong process problem-solving experience and rich manufacturing knowledge, this discrete and unstructured knowledge cannot be directly and efficiently applied to innovation design, nor is it conducive to knowledge capture and accumulation in manufacturing enterprises. Thereby, we need to explore an approach that can contact appropriate knowledge holders and make full use of their collective intelligence to participate in knowledge capture activities.

From the practical point of view of collective intelligence, the effect of knowledge capture and accumulation based on community is better than that based on the company's organization structure, because it can better share and focus the knowledge topics; knowledge refinement based on peer collaboration is better than that based on expert-centered editing, because it can narrow the distance between knowledge [26,53]. Thus, a novel manufacturing process innovation knowledge capture paradigm based on collective intelligence is proposed, just as shown in Figure 1. In an open knowledge–social community, personal knowledge can be gradually transformed into public innovation knowledge through knowledge–social activities among participants. The procedure of knowledge capture basically includes three main steps: knowledge contribution (KC), knowledge fusion (KF), and knowledge refinement (KR). Firstly, knowledge topics can be published according to the requirements of current manufacturing process innovation. Then interested users are gathered into a group through knowledge–social relationships. In the knowledge–social community, they discuss the topics and manifest their knowledge using knowledge templates from the viewpoint of individual specialty and experience. Then, the knowledge capture system will integrate this personal knowledge into the public knowledge fusion units under the semantic constraints of domain ontology. Thus, the knowledge fusion units will be iteratively edited and refined into formalized and systematic knowledge by refinement group. Subsequently, the captured process innovation knowledge can be effectively applied in the stage of innovation design.

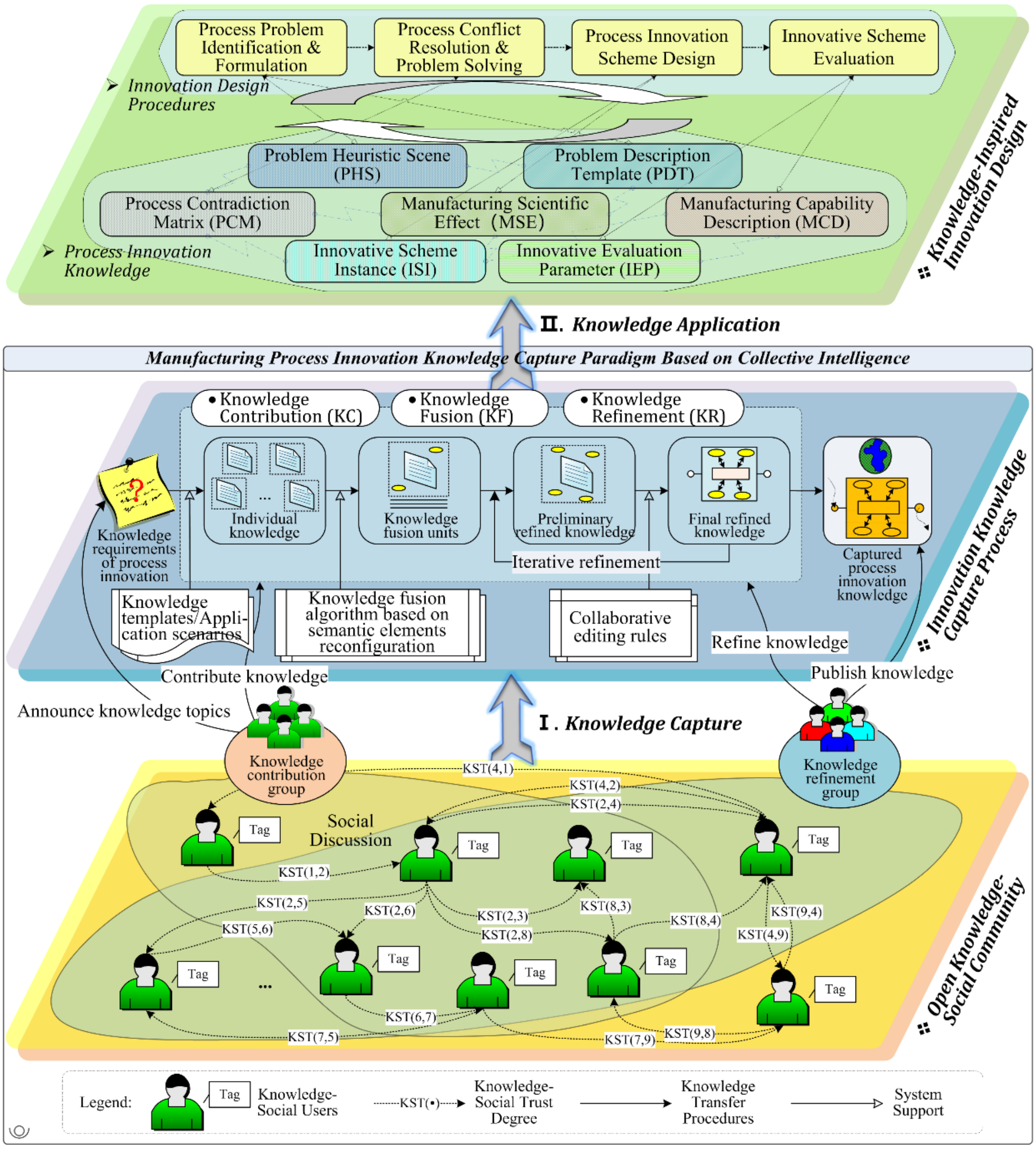

Figure 1. A novel process innovation knowledge capture paradigm based on collective intelligence.

4. The Proposed PIKC-CI Method

As revealed in Figure 1, we know that several knowledge activities, KC, KF and KR, are all needed for the integrated PIKC-CI method. Among them, multi-source knowledge fusion and collaborative knowledge refinement are the crux of the efficient innovation knowledge capture. In this section, the detailed approaches for multi-source innovation knowledge fusion, based on semantic elements reconfiguration, and collaborative innovation knowledge refinement, based on knowledge–social trust degree, are successively explored from the perspective of knowledge processing and transfer.

4.1. Multi-Source Innovation Knowledge Fusion Based on Semantic Elements Reconfiguration

For the convenience of detailed elaboration, this sub-section first presents the relevant definitions for process innovation knowledge and its fusion process.

Definition 1. *Manufacturing process innovation-oriented knowledge network is a set of spatial knowledge structure, formally represented as*

$$PIK_{\Omega} = \{KN, CTR, U\} \quad (1)$$

where KN is a set of multi-type process innovation knowledge units, CTR is a set of knowledge contextual relevance for specific process innovation scenarios, and U is a set of social-wiki users involved in knowledge capture.

The hierarchical structure of the process innovation-oriented knowledge network is shown in Figure 2 and formally defined as follows.

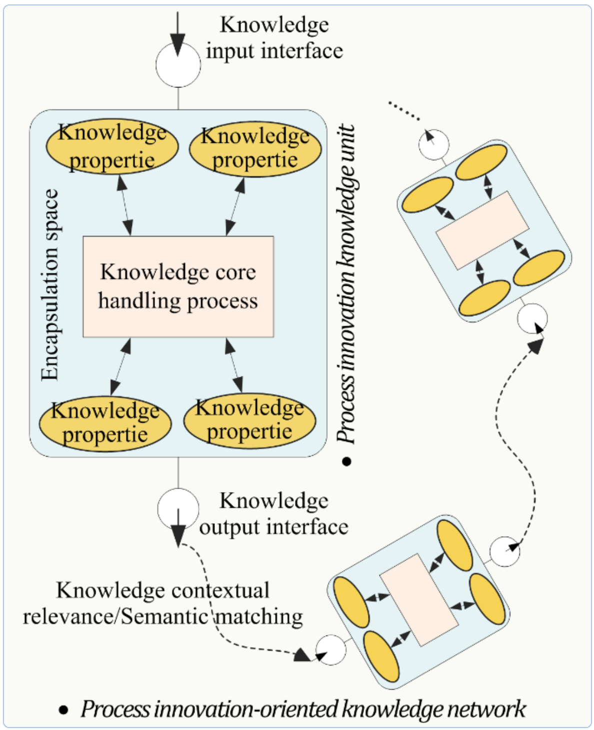

Figure 2. Schematic diagram of process innovation-oriented knowledge network.

Definition 2. *Process innovation knowledge unit is a local capability unit that has the ability to solve certain types of process problems and deliver information. It is defined as*

$$KN = < P, I_I, I_O, E, U > \quad (2)$$

where P is a set of knowledge properties, I_I and I_O represent the sets of knowledge input interface and knowledge output interface, respectively. E stands for an encapsulation space for complete knowledge units. Several types of innovation knowledge, $\Pi_{KN} = \{PHS, PDT, PCM, MSE, ISI, IEP, MCD\}$, are basically used in the innovation design process. Among them, PHS is the Problem Heuristic Scene, PDT is the Problem Description Template, PCM is the Process Contradiction Matrix, MSE is the Manufacturing Scientific Effect, ISI is the Innovative Scheme Instance, IEP is the Innovative Evaluation Parameter, and MCD is the Manufacturing Capability Description.

Definition 3. *Knowledge contextual relevance of manufacturing process innovation is further denoted by*

$$CTR = \{\langle kn, k, r, k', u\rangle | kn \in KN, k, r, k' \in \mathbb{O}, u \in U\} \quad (3)$$

where k, r, k' are ontological entities defined in process innovation domain ontology $\mathbb{O}$, and r is a contextual relationship between k and k'.

Definition 4. *Domain ontology $\mathbb{O}$ consists of a series of concepts and relationships that represent domain knowledge models. It is defined as*

$$\mathbb{O} := \left(C, R, \mathcal{E}_R, I_C \right) \tag{4}$$

where C *and* R *are a set of classes and a set of relations, respectively;* $\mathcal{E}_R \subseteq C \times C$ *represents a set of relationships between classes, which can be denoted as a set of triples* $\left\{ \left\langle c, r, c' \right\rangle \middle| c, c' \in C, r \in R \right\}$*; and* I_C *is a power set of instance sets of a class* $c \in C$*.*

The knowledge elements of process innovation knowledge are generally expressed in terms of domain terms or natural language descriptions. For example, process conflict parameters can be expressed as process parameters and their deformation, while process innovation principles can be expressed in natural language form. A knowledge element of natural language descriptions is composed of one or more propositions; a proposition is a complete semantic unit that contains terminology and predicate terms.

Definition 5. *Process innovation knowledge element represents a complete and indivisible knowledge unit in knowledge space* PIK_{Ω}*. It is defined as*

$$Ke = \left\{ \Sigma, \Lambda, \Theta \right\} \tag{5}$$

where $\Sigma = \left\{ t_1, t_2, \ldots t_i, \ldots t_n \right\}, t_i (i = 1, 2, \ldots, n)$ *is terminology, and* $\Lambda = \left\{ p_1, p_2, \ldots p_j, \ldots p_m \right\}, p_j (j = 1, 2, \ldots m)$ *is the predicate term.* $\Theta = \Sigma \oplus \Lambda = \left\{ t_1, t_2, \ldots t_i, \ldots t_n \right\} \oplus \left\{ p_1, p_2, \ldots p_j, \ldots p_m \right\}$ *denotes the logical plus operation of sets* Σ *and* Λ*.*

Thus, several general characteristics of knowledge elements can be introduced from Definition 5: (1) knowledge elements have a certain structure and constitute the smallest controllable unit of process innovation knowledge; (2) knowledge elements are logically complete and capable of expressing facts, principles, methods, and so on; (3) new knowledge can be generated by semantically correlating multi-sourced knowledge elements.

Definition 6. *Natural language description* D *and its composition proposition* P_i *of process innovation knowledge element can be further represented as*

$$\begin{gathered} D \triangleq \bigcup P_i (i = 1, 2, \ldots, n), \\ P_i \triangleq \bigcup (t_{ij}) \oplus \bigcup (p_{ij}) \ (i = 1, 2, \ldots, n; j = 1, 2, \ldots m) \end{gathered} \tag{6}$$

where $t_{ij} (i = 1, 2, \ldots, n; j = 1, 2, \ldots m)$ *is terminology of proposition, and* $p_{ij} (i = 1, 2, \ldots, n; j = 1, 2, \ldots m)$ *is the predicate of proposition.*

Knowledge fusion is a process of forming new knowledge, with the help of multi-source knowledge interaction and support. For terminology fusion, the terminology specification and terminology conflict resolution of the fusion process are based on domain ontology and semantic relationships. For knowledge element sets of natural language description, we can deconstruct them as subject–predicate–object (SPO) logical form triples and then reconfigure semantic elements through co-reference relationship identification under the domain ontology constraints.

The algorithm flow of knowledge fusion for process innovation knowledge is represented in Figure 3, and the specific process is given as follows:

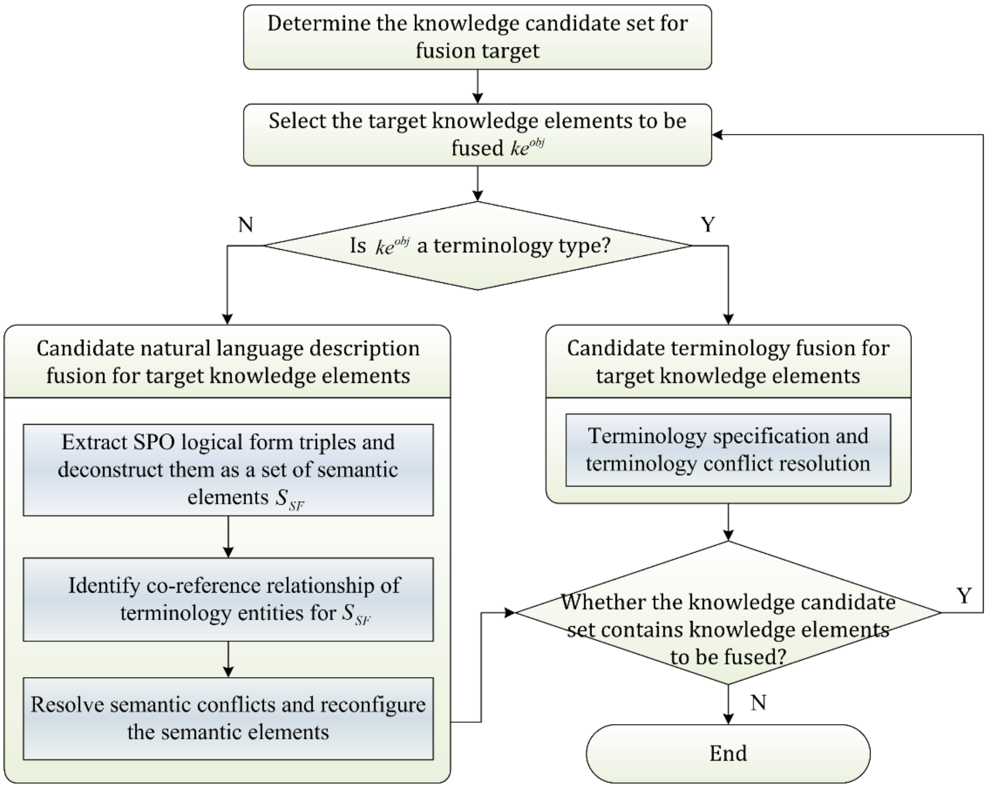

Figure 3. Algorithm flow of process innovation knowledge fusion based on semantic elements reconfiguration.

Step 1. Determine the knowledge candidate set for fusion target of knowledge unit KN_k^{cnd} and knowledge contextual relevance CTR_t^{cnd}.

$$\begin{aligned} KN_k^{cnd} &= \{ < P_k, I_{Ik}, I_{Ok}, E_k, u_k > | k = 1,2,\ldots,n \}, \\ CTR_t^{cnd} &= \{ \langle kn_t, k_t, r_t, k'_t, u_t \rangle | t = 1,2,\ldots,m \} \end{aligned}, \tag{7}$$

where n and m are the number of knowledge unit candidates and the number of knowledge contextual relevance candidates in the fusion process, respectively.

Step 2. Select the target knowledge elements of knowledge candidate set Ke^{obj}, and judge whether it is a terminology type. If so, then go to Step 3, otherwise turn to Step 4.

Step 3. Standardize the candidate terminology set and perform logical plus operation based on domain ontology. If completed, turn to step 7.

For two knowledge elements Ke_i, Ke_j in fusion process, if there are terminology items $t_i \in Ke_i$, $t_j \in Ke_j$ and terminology conflict $t_i \times t_j$, those conflicts will be resolved according to the following rules:

(1) When the terminologies have similar meanings but different expressions, we can map terminology items t_i, t_j into the terminology set logic tree T of domain ontology, and the result can be denoted by R. If $T(t_i) \subset T(t_j)$, then $R = t_j$; if $T(t_i) \supset T(t_j)$, then $R = t_i$; if $T(t_i) = T(t_j)$, then $R = t_i$ or t_j.

(2) When the terminology items have contrary logic, conflict resolution will depend on collective intelligence.

Step 4. Execute semantic and grammatical analysis for the candidate natural language descriptions, and extract SPO logical form triples by using semantic linguistic tool NLPWin [54], which provides deep syntactic and partial semantic analysis of text, then deconstruct them as a set of semantic elements S_{SF}.

Step 5. Identify co-reference relationship of terminology entities for S_{SF}. Terminology entities refer to the terms or phrases that are defined by the domain ontology, such as the manufacturing resources, processing objects, process methods, and so on.

Step 6. Perform the logical plus operation for deconstructed natural language descriptions of the candidate set, and reconfigure the semantic elements of S_{SF}. If completed, go to step 7.

For two knowledge elements Ke_i and Ke_j in fusion process, if there are semantic items $(t_i \oplus p_i) \in Ke_i$, $(t_j \oplus p_j) \in Ke_j$ and semantic conflict $(t_i \oplus p_i) \otimes (t_j \oplus p_j)$, those conflicts will be resolved according to the following rules:

(1) When concrete manifestation of semantic conflict is terminology conflict, those conflicts can be resolved according to Step 3.
(2) When predicate items have similar meanings but different expressions, we denote the usage frequency of predicate terms p_i, p_j by f_i and f_j, respectively. Similarly, the fusion result is denoted by R. If $f_i \prec f_j$, then $R = p_j$; if $f_i \prec f_j$, then $R = p_j$; if $f_i = f_j$, then $R = p_i$ or p_j.
(3) When predicate items have contrary logic, conflicts resolution will depend on collective intelligence.

Step 7. Judge whether the candidate knowledge sets KN_k^{cnd} and CTR_t^{cnd} still contain knowledge elements that need to be fused. If so, return to Step 2, otherwise end this algorithm.

4.2. Collaborative Innovation Knowledge Refinement Based on Knowledge–Social Trust Degree

Innovation knowledge fusion unit contains the wisdom of the participants' individual knowledge, yet to some extent it is rough or inaccurate and needs to be refined further by experts and authorities. Knowledge refinement is a collaborative editing process of preliminary knowledge by group members with a high knowledge–social trust degree (*KST*). In order to rapidly capture process innovation knowledge and ensure the credibility and orderliness of the knowledge refinement procedure, we regulate group members' knowledge behavior by applying a collaborative editing mechanism.

4.2.1. Credible Groups Construction

In the process of innovation knowledge capturing, knowledge–social members give comments and evaluations on other members' knowledge activities and establish social trust relationships among them. Here, the participants' knowledge–social trust degree in a knowledge community is measured by two aspects: individual trust (KST_{ind}) and community trust (KST_{com}).

Definition 7. *KST_{ind} is used to describe the trust level established on knowledge interaction between one user and another user. Suppose there are individuals d_i and d_j in the knowledge–social community, d_i and d_j had n_1 times knowledge–social activities which has an interactive type of P_h. Let $jud_{d_j}(d_i) \in [0,1]$ be an interactive evaluation of d_j toward d_i in a knowledge–social activity. Assuming that d_j has given m_1 times negative comment on d_i, the KST_{ind} of d_j toward d_i can be computed as:*

$$KST_{ind}(d_j, d_i) = \frac{\sum_{t=1}^{n_1} right(P_h) \times jud_{d_j}(d_i)}{n_1} \times \left(\frac{n_1 - m_1}{n_1} \right)^{\frac{1}{n_1 - m_1}} \tag{8}$$

where $right(P_h) \in [0,1]$ *is weight coefficient of interactive type. This formula introduces the weight concept of knowledge interaction and considers the influence of malicious interaction on subjective trust, which makes the calculation more reliable.*

Definition 8. *KST_{com} indicates the overall trust and reliability of users in the knowledge–social community, given by all members of the community in which the individual resides. The KST_{com} calculation depends on the following two factors: (1) the common evaluation for someone's knowledge–social behavior from all members of knowledge community; (2) the number of knowledge communities in which this individual resides. Suppose there is an individual $d_i \in V$ in multiple knowledge communities $V_1, V_2, \ldots, V_e$. Assuming that d_i has been evaluated by g members of knowledge communities $V_1, V_2, \ldots, V_e$, we can obtain the KST_{com} of d_i.*

$$KST_{com}(d_i) = 1/g \times \sum_{\substack{d_j \in V_1 \cup V_2 \cup \ldots \cup V_e \\ j \neq i}} \left[KST_{ind}(d_j, d_i)^{\frac{1}{|V_{d_j}|}} \times (KST_{com}(d_j)) \right], \quad (9)$$

where V is the knowledge community set, and $|V_{d_j}|$ is the number of knowledge communities $V_1, V_2, \ldots, V_e$ in which the individual d_j resides. Considering the extensive influence of community participants, the number of communities is introduced as a factor in KST_{com} calculation. If a participant has identities in multiple knowledge communities, the influence from his evaluation will be more than the one from only one community. In the process of knowledge refinement, the credibility of knowledge refined by participants with multiple identities will certainly be higher than that refined by the user with single community identity.

Suppose there are t members in a group G, the degrees of group knowledge-social trust $KST_{com}(d_i)$, $KST_{com}(d_j)$ have not been determined. The specific procedures of credible groups construction based on *KST* are summarized as follows:

Step 1. Compute individual knowledge–social trust degree $KST_{ind}(d_j, d_i)$ for t members of group G by using Formula (8).

Step 2. Initialize community knowledge–social trust degree for each group member i, $KST_{com}(d_i) = k \in (0,1]$.

Step 3. Calculate temporary community knowledge–social trust degree $\overline{KST_{com}(d_i)}$ of each group member by applying Formula (9):

$$\overline{KST_{com}(d_i)} = 1/g \times \sum_{\substack{d_j \in V_1 \cup V_2 \cup \ldots \cup V_e \\ j \neq i}} \left[KST_{ind}(d_j, d_i)^{\frac{1}{|V_{d_j}|}} \times (KST_{com}(d_j)) \right] \quad (10)$$

Step 4. Judge whether the KST_{com} satisfies accuracy error according to the following formula:

$$\sum \left| \overline{KST_{com}(d_i)} - KST_{com}(d_i) \right| < \Delta \quad (11)$$

where Δ is the setting accuracy error value. If so, go to Step 5; otherwise let $KST_{com}(d_i) = \overline{KST_{com}(d_i)}$ for each knowledge–social member, and return to Step 3.

Step 5. Structure the KST_{com} set of knowledge–social members, $KST_{com} = \{KST_{com}(d_i) | i \in V\}$. Select the members with higher *KST* to join the knowledge refinement group based on the following basic criterion:

$$KST_{com}(d_i) \geq \xi \quad (12)$$

where ξ is the knowledge–social trust threshold, which can be set based on the requirements of innovation knowledge refinement.

4.2.2. Procedure of Collaborative Knowledge Refinement

Knowledge refinement process requires collective participation of knowledge–social users, and refinement results should include ideas from knowledge refinement members as much as possible. In an open knowledge–social community, members of credible knowledge group have the permission of the corresponding knowledge editing and refinement. The procedure of collaborative process innovation knowledge refinement is displayed in Figure 4. Firstly, managers propose knowledge refinement requirements and build refinement groups according to the knowledge to be refined. Then group members discuss original knowledge object K_0, publish their suggestions for revision and post their attitudes toward the views of others. A suitable member u_1 will be selected as the knowledge editor to perform refinement transaction. Thus, a temporary knowledge version K_1^1 is formed by the first-round editor u_1. When knowledge editing of this round is completed, the members make an editorial comment on version K_1^1 again and carry out the procedure of knowledge refinement. Then repeat the above process until the knowledge is fully refined. As shown in Figure 4, through the gradual refinement for original knowledge object K_0 by editors $u_1 ... u_n$, multiple temporary versions may have been correspondingly formed as knowledge versions $K_1^1 ... K_1^n$. When the latest temporary version K_1^n reach the refinement requirements, it will be saved as the refinement result of this time K_1. In addition, with the knowledge application in manufacturing process innovation design, the new requirement of knowledge refinement will still be put forward.

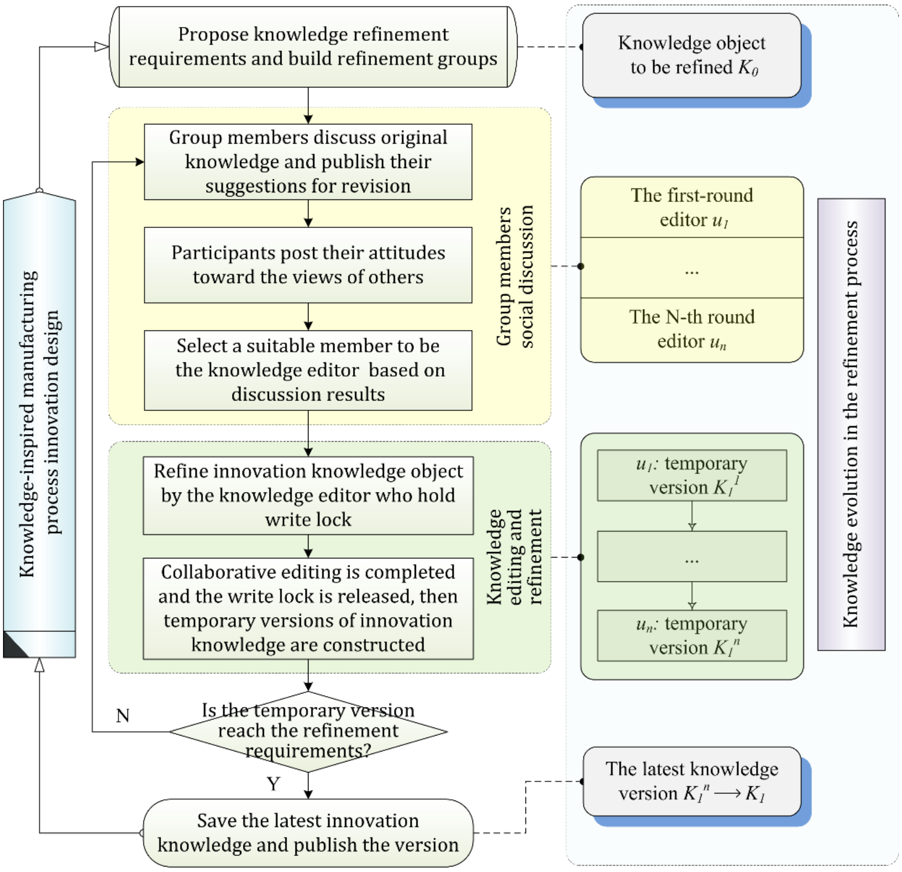

Figure 4. Procedure of collaborative knowledge refinement in an open knowledge–social community.

While accessing any knowledge elements of collaborative editing, group members can take the following actions: view and edit the existing knowledge. Because multiple users may execute transactions simultaneously in the refinement process and the transactions are atomic, knowledge element modification for different transactions should be mutually exclusive. Here, a lock-based knowledge collaborative editing and refinement solution is adopted to enable concurrent access to workflows for multiple knowledge editors, and its specific rules are shown in Table 1. Knowledge locks, in this study, basically consist of two types: read locks and write locks. The editor who owns the write lock has editing permission for the locked region, while the read lock owner is only allowed to read knowledge content. To avoid redundant effort and to prevent editors from destroying each other's work, the write locks are exclusive in this research.

Table 1. Rules for lock-based knowledge collaborative editing and refinement (adapted from [25]).

Rules	Descriptions
Rule 1	The read locks are compatible with each other. More than one read locks can be placed on one knowledge object at the same time. Group members of knowledge refinement are allowed to hold read lock of the corresponding knowledge objects.
Rule 2	The write locks are mutually exclusive with each other for a locked region. This means that only one write lock can be placed on the same knowledge object at a certain moment, and for a knowledge element only one editor may hold the write lock.
Rule 3	After participants publish their comments and exchange views on the knowledge object to be refined, members who obtained a positive evaluation of more than a certain level can apply to be the refinement editor.
Rule 4	If a knowledge element has been locked, the write lock requests will be put forward. Meanwhile, notifications are sent to the owners of write locks whenever the latter form queues in front of certain knowledge objects. Specifically, a system timer process, which sends time-stamped notifications to the owners of write locks, can be employed to prevent the starvation of other editing operations whenever there are editing operations waiting for more than a certain time to access certain objects.
Rule 5	Group managers have the permission to grant write locks to a suitable group member at all times.

5. Case Study

5.1. The Implementation of MPI-OKCS

Based on the proposed approach, this sub-section implements a prototype management system *MPI-OKCS* for open capturing systematic process innovation knowledge. It is integrated as a submodule into the pre-built general platform of CAPI system *pi*Pioneer, which contains the basic tools needed for the knowledge management system.

The *MPI-OKCS* has a 4-layer-architecture, as illustrated in Figure 5. The knowledge & data layer stores the basic data of the innovation system, knowledge–social information of the community, and captured process innovation knowledge. The service layer supports access to the knowledge and data layer, and provides various system background services of knowledge capturing process. The functional layer provides the functional components required for the system business logic of the three main modules, namely, knowledge capture, knowledge application, and system management. The interaction layer provides a visual man–machine interface for users from different departments and dispersed geographic locations, so that they can participate in the innovation knowledge processing activities of the corresponding roles in an open environment.

To facilitate the implementation process, we have invited seven domain experts from the Institute of CAPP & Manufacturing Engineering Software at NWPU (Xi'an, China) and the Department of Mechanical Design at CHD (Xi'an, China) to participate in innovation knowledge refinement. All graduate students from the above two departments were allowed to contribute their innovation knowledge. Additionally, about 20 engineers from the R & D department of Sinomach

Changlin Company Limited (Changzhou, China) have contributed their individual process knowledge to the system.

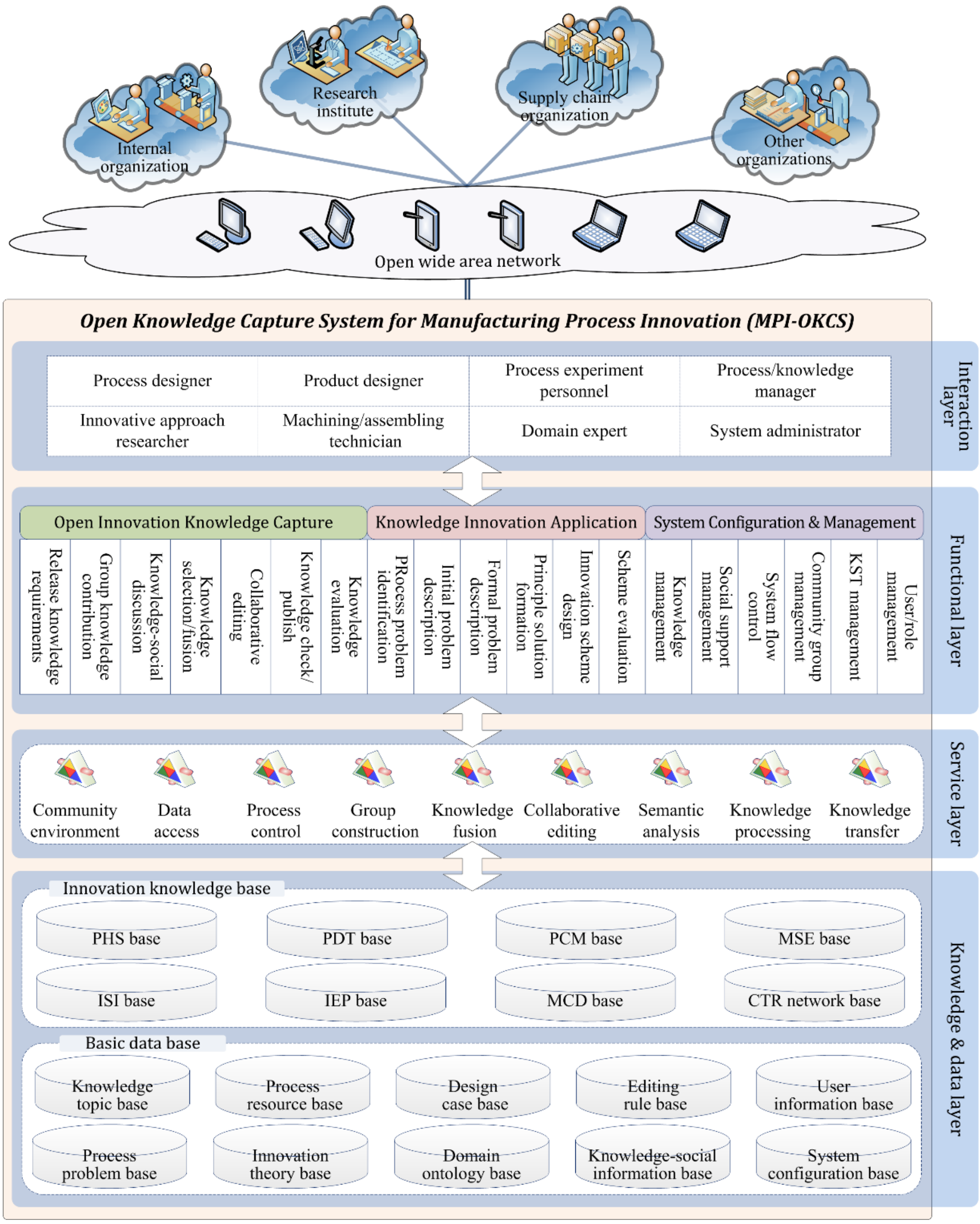

Figure 5. The system architecture of *MPI-OKCS*.

5.2. An Illustrative Example of Welding Process Innovation Knowledge Capture and Application

Welding technology is widely used in the manufacture of aerospace vehicles, electronic precision instruments, pressure vessels and so on. With the complexity and diversification of product requirements, the specific process issues to be solved in welding technology are also increasing. In the following, we take welding process innovation as an example to illustrate the concrete process of open innovation knowledge capture.

Figure 6 presents the procedures of knowledge capture for the circuit board welding process problem-solving of an electronic device. Firstly, the system publishes knowledge topics and problem-solving requirements, then notifies the related knowledge–social users. According to the situation of process problem solving, multiple types of innovation knowledge can be included: PCM, MSE, ISI, et al. Here, the knowledge type of process contradiction is selected as required in this round of knowledge capturing (as shown in Part 1 of Figure 6).

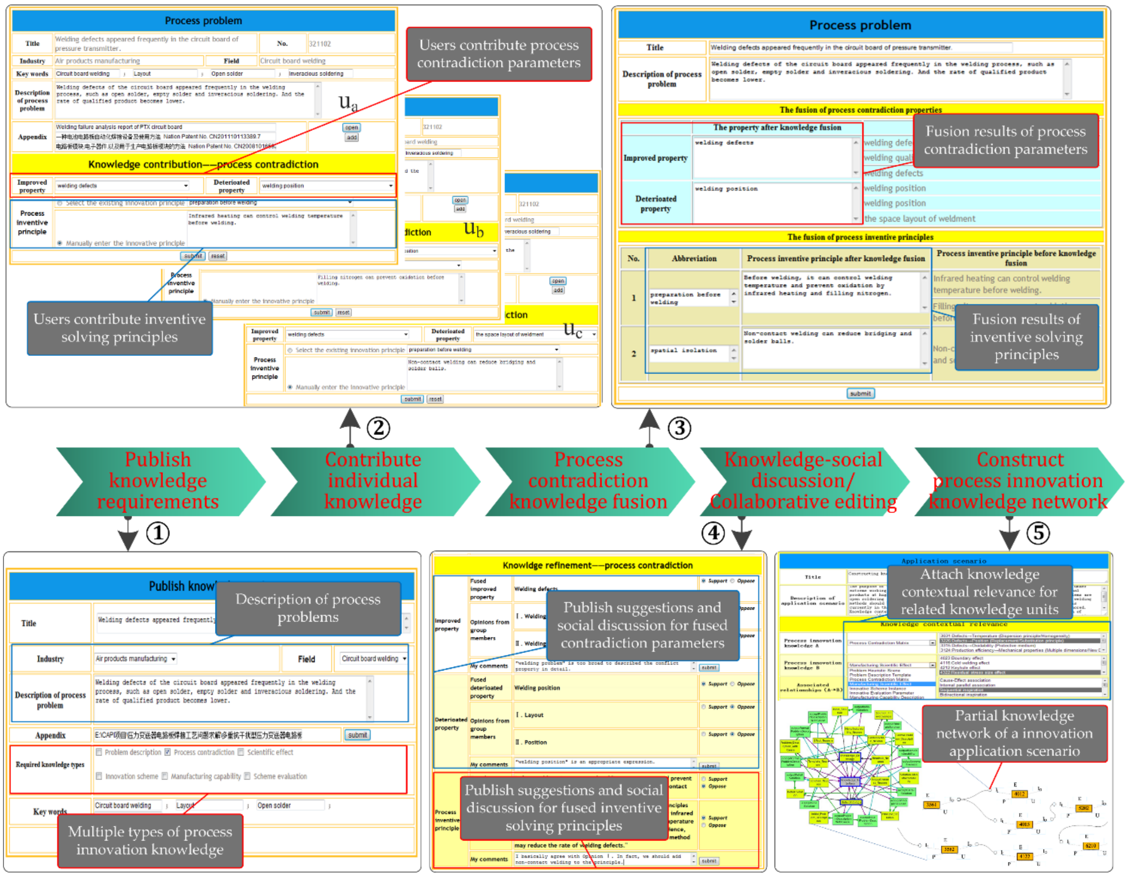

Figure 6. An instance of welding process innovation knowledge capture process. Part 1: Publish knowledge requirements; Part 2: Contribute individual knowledge; Part 3: Process contradiction knowledge fusion; Part 4: Knowledge-social discussion/Collaborative editing; Part 5: Construct process innovation knowledge network.

Those interested users are formed into the knowledge contribution group, then they discuss the knowledge topics and exchange views, and contribute their individual knowledge according to the corresponding knowledge templates. In Part 2, three members u_a, u_b and u_c have respectively contributed their process contradiction knowledge, which contain contradiction parameters and corresponding inventive solving principles. Three pairs of process contradiction parameters are as follows: P_a = <*welding defects → welding position*>, P_b = <*welding quality → welding position*> and P_c = <*welding defects → the space layout of weldment*>. And three natural language descriptions of inventive solving principles are as follows: D_a = {*Infrared heating can control welding temperature before welding*}, D_b = {*Filling nitrogen can prevent oxidation before welding*}, and D_c = {*Non-contact welding can reduce bridging and solder balls*}.

Subsequently, the above process contradiction knowledge is further fused together, as illustrated in Part 3 of Figure 6. According to the relationships of process terms ontology, three process parameters to be improved are fused into a result for the strengthening process parameter, *welding defects*. Similarly, the fusion result of the weakening process parameter, *welding position*, is obtained. Thus, the fused process contradiction parameters can be expressed as P_F = <*welding defects → welding position*>. Meanwhile, the system will extract the logical form triples of three innovation principle descriptions. From the extraction results in Figure 7, P_a and P_b have the specific semantic association, and they can form a fused semantic graph. Furthermore, with the support of process resources and knowledge of the general platform *pi*Pioneer, a fusion result of innovation principle descriptions can be formed using the semantic elements reconfiguration method. The fusion results are described as follows: D_F = {*By combining the use of infrared heating and filling nitrogen before welding, the welding temperature can be effectively controlled and the oxidation can be prevented*}. Figure 7 shows the fusion process of process innovation principle descriptions.

In a knowledge–social community, the preliminary fused process contradiction knowledge will be transferred to the credible knowledge refinement group formed with high *KST* members. Refinement members can publish revision suggestions and have a chance to get the write lock. Through knowledge–social discussion and multiple rounds of collaborative editing, the refined welding process contradiction knowledge for this knowledge topic/problem-solving is captured. In the same way, the capture procedures of other knowledge types are basically consistent with process contradiction.

Parts 1–4 of Figure 6 give the description for innovation knowledge capture of PCM type. Similarly, other types of process innovation knowledge units can also be captured by this way. When the number of process innovation knowledge units is sufficient, knowledge contextual relevance can be attached to the related units to form a specific knowledge network, which has a certain problem-solving ability in the semantic environment. Based on the published application scenario, knowledge–social users can contribute their individual knowledge contextual relevance by selecting knowledge types, knowledge entries, and the corresponding associated relationships, as shown in Part 5 of Figure 6. Correspondingly, innovation knowledge network construction for a specific innovation application scenario needs not only a large number of multi-type knowledge units, but also the new round of knowledge–social members' collaborative editing based on collective intelligence. In this case study, after about six months of open knowledge capture and welding knowledge accumulation in the pre-research stage, an innovation knowledge network for problem solving of circuit board welding was built in the *MPI-OKCS*. Part 5 of Figure 6 gives a partial knowledge network for the above innovation application scenario, which currently contains 223 refined knowledge units. Among them, a welding process contradiction matrix is captured, as illustrated in Figure A1 and Tables A1 and A2. With the aid of the innovation application module of *pi*Pioneer, the captured innovation knowledge units and knowledge networks have played an effective role in inspiring the process problem-solving for development of a new-type pressure sensor.

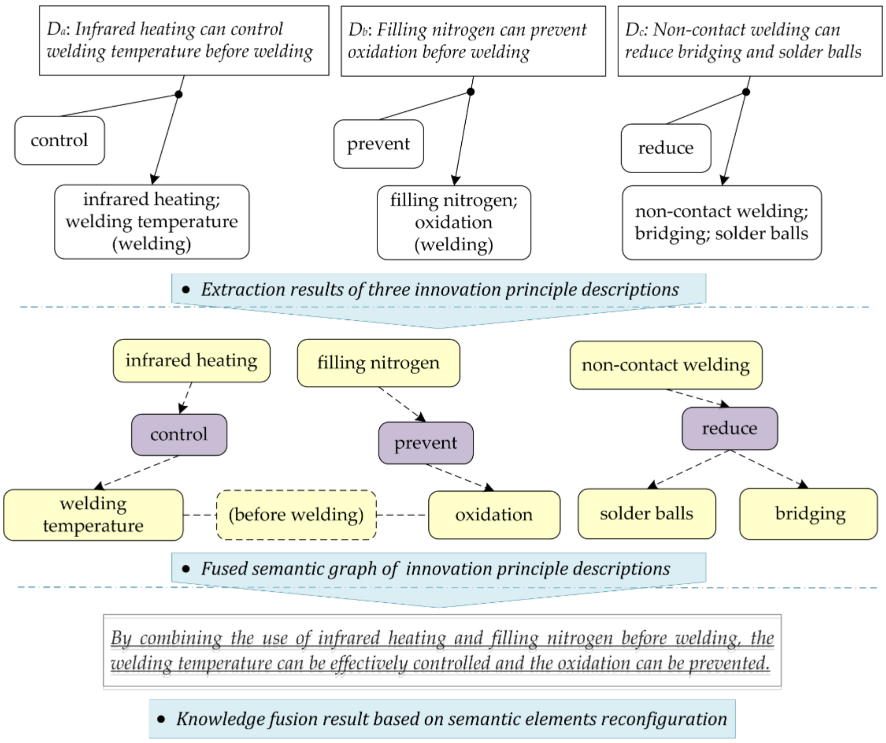

Figure 7. A fusion example of process innovation principle descriptions.

6. Conclusions and Implications

Manufacturing process innovation has been recognized as a key factor for reducing production costs, improving product quality, and enhancing sustainable competitive edge. Nevertheless, in the implementation of knowledge-driven CAPI, an important challenge that must be faced is how to effectively capture the structured, formalized, and associated innovation knowledge from empirical knowledge owners. In this paper, we have presented an integrated approach for processing innovation knowledge capture based on collective intelligence. Some of the main contributions of this research are listed below:

- By considering the multi-type knowledge organization in innovation design and building a knowledge–social community, a novel holistic knowledge capture paradigm of PIKC-CI is proposed, which can realize the transformation from individual empirical knowledge to public refined knowledge in an open environment.
- Based on the domain ontology constraints, a multi-source process innovation knowledge fusion algorithm based on semantic elements reconfiguration is raised, with the corresponding semantic conflict resolution rules. This algorithm can effectively support preliminary automatic fusion for the contributed knowledge.
- A collaborative editing strategy based on knowledge lock and *KST* is applied to the iterative refinement of process innovation knowledge, which ensures that refined knowledge embraces the collective intelligence of knowledge–social users.

Potential future studies related to this work are as follows. Firstly, in addition to the current static knowledge network for specific application scenarios, we are interested in studying how to construct the innovation problem-oriented dynamic knowledge network. Secondly, we will expand our approach to the automatic knowledge capture from problem-solving schemes of the process planning system, and manufacturing process-related text of the cloud manufacturing platform. Moreover, from the perspective of knowledge application, it is worth exploring how to realize just-in-time knowledge recommendations for innovation design life cycle.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix

See Figure A1 and Tables A1 and A2.

		The weakening process parameters												
		1	2	3	4	5	6	7	8	9	10	11	12	…
The strengthening process parameters	1			<7>							<7>	<7>		
	2	<7,9,10>	<8>	<3>			<6>							
	3											<7>		
	4	<7>						<1,4>						
	5		<6,3,2,10>		<1,2,8>									
	6			<3,6>										
	7				<4>									
	8													
	9	<7>		<10>					<6>		<9,10>			
	10	<9>	<9>										<3,8>	
	11				<7>	<2>	<6>	<2,8>	<5>	<7>	<9>			
	12		<3,8>									<3,8>		
	…													

Figure A1. Welding process contradiction matrix.

Table A1. Contradiction parameters of welding process.

No.	Parameters	Explanations
1	Material	Physical and chemical properties of materials
2	Mechanical properties	Stress, pressure, tensile strength etc.
3	Thickness	Thickness range of different materials can be welded
4	Strength	Mechanical strength after welding
5	Shape	Break/joint form, welding wire size, weld shape/aspect ratio, arc spacing etc.
6	Welding position	Butt contact, angular contact, lap joint, downward welding, vertical, horizontal and inverted welding, constraint degree
7	Temperature	Preheat temperature, heat treatment temperature, cooling temperature, temperature distribution etc.
8	Power	Welding current, arc voltage, power supply
9	Speed	Welding speed, wire feed speed, wire melting speed, cooling rate etc.
10	Oxidability	Heat input, weld/base metal oxidation
11	Welding defects	Appearance defects, surface defects, cracks, incomplete penetration, not fusion etc.
12	Production efficiency	Welding utilization, product efficiency
…	…	…

Table A2. Contradiction solving principles of welding process.

No.	Principles	Explanations
1	Separation/detachment/compromise	a. Divide objects into separate parts; b. Make the object detachable; c. Increase the object segmentation.
2	Preparation before welding	a. The choice and treatment of the crevasses form; b. Pre-calculation processing.
3	Change one-dimension to multi-dimension (new dimension)	a. The material motion in the form of point, one-dimensional, two-dimensional, three-dimensional spatial distribution or conversion; b. Replacing single layer structure with multi-layer structure; c. Incline, side, or invert the object; d. To the opposite or adjacent surface of a specified surface.
4	Heat treatment	a. Normalizing; b. Quenching; c. Tempering; d. Annealing.
5	Turn the harm into benefit	a. Use harmful factors (especially the harmful effects of the medium) to gain beneficial effects; b. Harmful factors can be eliminated by a combination of harmful factors and one or more other harmful factors; c. Improve the extent of the

		operation of the harmful factors in order to achieve a state of harmless.
6	Substitution/replacement principle	a. Using two or more welding methods instead of a single welding method; b. The new welding consumables and solder are used to replace the old ones; c. The quantitative and faintness factors, fixed and variable parameters, irregular and regular state are converted into each other in welding; d. Using high energy density energy.
7	Welding material selection	a. Select stainless steel consumables according to ASME specifications; b. Select welding consumables by application or composition.
8	Dispersion principle (homogeneity)	a. The welding consumables should be of the same material (or of the similar mechanical properties) when welding a given object. B. Distract the stress of the stress concentration part.
9	Setting media protection	a. Replacing the normal environment with an inert environment; b. Introduction of a mixture or additive; c. Welding process in vacuum environment.
10	Composite/hybrid principle	a. Transfer from the same material to the mixture; b. Substitute a composition for a similar substance.
…	…	…

Abbreviations

The following abbreviations are used in this manuscript:

CAPI	computer-aided process innovation
CAM	computer-aided manufacturing
CAPP	computer-aided process planning
CAD	computer-aided design
CAE	computer-aided engineering
CAI	computer-aided innovation
ICT	information and communication technology
KC	knowledge contribution
KF	knowledge fusion
KR	knowledge refinement
TRIZ	the theory of inventive problem solving
PIKC-CI	process innovation knowledge capture based on collective intelligence
PHS	problem heuristic scene
PDT	problem description template
PCM	process contradiction matrix
MSE	manufacturing scientific effect
ISI	innovative scheme instance
IEP	innovative evaluation parameter
MCD	manufacturing capability description
KST	knowledge–social trust degree
MPI-OKCS	open knowledge capture system for manufacturing process innovation

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