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A collective intelligence oriented three-layer framework for socialized and collaborative product design

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Abstract: Socialized and collective intelligence oriented product design (SCPD) is a new kind of design pattern emerged under the context of advanced internet technologies and sharing economic trend. It is usually carried out by large numbers of socialized and self-driven participators from different social backgrounds in an open, sharing, self-organized, distributed, and collaborative manner. These characteristics bring SCPD with advantages such as rich design resources, high innovation potentials, deep connection with customer-centric markets, etc., but the characteristics also cause the problems of low efficiency and low reliability during the collaborative design process of SCPD. To mitigate these problems, a collective intelligence oriented three-layer SCPD framework is established. The first layer focuses on design task decomposition and subtask analysis. The second layer focuses on generating alternative design solutions for the subtasks using a customized Blackboard model. The third layer focuses on identifying the most preferred solution using a fuzzy VIKOR algorithm driven consensus reaching model. The SCPD framework is able to support orderly interaction, mutual inspiration, group decision making, and participation stimulation among the socialized participators. In this way, the framework provides a more systematic and efficient approach to utilize the CI from SPs for product design, and thus enlarges the application scope of SCPD pattern from software and small-scale physical products to relatively complicated and high-value physical products. The operability of the framework is demonstrated through an innovative 3D printer design project.
Keywords: collective intelligence; socialized design; collaborative design; Blackboard model; consensus reaching; fuzzy VIKOR algorithm

1. INTRODUCTION

Collective intelligence (CI) generally indicates the group intelligence performance that emerges through information sharing, collaboration, and competition among diverse groups of individuals (Bücheler et al., 2010)(Maher et al., 2010, Trappey et al., 2015). Nowadays, advanced internet and social media technologies, and sharing economic trend boost the development of CI oriented product design (Gregg, 2010). For example, *Wikipedia*, *Threadless* (crowdsourcing garment design), *Local Motor* (crowdsourcing vehicle design), and may successful opensource software projects have shown that the CI of socialized, self-driven and relatively loosely connected individuals could generate decent design results under proper organization and management mechanisms(Panchal and Le, 2014). Here, this new kind of design project development pattern characterized by socialized participators (SP) and CI oriented execution process is defined as socialized and collaborative product design (SCPD).

The most noteworthy characteristic of SCPD is that the project is carried out by large numbers of SPs from different social backgrounds in a CI oriented, open, sharing, self-driven, and self-adaptive manner (Yang and Jiang, 2020a). This characteristic brings SCPD with many advantages, such as rich design resources (Simula and Ahola, 2014), high innovation potentials, deep connection with customer-centric markets, and relatively lower product design costs (Kohler et al., 2009). However, the characteristic also brings problems such as how to guarantee orderly communication and mutual inspiration among the SPs, how to support and manage individual solutions generation and collection, how to aggregate the individual solutions into collective solutions, and how to guarantee the participation motivation of the self-driven SPs, especially when they collaborate under asynchronous, distributed, and decentralized environment(Niu et al., 2019). All these problems lead to the situation that SCPD approach are usually uncontrollable and unreliable compared with centralized design approach, and are currently only applied in information products, software products, small scale and low-value physical products (Panchal and Le, 2014).

To address the aforementioned problems, a CI oriented three-layer framework is established to support the execution of socialized and relatively complicated design project. Specifically, **the first layer** decomposes relatively large and complicated design task into small and more operable subtasks, and analyzes the execution sequence and SCPD feasibility of the subtasks. **The second layer** uses a Blackboard model with customized components to organize and control the collaborative design process of the solutions for the subtasks. It is able to support SPs' interaction and mutual inspiration, and at the same time promotes the participation motivation of the self-driven SPs by distributing the profit of the design project to the SPs according to their contributions. **The third layer**, driven by an interval valued fuzzy VIKOR algorithm based consensus reaching model, focuses on identifying the most preferred design solutions based on the collective judgments of the SPs. All together, the three-layer framework provides an operable execution scheme to develop relatively large and high-value design projects based on the CI from SPs, and at the same time it improves the efficiency and reliability of the collaborative design process.

The rest of the paper is organized as follows. Section 2 introduces the researches related to the establishment of the SCPD framework. Section 3 demonstrates the detailed implementation techniques of the framework. Section 4 verifies the operability of the framework through an innovative 3D printer design project, Section 5 discusses the contributions and limitations of the research, and draws a conclusion.

2. Related works and research gaps

2.1 CI oriented product design

Generally, CI oriented product design indicates the design process that extracts, combines, and utilizes the design ideas, expertise, experiences, etc. from diverse groups of co-designers through mass information sharing, collaboration, competition, and group decision making(Trappey et al., 2015, Flores et al., 2015) (Maher et al., 2010). The commonly used CI oriented product design approaches are listed below.

Multi-agent based approach. Multi-agent system contains diverse group of distributed software components or agents each of which has independent functionality, and together these agents can solve complicated tasks that beyond the capability of any of them (Koźlak et al., 2018). Based on these characteristics, multi-agent system has been used for organizing the designers from different platforms to collaborate on the same design project. For example, Trappey et al. developed a novel architecture of JADE-based multi-agent system to support the communication and cooperation in distributed environments for collaborative IC product design (Trappey et al., 2009). Juan et al. proposed a process oriented multi-agent system to support the cooperation among heterogeneous workgroups during concurrent new product design process in computer network environment (Juan et al., 2009). Huang et al. developed an agent-based intelligent workflow system, where the agents can be modified to control the workflow function according to specific requirements, to support the collaboration during product design in distributed network environment (Huang et al., 2006). Sun et al. developed a multi-agent based current engineering system to support collaboration during product design and manufacturing planning among geographically distributed customers and suppliers(Sun et al., 2001).

Machine learning based approach. In this web 3.0 era, where huge amount of individuals are expressing their own ideas and knowledge about the products they concern on the internet, machine learning techniques are widely applied to extract and combine useful information from online individuals into CI to support design solution generation and design decision making. For example, Li et al. used machine learning techniques to continuously collect and analyze large amount of online affective responses from consumers to identify the most preferred design elements(Li et al., 2018). Wang et al. utilized Long short-term memory model and conditional random field to translate customer requirements from e-commerce websites into design parameters(Wang et al., 2018). Tsapatsoulis and Djouvas established a deep learning approach to extract the sentiment responses of consumers on commercial products from social media short texts(Tsapatsoulis and Djouvas, 2019).

Crowdsourcing approach. Crowdsourcing design is an internet-based collective problem-solving and innovation model aiming at seeking new ideas and solutions from SPs to increase the innovation capabilities of a limited number of internal experts(Simula and Ahola, 2014). After the SPs submit their individual solutions, the SPs whose solutions are accepted would be rewarded, and the copyright of the accepted solutions would be transferred to the project holders. During the process, different kinds of mechanisms could be used for solution selection. For example, *Threadless* selects through voting, and the *Amazon Mechanical Turk* selects directly by the project holders(Niu et al., 2019). However, crowdsourcing design model also has problems. For example, the SPs usually work competitively and independently when generating their own individual solutions, therefore they seldom communicate with or inspire each other, and this leads to the situation that each individual solution only represents the knowledge of its contributor not the entire group (Forbes and Schaefer, 2018). On the other hand, the commonly used organization mechanisms in crowdsourcing are usually inefficient for complex tasks where multiple individual solutions should be combined together.

Opensourcing approach. Opensource design projects are usually conducted voluntarily by SPs on opensource platforms. The SPs usually do not receive direct economic benefits for their contribution, and the design results are available to the public for using, modifying, and redistributing with no charge (Hars and Ou, 2002). During opensource design process, a SP could post his original design on the opensource platform, and then other SPs could made their modifications to the original design and submit the modifications to the original designer, and the original designer would decide whether or not to merge the modifications into the original design. Besides, other SPs can also post a new design developed on the basis of the original design. Opensource approach is mainly successful for software projects(Merilinna and Matinlassi, 2006) and a few physical product projects (e.g. *RepRap* 3D printer, *MK2* robot arm). However, it has a limitation that most projects are mainly contributed by the original designer himself and not the crowd, therefore does not fully explore the power of CI.

It can be seen that all these approaches have their advantages and applicable situations for CI oriented product design. However, how exactly to directly mobilize and organize large number of SPs and utilize their CI for collaborative design task still requires further study.

2.2 Blackboard model

Blackboard model is a structured problem-solving procedure which starts with a problem description and ends with solutions generated cooperatively by multiple knowledge sources. It has mainly three components, including Blackboard, Knowledge source, and Control module (Nii, 1986). The Knowledge sources, which cannot directly communicate with each other, provide resources to solve the problem. The Control modules control the problem solving process with predefined rules and constraints (Carver and Lesser, 1994). The Blackboards are databases that can be read by all the Knowledge sources and Control modules but can be only modified by Control modules.

Blackboard model based problem solving process is dynamic and incremental. After a target problem is published on the Blackboard, the Knowledge sources submit their resources to the Blackboards through the Control modules when their resources are useful to the current problem solving progress. Eventually, the problem would be solved piece by piece by all the Knowledge sources under the control of the Control modules(Lander et al., 1996).

The strength of Blackboard model lays in its capability to support the orderly cooperation among multiple heterogeneous Knowledge sources, and it can be effective in exploring the solution for complex and ill-structured problems. Further, the components of a Blackboard model can be customized according to the problems to be solved (Lou et al., 2012) (Roy and Liao, 1998). However, currently few researches are devoted on using Blackboard model to organize collaborative design process among human Knowledge sources, therefore how to customize the three components (especially the Control modules) for SCPD requires further study.

2.3 Consensus reaching process

Consensus reaching process (CRP) is a method to use CI from multiple human experts for decision making (Kacprzyk and Zadrożny, 2010). It is a dynamic and iterative process during which experts gradually bring their individual opinions closer enough to an acceptable level(Cabrerizo et al., 2010). CRP can be roughly separated into two phases: selection phase and consensus reaching phase (Pérez et al., 2014). In the selection phase, firstly the individual opinions from all the experts would be aggregated into a group opinion, and then exploited into detailed group decision result. In the consensus reaching phase, consensus degree of the group opinion (i.e. the level of consistency among all the individual opinions) and proximity degree of each expert (i.e. the level of consistency between an individual opinion to the group opinion) would be calculated, and the experts with low proximity degree would be given feedback advices to reconsider their individual opinions to eventually improve the consensus degree. The two phases usually repeat a few rounds until a final group opinion with an acceptable level of consensus degree has been reached (Cabrerizo et al., 2010).

Traditionally, the concept of consensus implies hard consensus, i.e. strict and full consistency among all the experts' opinions(Ben-Arieh and Easton, 2007). However, in SCPD projects, design decisions are usually made together by loosely connected and self-driven SPs, therefore it is difficult and unnecessary to reach hard consensus among the SPs. Hence, soft consensus is applied in our SCPD framework, indicating that consensus can be considered reached when a threshold level of agreements among the experts have been reached(Chiclana et al., 2001, Herrera-Viedma et al., 2007, Herrera-Viedma et al., 2002).

It can be seen that CRP is suitable for design solution selection, not only because the result of CRP represent the collective judgments of SPs, but it also gives a change to the SPs, who has the roles of both designer and consumer, to fully express their different individual preference through communication and negotiation, and thus helps the project stakeholder to better identify the design solution most preferred by the market.

Until now, many researches have been devoted to improve the usability of CRP models (Herrera-Viedma et al., 2007, Alonso et al., 2010)(Pérez et al., 2018)(Dong et al., 2018). However, these researches are mainly focused on single criterion situation(Pérez et al., 2018, Kacprzyk and Zadrożny, 2010, Dong et al., 2018), therefore cannot fully satisfy the complex SCPD decision making tasks where multiple criteria need to be concerned.

2.4 Fuzzy VIKOR algorithm

VIKOR algorithm was developed to generate compromise solution in multi-criteria decision making problems. It focuses on ranking a set of alternatives based on various and sometimes conflicting decision criteria with a particular indicator of "closeness" which indicates the distance from each alternative to the "ideal" (i.e. the alternative with best scores for each criterion)(Opricovic and Tzeng, 2007, Opricovic and Tzeng, 2004). Many researches have been conducted to study the advantages and applicable scenarios of VIKOR. For example, Opricovic and Tzeng compared VIKOR with TOPSIS(Opricovic and Tzeng, 2004). Opricovic and Tzeng compared VIKOR with ELECTRE, TOPSIS, and PROMETHEE(Opricovic and Tzeng, 2007). Chu et al. compared VIKOR with Simple Average Weight method(Chu et al., 2007). Ameri et al. compared VIKOR with Compound Factor method, Simple Average Weight method, etc. (Ameri et al., 2018)The results of these researches demonstrate that VIKOR has relatively better distinguishing ability (i.e. easier to assess similar alternatives) (Chu et al., 2007), and the ranking solution it provides seeks balance between minimizing the distance to the ideal and maximizing the distance to the negative ideal, and at the same time consider the weights of these distances(Opricovic and Tzeng, 2004). Based on these characteristics, it can be seen that VIKOR would empower the original CRP with the capability of handling multi-criteria situation, and the compromise solution it provides is more suitable to the nature of soft consensus than the original score comparing method applied in CRP (Chiclana et al., 2001).

However, the input of VIKOR calculation is a matrix which contains the utility scores of each alternative from the perspectives of multiple criteria, but it is difficult for SPs who usually do not have professional training to accurately provide such scores, especially when there are many alternatives and criteria to be considered at the same time. Therefore, fuzzy sets theory, which is capable of handling uncertainties in systematic and mathematical manner (Shemshadi et al., 2011)(Sanayei et al., 2010), should be applied in VIKOR to mitigate the influence of the subjective and vague inputs from SPs.

3. METHODOLOGY

In this section, the SCPD framework and its enabling techniques are established. The framework contains three layers, and the outputs of upper layers are the inputs of lower layers, as shown in Figure 1.

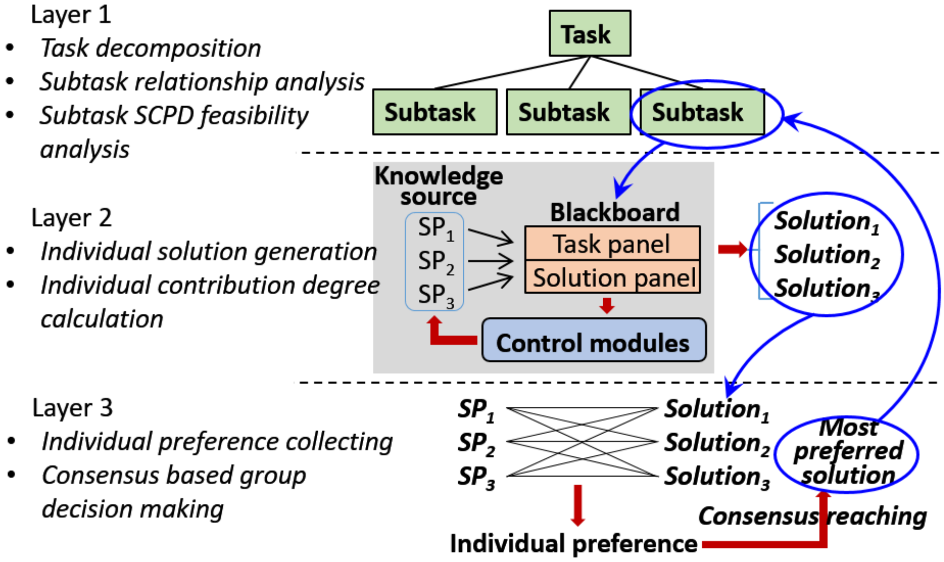

Fig. 1. The three-layer structure of the SCPD framework

3.1 First layer, task decomposition and subtasks analysis

On one hand, not every design tasks are suitable to be developed through SCPD approach. On the other hand, large and complicated design task would have higher requirement on group cooperation, designer participation enthusiasm, etc., and these are not the strength of SCPD. In this regard, the first layer of the framework focuses on separating a design task into several smaller and more operable subtasks, acquiring the execution sequence of the subtasks, and determining which subtasks are suitable for SCPD approach.

3.1.1 Design task decomposition

Three principles should be followed when decomposing relative larger design task into small subtasks.

Small scale. Each subtask should be small enough and ideally can be accomplished independently by one SP. This would avoid the low efficiency and potential chaos during the cooperation among multiple SPs who do not know each other.

High modularity. Each subtask should have high degree of cohesion within itself, and low coupling between each other. This helps to make the subtasks easier to be accomplished independently and concurrently.

Clearly defined contents, boundaries, and constraints. This would help to make sure that the solutions developed by different groups of SDs for different subtasks can be easily aggregated.

3.1.2 Subtasks relationship analysis

Analyzing the dependency relationship among the subtasks is important for making the optimal subtask execution sequence. It also helps to reduce the chance of rework and therefore maintain the participation enthusiasm of the SPs.

Here, a simplified Critical Path Method (Kohler, 1975) is applied to arrange subtasks' execution sequence based on their dependence relationship, and an example is used for demonstration. **Firstly**, the example task is decomposed into seven subtasks labeled as *A*, *B*, …, *G*, as shown in Figure 2(a). **Secondly**, the dependency matrix of all the subtasks is drawn, as shown in Figure 2(b)-Stage1. According to the matrix, the subtasks whose development depend on no other subtasks would be put in Stage 1 and be developed first. Then, draw the dependency matrix of the rest subtasks, and the subtasks whose development depend on no other subtasks would be put in Stage 2, as shown in Figure 2(b)-Stage2. Keep doing the same procedure until no subtasks left. **Thirdly**, express the execution sequence of the subtasks in the form of critical path graph according to the Stages acquired above, as shown in Figure 2(c).

3.1.3 Subtask SCPD feasibility analysis

Not all the subtasks are suitable to be developed through SCPD approach. We suggest using the project feasibility analysis model in (Yang and Jiang, 2019) to determine which subtask should be sent to the next layer for further execution, as shown in Figure 2(d).

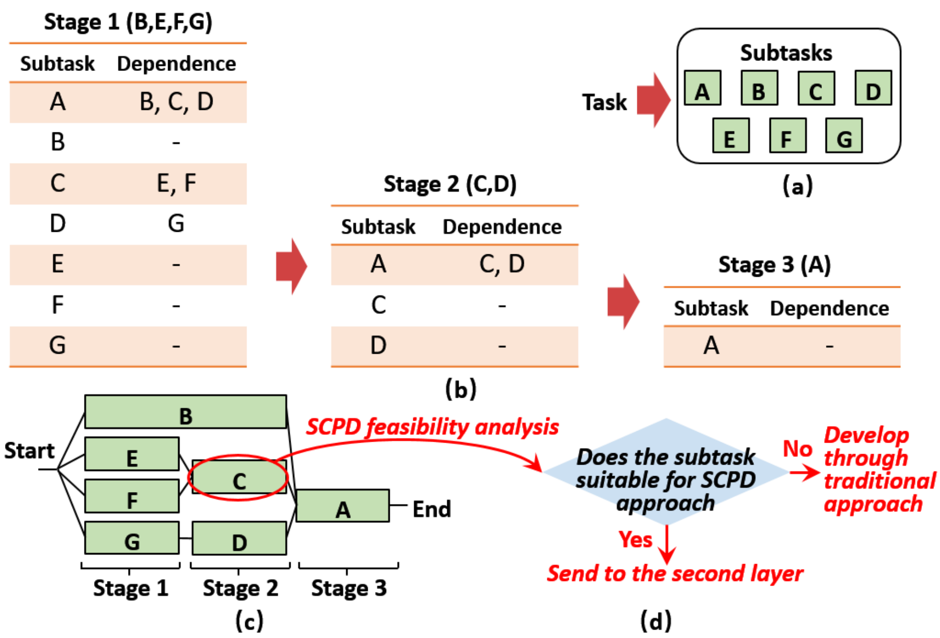

Fig. 2. First layer - Design task decomposition and subtasks analysis

3.2 Second layer, Blackboard model based alternative design solution generation

The second layer uses a customized Blackboard model developed on the basis of our previous work (Yang and Jiang, 2020b) to support the execution process of iteratively generating alternative design solutions for the subtasks from the first layer through orderly interaction and mutual inspiration among human Knowledge sources.

3.2.1 Blackboard model customization

Here, the Blackboard panels, Knowledge sources, and Control modules are specifically customized for SCPD, as shown in Figure 3.

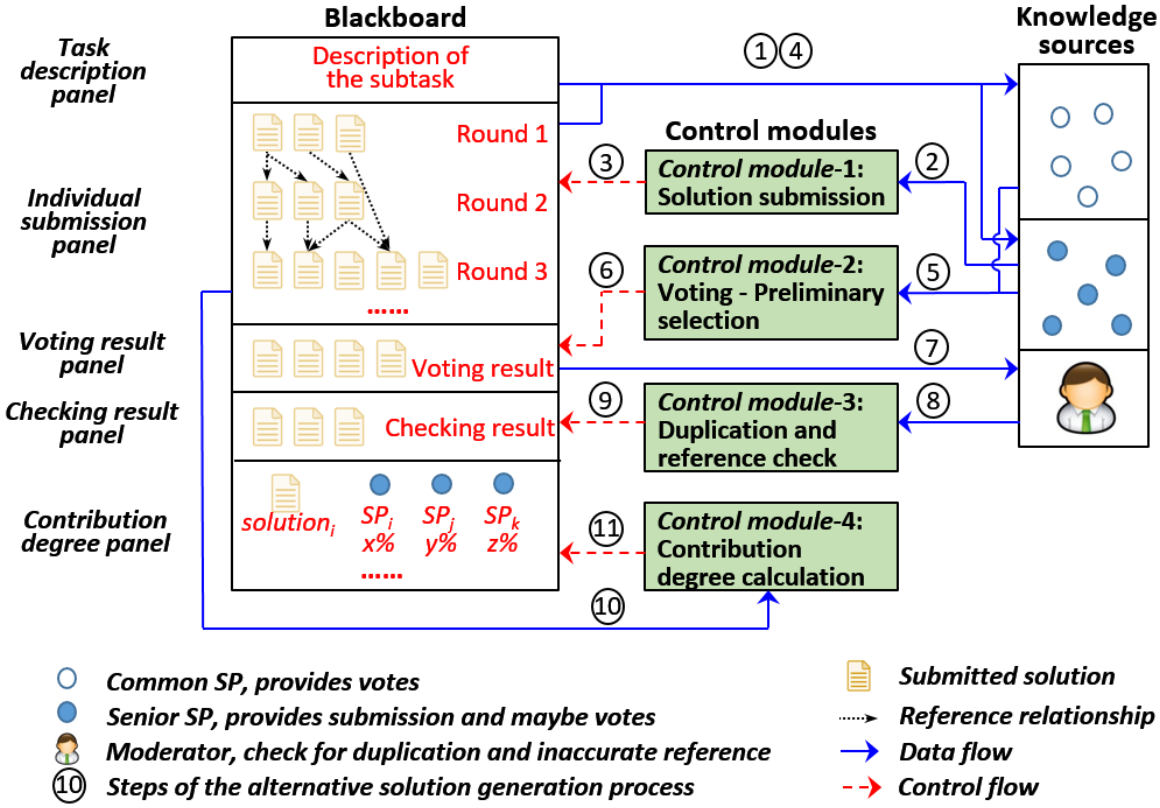

Fig. 3. Second layer – The structure and components of the Blackboard model for alternative solutions generation

Five Blackboard panels. The contents published on the *Task description panel* and *Checking result panel* are the inputs and outputs of layer two, respectively.

- *Task description panel* introduces the detailed contents of the problem to be solved and the constraints to be followed;
- *Individual submissions panel* records all the partial and complete solutions (together with the reference relationships among them) submitted by the Knowledge sources;
- *Voting result panel* records the solutions with highest votes among all the submitted solutions;
- *Checking result panel* records the solutions which pass the duplication and reference check of *Control module*-3;
- *Contribution degree panel* publish the contribution degrees of each SPs for the solutions selected from the third layer.

Three types of Knowledge sources. The Knowledge sources can check the information on the Blackboard panels, but they can only update the information through corresponding Control modules.

- *Common SPs*, the SPs who do not provide design solutions;
- *Senior SPs*, the SPs who provide solutions;
- *Moderator*, which could be the organizer of the design project, is responsible for checking the duplicate solutions and inaccurate reference relationships.

Four Control modules.

- *Control module*-1 for adding solutions on *Individual submission panel*;
- *Control module*-2 for identifying the most preferred solutions according to the votes from SPs, and adding them on *Voting result panel*;
- *Control module*-3 for handling duplicate solutions and inaccurate reference relationships in the voting results, and then adding the checked results on the *Checking result panel*;
- *Control module*-4 for calculating the contribution degrees of each SP for the solutions finally selected in the third layer. An example is shown in Figure 4 which calculates the contribution degrees of the SPs who cooperatively developed $S_{5\text{-}2}$ (i.e. $Solution_{5\text{-}2}$).

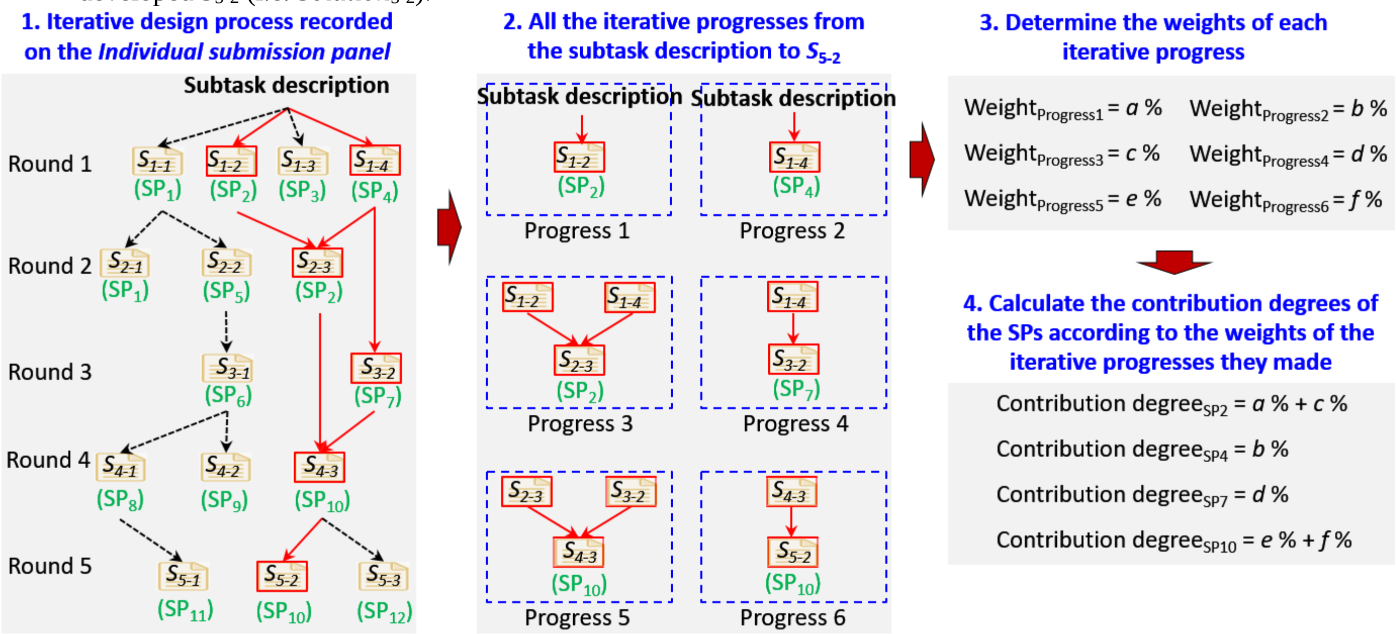

Fig. 4. An example of calculating the contribution degrees of the SPs in *Solution*$_{5\text{-}2}$

3.2.2 The execution process of Blackboard model based SCPD

The Blackboard based SCPD process includes four phases and eleven steps, as shown in Figure 3 and 5. It starts from task description and end up with a set of alternative design solutions.

Phase A. Individual solution generation. The three steps in this phase would repeat a few rounds to ensure adequate indirect interaction and mutual inspiration among the SPs.

- Step 1. SPs read the *Task description panel* and current design progress on the *Individual submission panel*;
- Step 2. *Senior* SPs voluntarily submit their solutions for the subtask to *Control module*-1, the IDs of the previous solutions that they referenced are also attached;
- Step 3. *Control module*-1 updates the information on the *Individual submission panel* according to the submissions.

Phase B. Voting based preliminary selection. This phase is only necessary when too many alternative solutions have been generated in Phase A.

- Step 4. The SPs read the solutions on the *Individual submissions panel*;
- Step 5. The SPs voluntarily submit their votes, which represent their preferences on the solutions, to *Control module*-2;
- Step 6. *Control module*-2 identifies the most preferred solutions according to the votes and publishes the result on the *Voting result panel*.

Phase C. Duplication and reference checking.

- Step 7. *Moderator* checks the solutions on the *Voting result panel* to identify duplicate solutions and the solutions with inaccurate references;
- Step 8. *Moderator* sends the report about duplicate solutions and inaccurate references to *Control module*-3;
- Step 9. *Control module*-3 extracts the solutions on *Voting result panel*, make modifications to these solutions according to the report from *Moderator*, and publishes the modified solutions on *Checking result panel*.

Phase D. Contribution degree calculation.

- Step 10. *Control module-4* checks the design process records of the solutions selected from the third layer, and then
- Step 11. Calculates the contribution degrees of the SPs in the selected solutions, and publishes the degrees on *Contribution degree panel*.

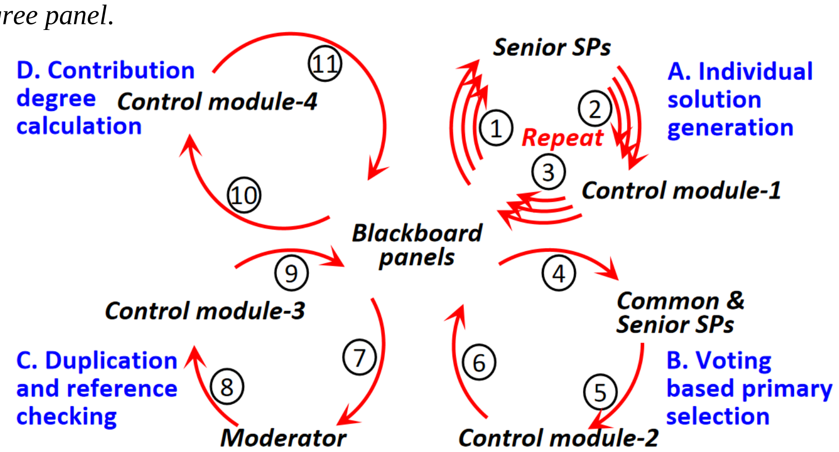

Fig. 5. The execution process and control loops of Blackboard model based SCPD

3.3 Third layer, Fuzzy VOKOR based CRP for solution selection

The third layer uses an interval valued fuzzy VIKOR algorithm driven CRP to identify the most preferred design solution among a set of alternative solutions (denoted as $a_1, a_2, \ldots, a_m$) generated from the second layer according to the consensus among a group of SPs ($SP_1, SP_2, \ldots, SP_n$) based on multiple criteria ($c_1, c_2, \ldots, c_l$). The CRP starts with pairwise comparison values (provided by the SPs) about the alternatives, and ends with a preference order of the alternatives, as shown in Figure 6. Note that the SPs who participate in CRP are not necessarily the same SPs who participate in the Blackboard model.

3.3.1 Input value transformation

Firstly, SPs' preference on the alternatives are collected in the form of pairwise comparison matrixes, and then transformed into utility scores matrix (which is the original input form of VIKOR calculation). The pairwise comparison matrixes are determined by the SPs according to Equation (1), where p_{ij} represents the preference value of a_i over a_j ($i \neq j$), and $p_{ij} + p_{ji} \approx 1$ (i.e. the transitivity constraint (Zhang et al., 2018)).

$$p_{ij} = \begin{cases} 0, & a_i \text{ is absolutly less than } a_j \\ (0, 0.5), & a_i \text{ is less than } a_j \\ 0.5, & a_i \text{ is as good as } a_j \\ (0.5, 1), & a_i \text{ is better than } a_j \\ 1, & a_i \text{ is absolutly better than } a_j \end{cases}$$

(1)

Here, the p_{ij} values are collected in the form of fuzzy interval values as $p_{ij} = [p_{ij}^L, p_{ij}^U]$ where p_{ij}^L and p_{ij}^U are the lower and upper boundaries of p_{ij}. Then, the fuzzy interval valued pairwise comparison information would be transformed into interval valued utility scores in the form of $u_{ik} = [u_{ik}^L, u_{ik}^U]$ with Equation (2), where u_{ik}^L and u_{ik}^U are the lower and upper boundaries of the utility score of a_i from the perspective of c_k. Note that multiple pairwise comparison matrixes provided by a SP from multiple criteria perspectives would be transformed into one utility scores matrix, as shown in Figure 6-①.

$$\begin{cases} u_{ik}^L = \sum_{j=1}^m p_{ij}^L, & j \neq i \\ u_{ik}^U = \sum_{j=1}^m p_{ij}^U, & j \neq i \end{cases}$$
(2)

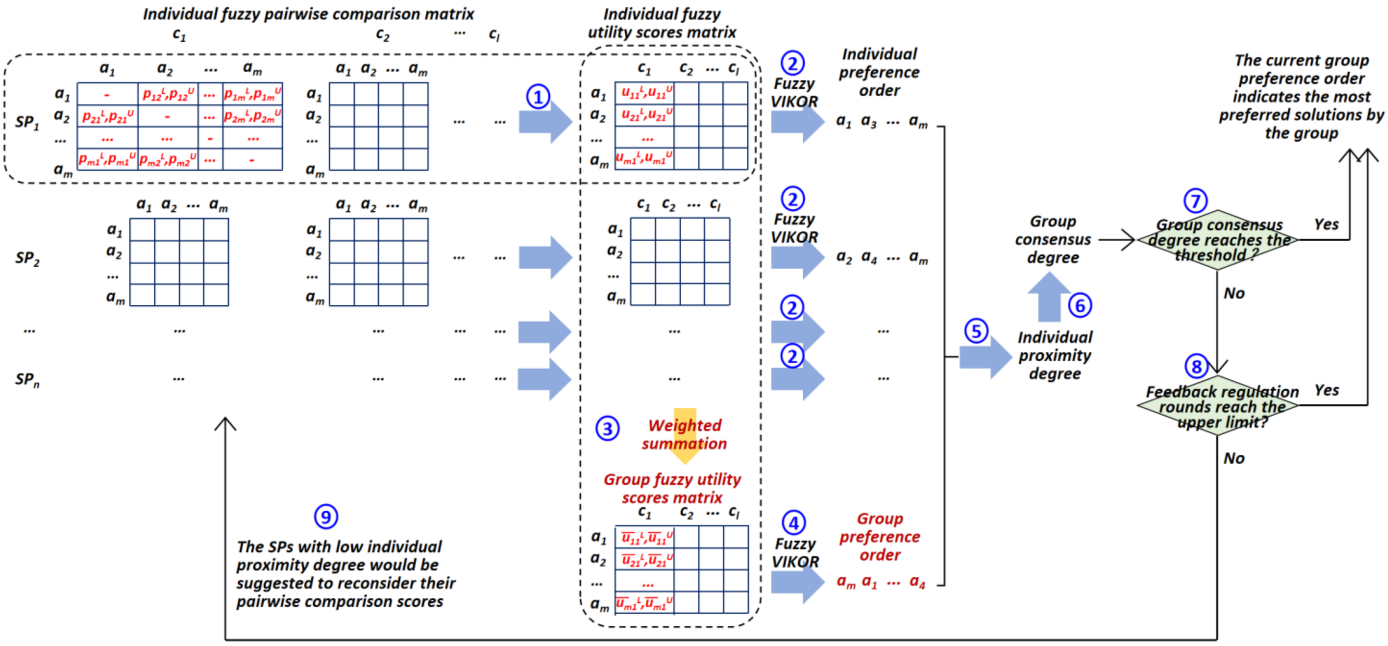

Fig. 6. Third layer - Fuzzy VIKOR based CRP for solution selection

3.3.2 Individual preference order acquiring

The inputs of this subsection are the individual fuzzy utility score matrixes from each SPs, and the outputs are the individual preference orders (of the alternatives) of each SPs, as shown in Figure 6- ②. The process is conducted with interval valued fuzzy VIKOR algorithm (Sayadi et al., 2009). It contains mainly four steps, including *Identifying the positive and negative ideal solution*, *Calculating group utility indicator and individual regret indicator*, *Calculating the Q indicator*, and *Acquiring the preference order of the alternatives*. The detailed calculation process is attached in the Appendix.

3.3.3 Group preference order acquiring

This subsection focuses on acquiring the group preference order which represents the preference of all the SPs. The process contains mainly two steps:

Step 1. Aggregating the individual utility scores matrixes from multiple SPs into a group utility scores matrix. The values in the group utility score matrix are acquired with Equation (3), where $\bar{u}_{ik}^L$ and $\bar{u}_{ik}^U$ represent the lower and upper boundaries of the utility score of a_i from the perspective of c_k; w'_g is the weight of SP_g, and $g = 1, 2, \ldots, n$; u_{ikg}^L and u_{ikg}^U are the u_{ik}^L and u_{ik}^U in the individual utility scores matrix from SP_g. This step corresponds to Figure 6-③.

$$\begin{cases} \bar{u}_{ik}^L = \sum_{g=1}^n w'_g u_{ikg}^L \\ \bar{u}_{ik}^U = \sum_{g=1}^n w'_g u_{ikg}^U \end{cases}$$
(3)

Step 2. Acquiring the group preference order based on the group utility scores matrix. Based on the group utility scores matrix acquired in Step 1, group preference order can be acquired with the same method in 3.3.2. This step corresponds to Figure 6-④.

3.3.4 Feedback regulation for consensus reaching

CRP not only identifies the most preferred solutions, but also tries to reach group consensus among the SPs. This is achieved by identifying the SPs whose individual preference orders are distant from the group preference order, and then suggesting them to reconsider their preference judgments until an acceptable level of consistency among the SPs has been reached. Two indicators which evaluate the aforementioned consistency are proposed, as shown below.

Indicator 1. Individual proximity degree (IPD). In the existing CRP researches, IPD is usually measured by calculating the Euclidean distance between group preference order and individual preference order (Pérez et al., 2018), and the rank orders of all the alternatives are considered equally important. However, our solution selection task is to identify the most preferred solutions, which means the alternative solutions with higher ranks in the preference order are more important. In this regard, an IPD indicator is defined to measure the consistency between an individual preference order and the group preference order, the alternatives with higher ranks in the preference order would have higher weights when calculate the consistency (i.e. top-weightiness characteristic), and larger IPD value indicates higher level of consistency.

$$\mathrm{IPD}_g = \frac{1}{\beta}\sum_{r=1}^{\beta}\frac{\sigma(r)}{r} \quad (4)$$

where IPD_g represents the IPD of SP_g; β indicates the number of top rank alternatives in the preference order that are considered in IPD calculation; $\sigma(r)$ represents how many alternatives from the top r ranks of the individual preference order are same to the alternatives in the top r ranks of the group preference order. An example of IPD calculation is shown in Figure 7.

The value range of IPD is [0, 1]. The situation of IPD = 1 happens when the alternatives in the top β ranks of the individual preference order and the group preference order are the same, and the situation of IPD = 0 happens when the alternatives in the top β ranks of the individual preference order and the group preference order are totally different (the second scenario only happens when $\beta \leqslant m/2$). According to our experience, IPD $\geqslant$ 0.5 is acceptable.

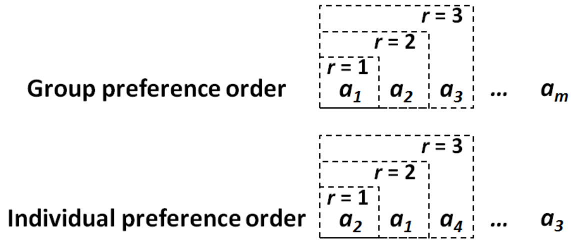

Fig. 7. An example of IPD calculation where β =3 and IPD = 1/3 (0/1+2/2+2/3)

Indicator 2. Group consensus degree (GCD). A GCD indicator is defined to measure the consistency among the individual preference orders from all the SPs. GCD indicator is developed on the basis of IPD indicator, and therefore it also has top-weightiness characteristics. The value range of GCD is [0, 1), and larger GCD value indicates lower group consensus among all the individual preference orders. The value of GCD is always smaller than 1, because the situation of GCD = 1 requires the IPD of all the SPs equal to 0, and this cannot happen. According to our experience, GCD $\leqslant$ 0.5 is acceptable.

$$\mathrm{GCD} = \sqrt{\frac{1}{n}\sum_{g=1}^{n}(1-\mathrm{IPD}_g)^2} \quad (5)$$

Based on the two indicators, the feedback regulation for consensus reaching can be conducted through three steps:

Step 1.Checking the current GCD value. Calculate the current GCD value, and compare it with the GCD threshold determined by the project stakeholder. If the current GCD is lower than the threshold, then the current group preference order would be the final result, and the alternatives in the top ranks of the current group preference order would be considered as the most preferred solutions. If the current GCD is higher than the threshold, then move on to the next step. This step corresponds to Figure 6-⑦.

Step 2. Checking how many rounds of feedback regulation have been conducted. If the feedback rounds have reached the upper limit, then the current group preference order would be considered as the final result. If not, then move on to the next step. This step corresponds to Figure 6-⑧.

Step 3. Feedback regulation. Compare the IPD values from all the SPs, and the SPs with lower IPD values would be suggested to reconsider their pairwise comparison judgments on the alternatives. This step corresponds to Figure 6-⑨.

4. CASE STUDY

Desktop 3D printer is one of the physical design projects that can be developed through SCPD approach (e.g. *RepRap* project(RepRap, 2019)). In this section, an innovative desktop 3D printer design project is used as case study to demonstrate the operability of our SCPD framework.

4.1 Design task decomposition and analysis

Based on the structure and function components of a desktop 3D printer (RepRap, 2019) and the three decomposition principles in Section 3.1.1, the design task of a 3D printer is decomposed into twelve subtasks, as shown in Table 1, and the dependency relationships among the 12 subtasks were analyzed with the method in Section 3.1.2, as shown in Figure 8.

Table 1 Subtasks decomposed from an innovative desktop 3D printer design project

Subtask	Description
A. Basic parameter design	Determine the basic parameters of the printer, e.g. the size of the print space, maximum print speed, single or multiple print head.
B. Mechanical structure design	Determine the mechanical structure, axis motion, kinematic pair, etc. of the printer.
C. Belts & pulleys configuration	Determine the size, types, numbers, position, etc. of the belts and pulleys.
D. Thread rod configuration	Determine the size, types, numbers, etc. of the threaded rod.
E. Extruder configuration	Determine the size, types, numbers, position, etc. of the extruders.
F. Heat bed configuration	Determine the size, max temperature, material, power, etc. of the heat bed.
G. End stops configuration	Determine the size, types, numbers, position, etc. of the end stops.
H. Stepper configuration	Determine the numbers, rated speed, power, position, etc. of the steppers.
I. Controller configuration	Select and configure the compatible controller for the electronics in the printer.
J. Stepper driver configuration	Select and configure the compatible driver for the steppers.
K. Firmware configuration	Select and configure the compatible firmware for the printer.
L. Software configuration	Select and configure the compatible software for the printer.

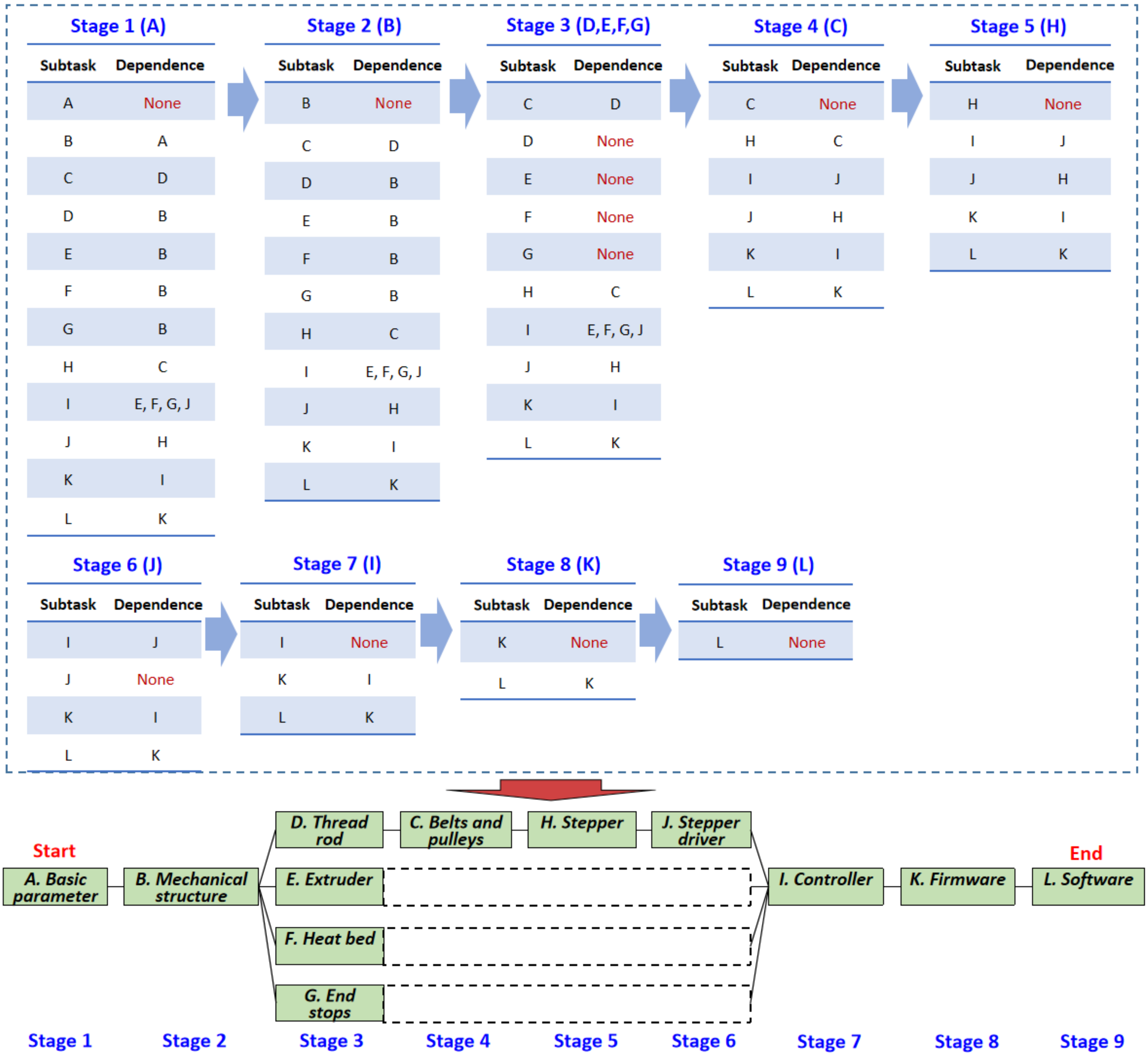

Fig. 8. Dependency relationships among the subtasks

4.2 Alternative design solution generation

This subsection demonstrates the process of using the Blackboard model in Section 3.2 to generate design solution alternatives for *Mechanical structure design* subtask, which is considered feasible for SCPD approach with the method in 3.1.3. During the process, one PhD student participated as *Moderator*, forty other students participated as SP, among which 17 SPs submitted 24 partial/complete solutions. The requirements for the design task, the solutions, the iterative design process, and the contribution degrees of the SPs who collaboratively developed one of the solutions are shown in the left side of Figure 9. Five of the 24 solutions were picked out by *Control module*-2 for further analysis in third layer, and the brief introductions of the five are listed in Table 2.

Table 2 Brief introductions of the solutions selected through voting

Solutions	Introductions
24	Triangular prism structure improves the frame stability; Polar coordinates printing trajectory realized with trolley driven print head has less vibration compared to swing arm print head driven structure in solution 13.

21	Liftable print bed driven by crank connecting rod; Print head driven by crank blocks. Stable frame structure but relatively less printing accuracy in Z axis direction.
22	Delta structure print head driven system enables fast and accurate plane printing; Conveyor belt driven print bed enables continuous printing of small workpieces; Adjustable print bed surface enables reducing the use of print support for workpieces with inclination.
13	Rotatable print bed; Bipolar coordinates printing trajectory driven by gear drive double swing arms; Compact structure and high print space ratio.
18	Rotatable and tiltable print bed supported by spherical hinge, has advantages for printing workpieces in revolving body shape and reducing the use of print support for workpieces with inclination.

4.3 Solution selection

This subsection demonstrates the process of using the CRP model in Section 3.3 to identify the most preferred solutions by the crowd from $solution_{24}$, $solution_{21}$, $solution_{22}$, $solution_{13}$, $solution_{18}$. During the process, seven SPs (SP_1, SP_2, …, SP_7) provided pairwise comparison information about the five design solutions based on the four criteria (c_1, c_2, …, c_4) in Table 3.

Table 3 The criteria used to determine the most preferred design solutions

Criteria	Description	Category
Completion degree (c_1)	Indicates to what extent the solution has completely meet the design requirement	Benefit criterion
Creativity (c_2)	Indicates the creativity and novelty of the design solution.	Benefit criterion
Practicality (c_3)	Indicates whether the design is practical and whether the design solution can be further developed into real product	Benefit criterion
Economic efficiency (c_4)	Indicates whether the designed product could be afforded by normal customers.	Benefit criterion

Firstly, the interval valued fuzzy pairwise comparison information about the alternative solutions from the perspectives of the four criteria was collected from the seven SPs, and the information was recorded in twenty eight matrixes (four matrixes from each SP). The four matrixes from SP_1 are shown in Table 4-7 for demonstration.

Table 4 Interval valued fuzzy pairwise comparison matrix of c_1, provided by SP_1

	***solution*₂₄**	***solution* 21**	***solution* 22**	***solution* 13**	***solution* 18**
***solution* 24**	-	[0.6, 0.7]	[0.2, 0.3]	[0.5, 0.5]	[0.2, 0.3]
***solution* 21**	[0.4, 0.5]	-	[0.2, 0.3]	[0.4, 0.5]	[0.2, 0.3]
***solution* 22**	[0.6, 0.7]	[0.7, 0.8]	-	[0.6, 0.7]	[0.5, 0.5]
***solution* 13**	[0.5, 0.5]	[0.6, 0.8]	[0.3, 0.4]	-	[0.3, 0.4]
***solution* 18**	[0.6, 0.7]	[0.7, 0.8]	[0.5, 0.5]	[0.7, 0.7]	-

Table 5 Interval valued fuzzy pairwise comparison matrix of c_2, provided by SP_1

	***solution* 24**	***solution* 21**	***solution* 22**	***solution* 13**	***solution* 18**
***solution* 24**	-	[0.5, 0.5]	[0.3, 0.4]	[0.3, 0.4]	[0.5, 0.6]
***solution* 21**	[0.5, 0.6]	-	[0.2, 0.3]	[0.3, 0.4]	[0.4, 0.5]
***solution* 22**	[0.7, 0.7]	[0.7, 0.8]	-	[0.6, 0.7]	[0.6, 0.6]
***solution* 13**	[0.7, 0.8]	[0.6, 0.7]	[0.4, 0.5]	-	[0.5, 0.5]
***solution* 18**	[0.6, 0.6]	[0.6, 0.6]	[0.4, 0.5]	[0.5, 0.6]	-

Table 6 Interval valued fuzzy pairwise comparison matrix of c_3, provided by SP_1

	***solution* 24**	***solution* 21**	***solution* 22**	***solution* 13**	***solution* 18**
***solution* 24**	-	[0.5, 0.5]	[0.4, 0.4]	[0.3, 0.4]	[0.3, 0.4]
***solution* 21**	[0.6, 0.6]	-	[0.3, 0.4]	[0.4, 0.5]	[0.5, 0.5]
***solution* 22**	[0.6, 0.7]	[0.5, 0.5]	-	[0.6, 0.6]	[0.5, 0.6]
***solution* 13**	[0.7, 0.7]	[0.5, 0.5]	[0.4, 0.5]	-	[0.4, 0.5]
***solution* 18**	[0.7, 0.7]	[0.6, 0.6]	[0.5, 0.5]	[0.5, 0.6]	-

Table 7 Interval valued fuzzy pairwise comparison matrix of c_4, provided by SP_1

	***solution* 24**	***solution* 21**	***solution* 22**	***solution* 13**	***solution* 18**
***solution* 24**	-	[0.3, 0.4]	[0.5, 0.5]	[0.5, 0.5]	[0.6, 0.6]
***solution* 21**	[0.5, 0.6]	-	[0.6, 0.6]	[0.6, 0.7]	[0.7, 0.8]
***solution* 22**	[0.4, 0.5]	[0.4, 0.4]	-	[0.5, 0.5]	[0.6, 0.6]
***solution* 13**	[0.5, 0.5]	[0.4, 0.4]	[0.5, 0.5]	-	[0.5, 0.6]
***solution* 18**	[0.5, 0.5]	[0.3, 0.4]	[0.5, 0.5]	[0.4, 0.5]	-

And then, the utility scores matrix of SP_1 on the five alternatives covering all the four criteria were calculated with Equation (2) based on the information in Table 4-7, as shown in Table 8.

Table 8 Interval valued fuzzy utility scores matrix of SP_1

	c_1	c_2	c_3	c_4
***solution* 24**	[1.5, 1.8]	[1.6, 1.9]	[1.5, 1.7]	[1.9, 2.0]
***solution* 21**	[1.2, 1.6]	[1.4, 1.8]	[1.8, 2.0]	[2.4, 2.7]
***solution* 22**	[2.4, 2.7]	[2.6, 2.8]	[2.2, 2.4]	[1.9, 2.0]
***solution* 13**	[1.7, 2.1]	[2.2, 2.5]	[2.0, 2.2]	[1.9, 2.0]
***solution* 18**	[2.5, 2.7]	[2.1, 2.3]	[2.3, 2.4]	[1.7, 1.9]

And then, with the interval valued fuzzy VIKOR method demonstrated in Section 3.3.2, the Q values of the five alternatives were calculated as $Q_1 = [0.493, 1]$, $Q_2 = [0.269, 0.911]$, $Q_3 = [0, 0.287]$, $Q_4 = [0.152, 0.464]$, $Q_5 = [0.249, 0.689]$, and thereby the individual preference order (of SP_1) of the five alternatives can be acquired, as shown in the first row of Table 9. During the process, the weights of all the criteria are considered equally as 0.25. The individual preference orders of the other six SPs, acquired with the same method, are also shown in Table 9.

Table 9 Individual preference orders from the seven SPs

	Individual preference order
SP_1	***solution* 22>*solution* 13>*solution* 18>*solution* 21>*solution*24**
SP_2	***solution* 18>*solution* 13>*solution*24>*solution* 22>*solution* 21**
SP_3	***solution* 18>*solution* 22>*solution* 21>*solution* 13>*solution*24**
SP_4	***solution* 18>*solution* 13>*solution*24>*solution* 22>*solution* 21**
SP_5	***solution* 13>*solution* 18>*solution* 22>*solution*24>*solution* 21**
SP_6	***solution* 18>*solution* 22>*solution* 13>*solution* 21>*solution*24**
SP_7	***solution* 18>*solution* 13>*solution* 22>*solution*24>*solution* 21**

When acquiring the group preference order, firstly the interval valued fuzzy utility scores matrixes of all the seven SPs were aggregated with Equation (3) in Section 3.3.3, as shown in Table 10. During the process, the weights of all the SPs are considered equally as 1/7. And then, the group preference order of the seven SPs was acquired with the same method. Currently the group preference order is $solution_{18}$> $solution_{13}$> $solution_{22}$> $solution_{24}$> $solution_{21}$.

Table10 Interval valued fuzzy utility scores matrix of the group

	c_1	c_2	c_3	c_4
***solution* 24**	[1.35, 1.77]	[1.63, 1.73]	[1.53, 1.73]	[1.87, 2.14]
***solution* 21**	[1.03, 1.46]	[1.11, 1.75]	[1.82, 1.96]	[2.13, 2.36]
***solution* 22**	[2.11, 2.27]	[2.57, 2.71]	[2.14, 2.34]	[1.83, 1.94]
***solution* 13**	[1.73, 2.06]	[2.22, 2.47]	[1.92, 2.31]	[1.87, 2.13]
***solution* 18**	[2.71, 2.91]	[2.24, 2.44]	[2.58, 2.69]	[1.56, 2.04]

And then, the IPDs of each individual preference orders and the GCD among all the individual preference orders are calculated with Equation (4) and (5), and $IPD_1 = 0.5$, $IPD_2 = 0.89$, $IPD_3 = 0.72$, $IPD_4 = 0.89$, $IPD_5 = 0.67$, $IPD_6 = 0.72$, $IPD_7 = 1$, and GCD = 0.28. During the process, β was set as 3 indicating that only the top three alternatives with highest ranks in the preference orders were considered when calculating the indicators. According to the results, an acceptable level of soft consensus had been reached among the SPs (i.e. GCD $\leqslant$ 0.5), and therefore the current group preference order was considered as the final result. However, if the stakeholder believes it is necessary, SP_1 could be asked to reconsider his/her preference opinions because he/she has the lowest IPD value.

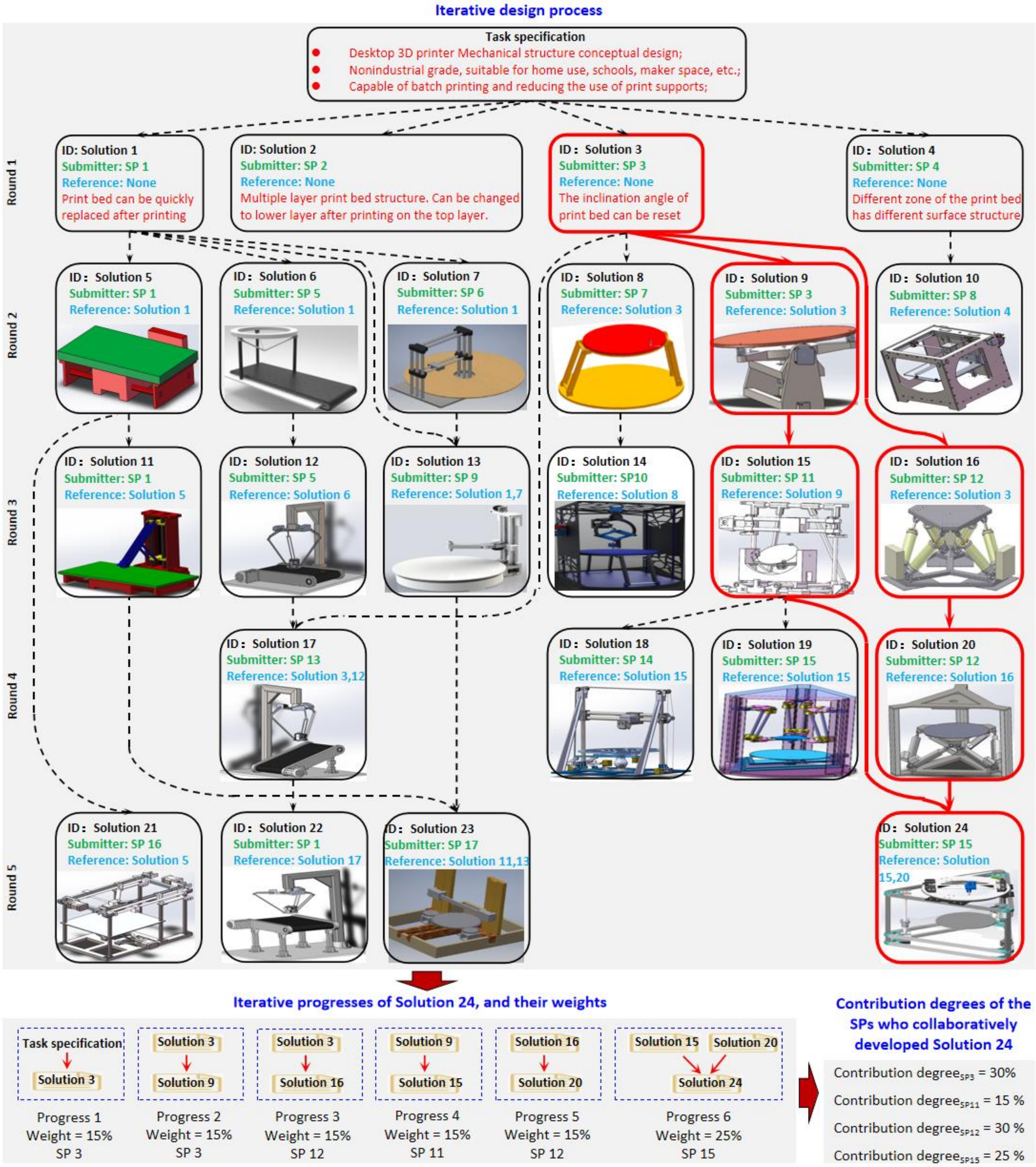

Fig. 9. The iterative design process of *Mechanical structure design* subtask, and the contribution degree analysis of the SPs who collaboratively developed Solution 24

A Web APP demo embedded with the Blackboard and CRP models is developed to support the design interaction among Knowledge sources. The key operation interfaces for SPs are shown in Figure 10 and 11.

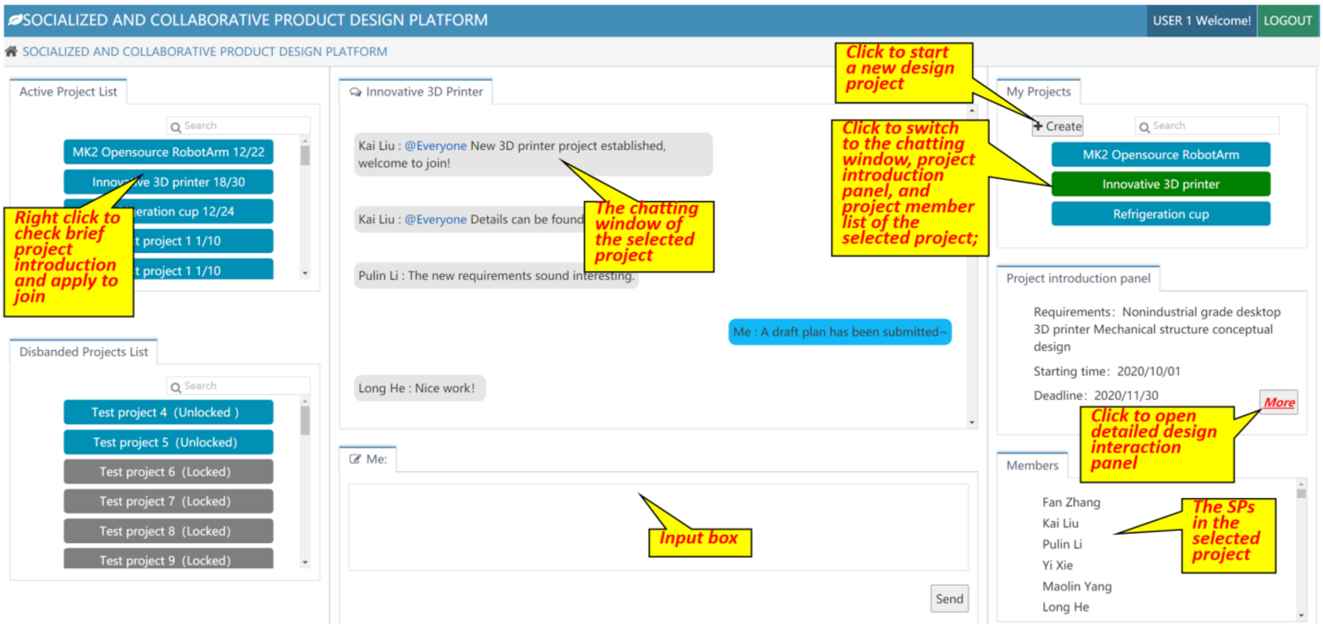

Fig. 10. The main operation interface of the SCPD Web APP

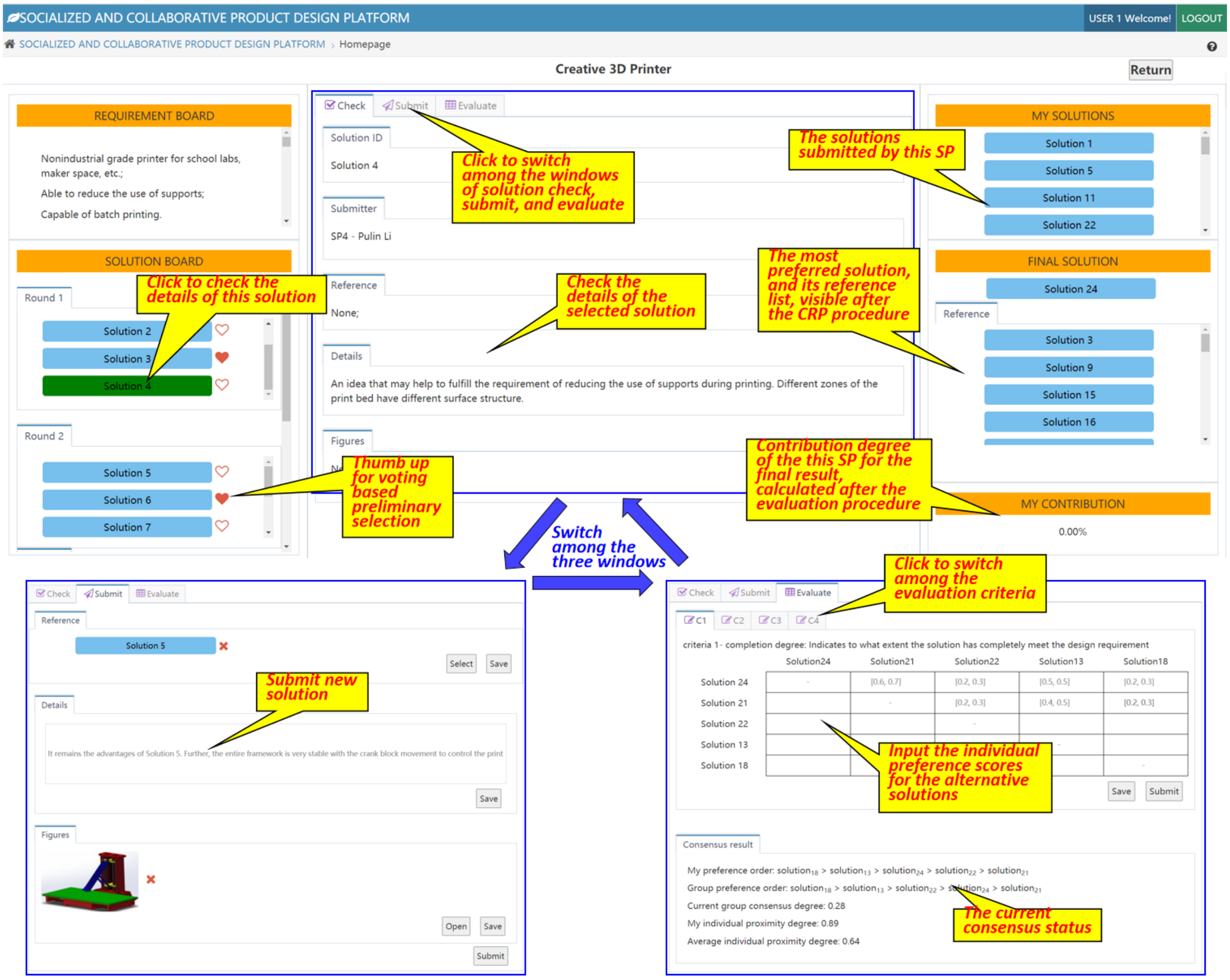

Fig. 11. The detailed design interaction interfaces to check/submit design solutions and submit individual preference

5. DISCUSSION AND CONCLUSION

In this paper, a three-layer framework and its enabling techniques is established to realize orderly and efficient execution of CI oriented SCPD. The contributions, application perspectives, and limitations of the work are discussed below.

5.1 Contributions

5.1.1 From the application perspective of the entire framework

SCPD is known for its advantage in utilizing the CI from SPs to increase the design power of internal R&D teams of companies, and it has drawn the attention from both academic and industrial fields **(Panchal and Le, 2014)**. However, the key characteristic of SCPD (i.e. self-driven, self-adaptive, decentralized, and distributed design collaboration among SPs) brings not only advantage but also problems of low reliability, low efficiency, and limited application scope. The SCPD framework established in this paper is able to mitigate these problems. It provides a systematic approach to support the orderly execution of SCPD project by decomposing large design task into relatively more operable small subtasks, identifying the subtasks that are suitable for SCPD approach, and then supporting the orderly collaboration among SPs to realize individual solution generation, group solution aggregation, group decision making, and design contribution analysis based participator stimulation. By applying the framework, the advantage of SCPD pattern in utilizing the CI from SPs can be remained, and at the same time the controllability, reliability, and execution efficiency of SCPD can be improved. In this way, the application scope of SCPD can be enlarged to not only software and small scale physical products, but also relatively larger and complicated physical products with higher values or intellectual properties.

5.1.2 From the perspective of the enabling techniques

The customized Blackboard model for design solution generation. A distinguishing advantage of Blackboard model is its capability to organize orderly cooperation among multiple heterogeneous knowledge sources to carry out a common task. Existing researches on Blackboard model were mainly devoted to the scenarios with non-human Knowledge sources (e.g. AI agents), in which the Knowledge sources would be invoked only when their knowledge or functions are considered useful to the current problem solving progress by the Control modules(Lou et al., 2012). The Blackboard model in this paper, however, is customized to support the collaboration among human Knowledge sources who are able to decide whether their knowledge are useful to the current design progress. The Control modules here are not to activate Knowledge sources opportunistically, but to provide rules and constraints to make sure that the self-driven Knowledge sources can collaborate orderly. Supported by this customized Blackboard model, the interaction, mutual inspiration, competition, and stimulation among the SPs during SCPD process can be organized in an relatively more orderly and efficient manner compared with the totally self-driven, self-adaptive and decentralized SCPD activities such as opensource design, and the final solutions of the iterative design process would contain the contributions of all the Knowledge sources who participated. In this way, the customized Blackboard model not only supports the emergence of CI during SCPD process, but also makes the process more controllable and reliable.

Customized CRP model for design solution selection. Mainly two modifications are made to the classical CRP model to fit the purpose of identifying the most preferred design solution according to the collective judgments of the SPs. **First**, the existing researches on CRP are mainly focused on single criterion situation (Pérez et al., 2018, Kacprzyk and Zadrożny, 2010, Dong et al., 2018) and therefore may not be able to fully satisfy the situations where multiple criteria should be concerned. Our model solved this problem by integrating VIKOR algorithm in CRP to handle multiple and even conflicting criteria. **Second**, in classical CRP task, the goal is to reach consensus on the preference order of all the alternatives, while in our design solution selection task the goal is to identify the most preferred solutions. In another word, only the alternatives in the top ranks of the preference order are important for consensus reaching. In this regard, two consensus indicators with top-weightiness characteristics are proposed, and consequently the efficiency of consensus reaching improved.

Reducing the difficulty of VIKOR application. Two techniques are applied to reduce the difficulty for the SPs to provide the inputs for VIKOR calculation. **First**, the usually used forms of preference judgment on a set of alternatives includes (*a*) preference order of the alternatives, (*b*) utility scores of each alternatives, and (*c*) pairwise comparison values between each pairs of alternatives. For human experts the difficultly level of expressing these forms of judgment is (*a*) > (*b*) > (*c*) (Ureña et al., 2019). The original input of VIKOR calculation is (*b*) and its output is (*a*), while in our method the input is (*c*) and the output is (*a*). **Second**, interval valued fuzzy number can effectively handle uncertain values and it is also the simplest form of fuzzy representation (Sayadi et al., 2009), therefore applying interval valued fuzzy number further reduces the difficulty for SPs to provide the inputs for VIKOR calculation.

5.2 Limition

The feedback regulation mechanism in Section 3.3.4 follows an adaptive approach (Mata et al., 2009), i.e. the SPs with low IPD would be asked to reconsider their preference judgments. However, detailed feedback regulation rules have not been established, and this could be our future direction.

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APPENDIX

The appendix details the calculation process of acquiring the preference orders among the alternative solutions based on the fuzzy utility score matrixes.

Step 1. Identifying the positive and negative ideal solution. VIKOR algorithm is based on the concept of "closeness" which is calculated with L_p*-metric*, as shown in Equation (6), where $1 \le q \le \infty$; i is the number of alternative ($i = 1, 2, \ldots, m$); k is the number of criterion ($k = 1, 2, \ldots, l$); w_k is the weight of c_k; u_{ik} is the utility score of a_i from the perspective of c_k; u_k* is the Positive ideal solution (i.e. the best score on c_k from all the alternatives), and u_k^- is the Negative ideal solution (i.e. the worst score on c_k from all the alternatives).

$$L_{q,i} = \left\{\sum_{k=1}^{l}\left[\frac{w_k(u_k^*-u_{ik})}{u_k^*-u_k^-}\right]^q\right\}^{1/q}$$

(6)

Define B and C are the sets of benefit criteria and cost criteria, respectively. Then for the criteria in B, $u_k^- < u_{ik}^L < u_{ik}^U < u_k^*$; while for the criteria in C, $u_k^* < u_{ik}^L < u_{ik}^U < u_k^-$. Then we have

$$u_k^* = \begin{cases}\max\limits_i u_{ik}^U, & k \in B \\ \min\limits_i u_{ik}^L, & k \in C\end{cases} \tag{7}$$

$$u_k^- = \begin{cases}\min\limits_i u_{ik}^L, & k \in B \\ \max\limits_i u_{ik}^U, & k \in C\end{cases} \tag{8}$$

Step 2. Calculating group utility indicator and individual regret indicator. In Equation (6), $L_{1,i}$ is the ranking indicator from the perspective of group utility, denoted as S_i, and lower S_i indicates that a_i has higher group utility for all the criteria; $L_{\infty,i}$ is the ranking indicator from the perspective of individual regret, denoted as R_i, and lower R_i indicates that a_i has lower individual regret for each criterion. S_i and R_i can be calculated as

$$\begin{cases}S_i^L = \sum_{k\in B} w_k\left(u_k^* - u_{ik}^U\right)/(u_k^* - u_k^-) + \sum_{k\in C} w_k\left(u_{ik}^L - u_k^*\right)/(u_k^- - u_k^*) \\ S_i^U = \sum_{k\in B} w_k\left(u_k^* - u_{ik}^L\right)/(u_k^* - u_k^-) + \sum_{k\in C} w_k\left(u_{ik}^U - u_k^*\right)/(u_k^- - u_k^*)\end{cases}$$

(9)

$$\begin{cases}R_i^L = \max\{w_k(u_k^* - u_{ik}^U)/(u_k^* - u_k^-)\ |k \in B,\ w_k(u_{ik}^L - u_k^*)/(u_k^- - u_k^*)\ |k \in C\} \\ R_i^U = \max\{w_k(u_k^* - u_{ik}^L)/(u_k^* - u_k^-)\ |k \in B,\ w_k(u_{ik}^U - u_k^*)/(u_k^- - u_k^*)\ |k \in C\}\end{cases}$$

(10)

Step 3. Calculating the Q indicator. Q_i is established to represent the balance between group utility and individual regret on the criteria:

$$\begin{cases}Q_i^L = v(S_i^L - S^*)/(S^- - S^*) + (1-v)(R_i^L - R^*)/(R^- - R^*) \\ Q_i^U = v(S_i^U - S^*)/(S^- - S^*) + (1-v)(R_i^U - R^*)/(R^- - R^*)\end{cases}$$

(11)

where

$$S^* = \min_i S_i^L, \quad S^- = \max_i S_i^U \tag{12}$$

$$R^* = \min_i R_i^L, \quad R^- = \max_i R_i^U \tag{13}$$

and v is the weight of the strategy of maximum group utility (Sayadi et al., 2009, Opricovic and Tzeng, 2004). In our research v is set as 0.5, indicating that maximum group utility and minimum individual regret are considered with equal importance.

Step 4. Acquiring the preference order of the alternatives. Lower Q_i of a_i indicates that a_i is closer to the positive ideal solution and therefore more preferred by the SPs. Thus, by comparing the Q_i value of each alternative solution, the preference order of the solutions can be acquired.