SME-oriented flexible design approach for robotic manufacturing systems

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Abstract: Continuously growing pressures due to the shorter development lead-time and the uncertainty of increasingly complex market require a high flexibility from production companies and their manufacturing systems. Comparing with large enterprises, small and medium-sized enterprises (SMEs) which lack concentrated market power and powerful original equipment manufacturers (OEMs) have difficulty and risk to develop flexible and customised robotic manufacturing systems. Nowadays, although various design methods for robotic manufacturing systems have been made to fix this problem, however, there still exist two main challenges: flexibility in design and high degree of customisation.

To deal with the existing challenges, this paper proposes an SME-oriented design approach based on a configuration design paradigm. This method can offer decision support to designers to form flexible architecture for robotic manufacturing systems and, at the same time, give more interactive configuration freedom to customers so as to achieve a high productivity and flexibility for customisation but with less risk and cost of product development. To validate the proposed method, two design cases of robotic manufacturing systems are presented for demonstration.

Keywords: Small and medium-sized enterprises, manufacturing system flexibility, robotic manufacturing system, configuration design

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1. Introduction

Over the past few years, manufacturing SMEs have played a significant role in the global economy, constituting 99% of all enterprises and offering more than 60% of all employment [1,2]. In the US, manufacturing SMEs are considered as the backbone of the U.S. economy. According to the survey carried out by the U.S. Department of Commerce in 2017, 96.4% of manufacturing exporters are SMEs and they contribute 20.3% of the sector's $798 billion in exports, while 93.5% of manufacturing importers are small- and medium-sized; they account for 14.5% of the sector's $826 billion in imports [3]. In the EU, SMEs make up 99.8% of all enterprises in the non-financial business sector, in which manufacturing sector is one of the most important among the five key sectors [4,5]. In China, over 90% of Chinese enterprises can be categorised as SMEs, which contribute to more than half of China's tax income and more than 80% of employment [6]. In recent years, more than 29 million manufacturing SMEs have emerged in China, which contributed to 60% of China's industrial output, and the number of Chinese industrial SMEs will steadily with an average annual growth rate of 8% [7].

For the manufacturing SMEs, various products of very similar type are always required, but sometimes their quantity to be produced is quite small [8]. As a result, most of the manufacturing SMEs still adopt handwork manufacturing process due to the diversity of products and their small batch sizes. Moreover, continuously growing pressures from competitive market require manufacturing enterprises to be more productive but with less risk and cost. Robotic flexible manufacturing systems are considered as an effective solution in solving the aforementioned problems. There are several similar definitions of flexible manufacturing systems proposed by different researchers from various perspectives. The term of the flexible manufacturing system is proposed by Stecke for the first time as "an integrated, computer controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium-sized volumes of a variety of part types" [9]. Chang et al. propose the definition of the flexible manufacturing system as "an integrated system of equipment and processes via computer or network of computers that is capable of producing a variety of products economically" [10]. Borenstein et al. define flexible manufacturing systems as "automated, integrated systems of equipment and information flow, arranged for the economic production of small batches of complex components" [11]. According to the above definitions, robotic manufacturing systems are flexible because they produce a variety of products very quickly and economically. However, Koren and Shpitalni state that flexible manufacturing systems should not only facilitate the changes in products manufactured, but should mean more than that [12]. For example, Browne et al. believe that a flexible manufacturing system should have the capability of building a system, and expanding it as needed, easily and modularly [13]. Holzner et al. mention that attention should be also paid to the personal deployment flexibility, which means that the robotic manufacturing system should be easily operated by a variable number of employees or workers with different skills [14]. Wadhwa define the flexibility in the context of manufacturing SMEs as the ability to response efficiently to the changing demands of customers [15].

As previously mentioned, one of the hallmarks of robotic flexible manufacturing systems is to improve the reliability, productivity, versatility and availability of manufacturing enterprises. After the implementation in large enterprises to achieve better product quality, lower production cost and higher customer satisfaction rates, robotic flexible manufacturing systems have attracted more attention from manufacturing SMEs. Not only does the robotic flexible manufacturing system permit significant manufacturing time and cost saving for SMEs, it also frees up time for increasing the product diversity and the ability to adapt to small production batches. However, it is difficult for the manufacturing SMEs to adopt robotic flexible manufacturing systems due to the lack of concentrated market power and powerful original equipment manufacturers (OEMs) and their limited technical and financial resources [2]. To further understand their difficulties, the authors research team not only conducted a number of semi-structured interviews within the CEOs, managers and manufacturing consultants of five Chinese manufacturing SMEs, whose scopes of manufacturing activities include composite manufacturing, shipbuilding, shoemaking, mechanical component manufacturing and lens manufacturing, respectively, but also organised in-depth discussions with the engineers from three industrial automation companies, which offer industrial robotic solutions to manufacturing companies. The duration of each interview was 0.5-1h. During this period, 25 participants from SMEs and 15 participants from industrial automation companies were asked a series of questions according to their own understandings of the challenges to find out the factors which hinder the implementation of robotic flexible manufacturing systems in SMEs, these being:

(1) High development cost
(2) Long development lead-time
(3) Large space requirement
(4) Complex operating process
(5) Difficulty in capturing customer requirements
(6) System unstability
(7) High maintenance cost
(8) Laws or regulations which constrain the development of robotic manufacturing systems in SMEs

A five-level scoring method is used to indicate the grades of each factors which hinders the implementation of robotic flexible manufacturing systems in SMEs. Table 1 illustrates the relationship between the scores and grades.

Table 1 Relationship between scores and difficulty levels

Importance level	Score
Very low	1
Low	3
Neutral	5
High	7
Very high	9

Fig. 1 presents the results of the interviews with the participants from SMEs and industrial automation companies. From the perspective of customers from SMEs, two of the top three factors which hinder the implementation of robotic flexible manufacturing systems are related to the system costs. Moreover, many interviewees are afraid that their required functionalies may not be realised completely by designers. From the point of view of participants from industrial automation companies, they believe that the high development cost and long development lead-time make it difficult to implement robotic flexible manufacturing systems in SMEs. Additionaly, they also insist that the difficulty in capturing customer requirements severely affect the successful implementation of robotic flexible manufacturing systems in SMEs.

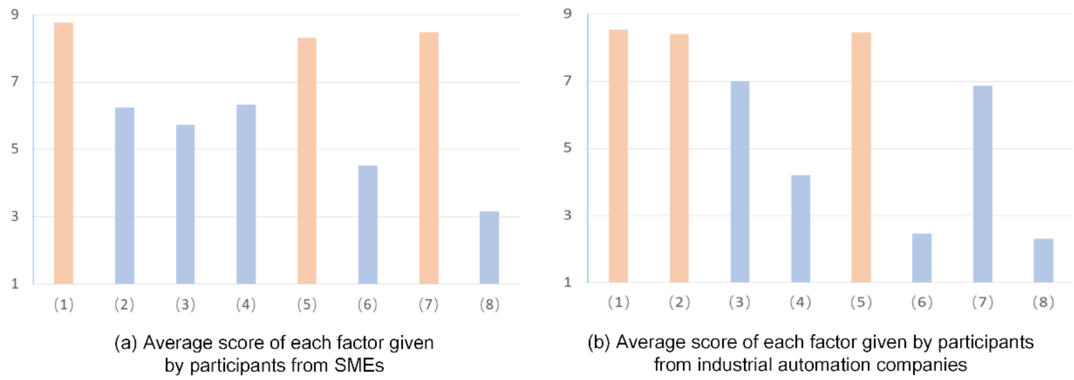

Fig. 1 Results of interviews with participants from SMEs and industrial automation companies

Analysing the results of the interviews, the authors propose the challenges regarding the implementation of robotic flexible manufacturing systems in SMEs as follows:

- Conflict between professional designers and non-professional manufacturing SMEs: designers define the architecture of flexible manufacturing systems according to the requirements of SMEs because there is always a lack of ability for SMEs to develop their own manufacturing systems. However, different perspectives from designers and SMEs may lead to totally different comprehension of manufacturing systems. On the one hand, designers may miss some industrial problems which SMEs need to solve by the manufacturing system; on the other hand, SMEs may propose some special requirements which can hardly be realised by designers due to the limited basic engineering knowledge in SMEs. As a result, sometimes the manufacturing system cannot fully meet requirements of SMEs [16]. The conflict of professional designers and non-professional SMEs indicates that it is necessary to shift from the "professional designers-leading" design approach to the design process in which manufacturing SMEs can participate.

- Conflict between development cost of flexible manufacturing systems and financial burdens of SMEs: although flexible manufacturing systems provide designers with a low-cost manufacturing process; however, the high cost of development of such flexible manufacturing systems becomes one of the most significant barriers toward the implementation of flexible manufacturing systems in SMEs due to their scarce financial resources [17]. Most of current SMEs still adopt traditional manufacturing mode, e.g., handwork manufacturing process due to their heavy financial burdens [18]. However, traditional manufacturing mode not only leads to long manufacturing lead-time, but also results in environmental pollution and resource abuse problems [7]. Therefore, a low-cost development approach for flexible manufacturing systems are necessary for designers. On the one hand, it can encourage SMEs to choose flexible manufacturing systems rather than traditional manufacturing process, so that the environmental pollution can be greatly reduced. On the other hand, both sales and profits of flexible manufacturing systems can be increased for the side of designers.

Considering the aforementioned two challenges, the authors propose two types of flexibilities which should be attained for the implementation of robotic flexible manufacturing systems in SMEs.

- Flexibility in customisation: in the design process of manufacturing systems, the iterations between designers and manufacturing SMEs often lead to increasing development cost and lead-time because the needs of manufacturing SMEs are not satisfied completely. Flexibility in customisation allows SMEs to customise the required manufacturing system by themselves. In other words, the final manufacturing system is not only completed by the designers, but by the SMEs according to their own needs as well [16].
- Flexibility in design: flexibility in design is the capability of the design for new robotic manufacturing systems based on existing systems as needed, easily and economically. Similar terms, such as changeable manufacturing systems, design for variety, variety management, and product family architecture have been proposed by researchers in engineering and business. Thanks to flexibility in design, designers can develop new manufacturing systems easily by making appropriate changes from the existing ones, and the development cost can be therefore greatly reduced [13].

The paper intends to propose a SME-oriented design approach for robotic flexible manufacturing systems by focusing on the aforementioned two types of flexibilities. Section 2 reviews the current design methods for flexible manufacturing systems and evaluates each method by the challenges stated previously. Section 3 introduces the proposed design approach which can be considered as an effective solution to the challenges relating to the implementation of flexible manufacturing systems in SMEs. The application of the proposed design approach is demonstrated by industrial case studies in Section 4. Section 5 provides a detailed discussion of the proposed design approach. Finally, the authors draw the conclusion in Section 6.

2. Related works

According to the principle of systems engineering, solving a complex engineering problem often requires a technique to decompose the problem into smaller, more manageable sub-problems that are easier to solve, and then to join them together [19]. The design of robotic flexible manufacturing systems is an example of such complex problems; decomposing the robotic flexible manufacturing systems into smaller and manageable elements is thus a common technique to help designers to obtain the design solutions, which results in the agent-based design paradigm and configuration design paradigm. The former demands designers to break a flexible manufacturing system down into manageable agents, while the latter decomposes the manufacturing system into reconfigurable modules. Considering different dimensions of manufacturing flexibilities, current design approaches for robotic flexible manufacturing systems based on the two design paradigms will be reviewed hereafter.

2.1 Agent-based design paradigm

Agent is composed of states; social, environmental and personal knowledge; a perception function; and behavioural rules [20]. The agent-based design paradigm is therefore a distributed problem-solving paradigm that decomposes a complex manufacturing problem into a large number of small manageable agents which are autonomous having intelligence to take their own decision [21]. Similar to the concept of "agent", the word "holon" is proposed to describe the hybrid nature of sub-wholes/parts in real-life systems by Koestler at the end of 1980s [22]. Holon is defined as an autonomous and co-operative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. In fact, a holon can be regarded as a special kind of large-grain reactive agent [23].

Based on the agent-based design paradigm, different agents (or holons) are able to exchange information efficiently, and communicate and cooperate effectively [24]. Therefore, it is widely used in solving scheduling and planning problems to achieve the flexibility in automated line during manufacturing process [25]. Currently, different agent-based design approaches are proposed to aid manufacturing systems in achieving the flexibility in automated line. The agent-based design approaches can be generally classified into the following three types: (1) Modelling manufacturing stages by agents: in this type of design method, each manufacturing stage is considered as an autonomous agent. The action that each manufacturing stage or task takes is based on the local state and the messages received from other agents [26–28]. (2) Modelling stakeholders by agents: based on this proposition, stakeholders in charge of cost estimation, assimilability evaluation, process planning, manufacturability evaluation, etc. are modelled as different agents. The coordination and conflict detection among stakeholders during the design process can be realised by the communication among different agents [29–31]. (3) Modelling control parts by agents: the control part is regarded as an agent, which manages information and data flows in flexible manufacturing systems so that the adaptability to change the manufacturing environment can be achieved [32–34].

Previous review indicates that the problems related to flexibility in automated line (e.g., manufacturing scheduling, production planning, etc.) during manufacturing process can be well solved by the design approaches based on the agent-based paradigm; however, none of them can fully support the aforementioned two types of flexibility (i.e., flexibilities in customisation and design) which play a significant role in the implementation of flexible manufacturing systems in SMEs. A non-exhaustive list of design approaches for flexible manufacturing systems based on the configuration design paradigm are presented hereafter.

2.2 Configuration design paradigm

Configuration design was firstly proposed by Mittal and Frayman in 1989, which is defined as "taking a set of predefined components, add the search for an assembly of components that satisfies a set of requirements and obeys a set of constraint" [35]. When applying the configuration design paradigm on the design of manufacturing systems, the term of component always represents the physical artefacts, i.e., reconfigurable modules. Based on the configuration design paradigm, designers should select and integrate reconfigurable modules to satisfy customer requirements and accomplish certain manufacturing tasks. National Research Council insists that the configuration design paradigm is a priority technology to address the issue of flexibilities related to manufacturing systems [36].

The idea of decomposing a complex manufacturing system into reconfigurable modules to achieve rapid change in architecture has received attention from both academia and industry for long time. In 1995, the concept of Reconfigurable Manufacturing Systems (RMS) is proposed in a proposal from University of Michigan [12]. According to the definition proposed by Koren et al., RMS can be designed at the outset for rapid change in structure, hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements [37,38]. However, compared to the design of traditional manufacturing systems, the design of RMS represents a significant challenges, such as how much variety to cover in the RMS, how to determine the level of reconfigurability [39]. Considering the challenges relating to the design of RMS, different approaches for the design of RMS have been proposed. After pointing out the core characteristics and design principles of RMS, Koren and Shpitalni discuss how RMS are configured and propose a means for calculating the number of possible RMS configurations based on the number of machines in the system [12]. Galan et al. believe that RMS allow the production of different products together to help customers to achieve product flexibility. They propose a methodology for calculating the similarity values between products in order to form the best set of product families [40]. Lameche et al. discuss the possibility to adopt modular design principles for the design of RMS. In their proposition, Design Structure Matrix (DSM) is adopted to help designers to organise subsystems and components in RMS [41]. Al-Zaher et al. proposes a design methodology by using the design principles of reconfigurable manufacturing systems for automotive framing systems. This modular design methodology can both eliminate the coupling design and enable increases of variants within a product family during production [42]. Compared to the multi-agent manufacturing systems focusing on the flexibility in automated line, RMS are considered as an effective support to aid customers in achieving product flexibility [43]; however, current design approaches for RMS seldom take the context of manufacturing SMEs into consideration. Therefore, the flexibilities in design and customisation cannot be fully supported by current design approaches for RMS.

Besides RMS, the configuration design paradigm has been widely adopted by current design approaches for manufacturing systems. The configuration design for manufacturing systems requires designers to assemble a set of predefined modules to satisfy customer requirements and obey a set of constraints [44]. Based on this principle, various configuration methods are proposed to aid designers in selecting the "best" option from different alternative assembly results. Current configuration methods can be generally divided into the following three classes: KBE (Knowledge Based Engineering) - based approaches, ranking methods, and mathematical optimisation methods.

Knowledge based engineering is initially proposed to capture the knowledge and the historical trace of experiences in a particular discipline of interest, and it can help designers to make better-informed decisions during the design process. Wielinga and Schreiber confirm the possibility and necessity of knowledge in configuration-design problem solving [44]. Mellichamp et al. propose a knowledge base of the expert system for manufacturing system design. Knowledge and experiences of previous genuine designers related to production output (i.e., production output of manufactured parts per unit of time by the manufacturing system) and capital investment (i.e., the cost per part manufactured by the manufacturing system) are stored in the expert system to help designers to choose the best components of manufacturing systems among potential alternatives [45]. Alsafi and Vyatkin use ontological knowledge to help designers to produce the new configurations of manufacturing systems reacting on changes in the requirements or the manufacturing environment [46]. For the KBE-based approaches, it is the designers who are in charge of capturing of the design knowledge from previous design cases or experiences and defining the architecture of the required manufacturing system, and SMEs are not involved in such design process. Therefore, current KBE-based approaches do not allows SMEs to customise the required manufacturing system by themselves.

Ranking methods need designers to score each of the attributes in a quantitative or qualitative way and provide related weights for them according to customer requirements. Different models or methods, such as the multi-attribute utility analysis (MAMU) [47,48], the fuzzy methods [49,50], the analytic hierarchy process (AHP) [40,51], are applied to evaluate all of the scored attributes, giving a comprehensive index value for each alternative as for ranking. This type of methods can order alternatives from the best to the worst with the analysis result of customer requirements [52]. Designers complete the main processes of ranking methods, such as selecting the evaluation attributes, assigning the attributes' weights and scoring the alternatives after carefully considering customer requirements. However, how to capture design requirements, especially the informal requirements from customers and usage scenarios related to SMEs is still a critical issues for designers, because the capture of informal design requirements is not merely a technological challenge, but a complex social process [53]. The raking methods require designers to capture and specify customer requirements, and customers are not really involved during the ranking methods; therefore, the different perspectives from customers may lead to totally different comprehension of customers' real requirements.

As for mathematical optimisation methods, objective functions are constructed to represent different factors or attributes along with their interrelationships. Designers aimed to find a set of ideal optimal solutions among the infinite solution space in theory when selecting the best configuration. The objective function of optimisation always considers the profit maximisation, customer satisfaction, development lead-time, etc. [54]. Similarly to the ranking methods, the main difficulty within the mathematical optimisation methods is that the suitable objective functions are selected by designers according to their understanding of customer requirements, which may lead to the misunderstanding of customers' real intention due to different perspectives between designers and SMEs [55].

In order to implement the configuration design paradigm for the design of robotic manufacturing systems, a common representation for reconfigurable modules is needed, because one manufacturing system should be configured from modules by designers of different disciplines. In order to provide designers with a common representation, the first task is to clarify which kind of information should be represented for the modelling of modules and interfaces. Du et al. [56] propose that each module can be described by some attributes; and each attribute assumes certain values. Jiao and Tseng [57] use design parameters to represent module functional and structural aspects. Tsai and Wang [58] do not propose the internal structure of module; on the contrary, they believe that exploring the parameter flow between modules is a feasible approach to represent the function of modules. Four types of flows, i.e., geometry constraints, mechanical strength, energy flow and signal flows, are proposed to represent the relationship between different modules. Pahng et al. [59] integrate data and mathematical models to represent modules. They point out that modules interact with each other if the interfaces are compatible, but details of interface model and interface compatibility have not been presented. Li et al. [60] adopt function realisation and internal structure to describe the module, while the interface which connects different modules is represented by interface size, interface location and communication standard. Above studies focus on the information which should be expressed by modules and interfaces; however, a unified form in which the information is structured should be also proposed to facilitate the understanding of designers from different disciplines.

Object-oriented technology was initially proposed to offer a revolution in software engineering discipline that is resolving the problems inherent in developing and managing organisational information processing capabilities [61]. The concept of modularity is the basis of the object-oriented modelling approach in software engineering discipline [62]; therefore, by integrating with the configuration design paradigm, several researchers intend to use the object-oriented modelling approach to model the modules. The module models based on the object-oriented technology provide a unified form in which the information is structured to facilitate the understanding of designers from different disciplines. Various object-oriented models, such as STandard for the Exchange of Product model (STEP) [63], Core Product Model [64], Product-Process-Organisation (PPO) model [65], have been developed by experts worldwide. However, to achieve the flexibility in customisation, customers should be also involved in the design process, and the customers' view about the information representation of reconfigurable modules is not considered by current studies on module model.

Table 1 shows the assessment result of current design approaches regarding the flexibilities in design and customisation. The design approaches based on the agent-based design manufacturing paradigm [26,27,29,30,32,33] mainly focus on the flexibility in automated line, while the design approaches for RMS focus on the flexibility in product. In other words, none of them can fully support the flexibilities in customisation and design simultaneously, which play a significant role in the implementation of flexible manufacturing systems in SMEs. Some design approaches based on the configuration design paradigm can partially support the flexibilities in design and customisation for the design of manufacturing systems, but the context of manufacturing SMEs has not been taken into consideration. Therefore, the authors propose a SME-oriented design approach based on the configuration design paradigm for the robotic flexible manufacturing systems.

Table 2. Assessment of design approaches regarding flexibilities in design and customisation

Design approach		**Flexibilities in design**	**Flexibility in customisation**
Agent-based design paradigm	Modelling manufacturing stages by multi-agent [26–28]	**No** (only focus on **the flexibility in automated line**)	**No** (only focus on **the flexibility in automated line**)
	Modelling stakeholders by multi-agent [29–31]		
	Modelling control parts by multi-agents [32–34]		
Configuration design paradigm	Design approaches for RMS [12,37,38,40–43]	**No** (only focus on **the flexibility in product**)	**No** (only focus on **the flexibility in product**)
	Design approaches based on KBE [44–46]	**Partial** (do not consider the context of manufacturing SMEs)	**Partial** (do not consider the context of manufacturing SMEs)
	Ranking methods [40,47–51]		
	Mathematical optimisation methods [54]		
	Module representation approaches [56–60,63–65]		

3. SME-oriented design approach for robotic flexible manufacturing systems

Normally, designers should capture customer requirements to define the architecture of complex systems. However, it is a challenging task to capture the customers' informal design requirements. If customer requirements are not fully understood by designers, the performance of the product will not entirely meet customers' expectations. In this case, designers should modify their design, and sometimes this process will be repeated a few times. On the other hand, due to the limitation of basic engineering knowledge, SMEs may propose some requirements, the development cost of which may not be afforded by SMEs, or even sometimes their requirements may hardly be realised by existing technologies. In order to achieve such flexibilities in design and customisation, the authors propose a design approach which allows the SMEs to choose their own architecture from different choices provided by designers after the designers carefully consider customer requirements and financial resources. In this section, the template model of robotic flexible manufacturing systems will be firstly introduced, which is considered as the key part of the design approach. Then, based on the template model, the SME-oriented design approach for robotic flexible manufacturing systems will be presented.

3.1 Template model of robotic flexible manufacturing systems

Based on the template model, designers can define the architectures of different robotic flexible manufacturing systems by carefully considering their design experiences, existing technology accumulation and customer requirements, which provides the SMEs with various design solutions. The proposed template model of robotic flexible manufacturing systems is illustrated in Fig. 2.

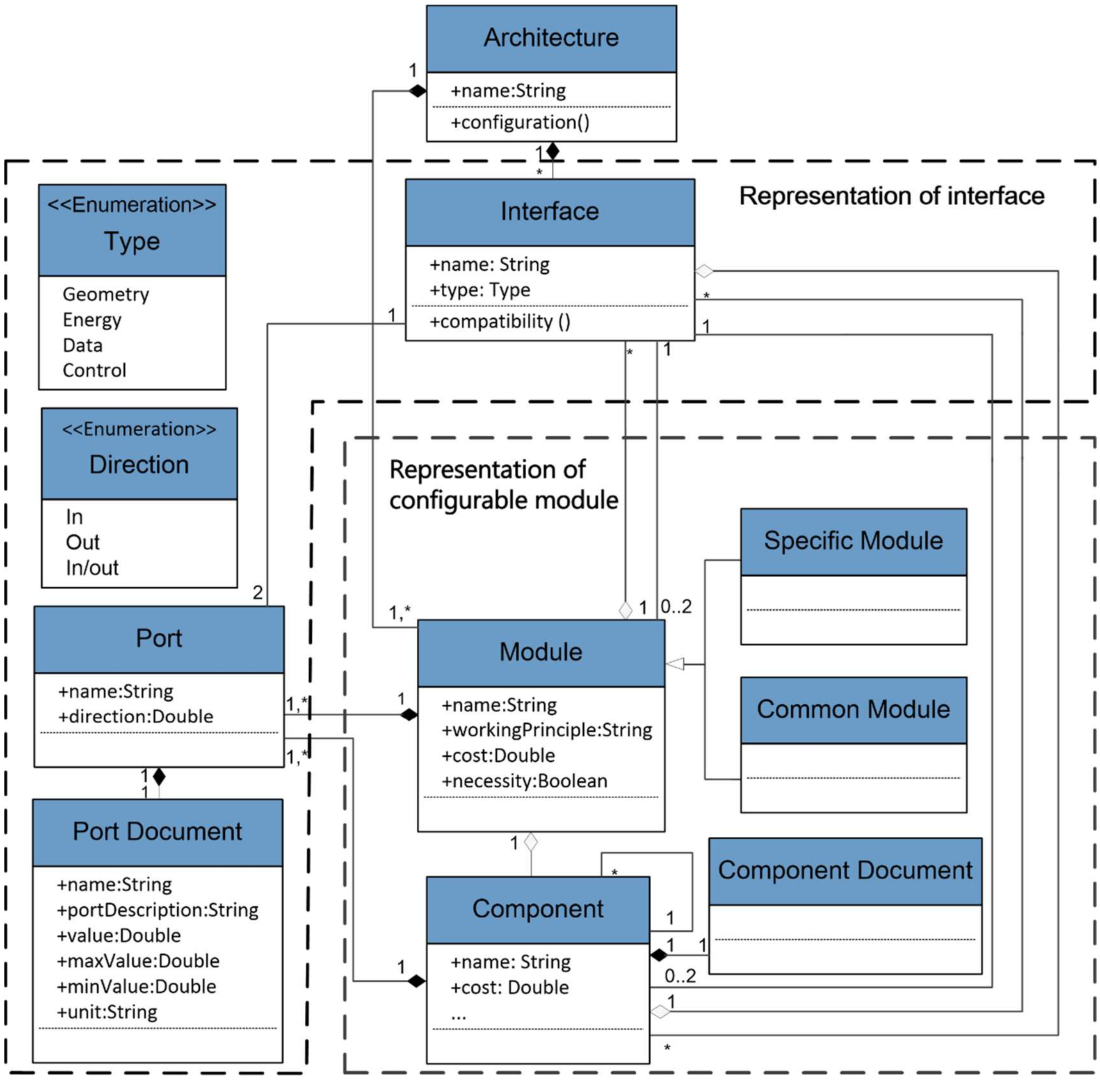

Fig. 2 Representation of template model in UML class diagram

3.1.1 Representation of configurable modules in template model

The configurable module is considered as the encapsulation of functional realisation, and can be integrated with other modules through the interfaces. The modelling principles of the configurable module will be illustrated by using Fig. 2 as follows:

- Class **Module**: four attributes, i.e., **name**, **workingPrinciple**, **cost** and **necessity**, are proposed in the class **Module**. The attribute **name** is used to store the name of the module and to distinguish it from the others. The attribute **workingPrinciple** briefly describes the working principle of the module. The attribute **cost** stores the development cost estimated by designers. The attribute **necessity** adopts a Boolean data type to express whether the module is necessary to fulfil the basic function or to provide an additional function for the robotic manufacturing system. For example, for a robotic welding system, the welding module is considered as a necessary module because the robotic welding system cannot achieve its basic function without the welding module; however, the vision module can provide an additional function to the robotic welding system, which generates the collision-free trajectory by capturing the workpiece's welding seams with cameras instead of analysing workpiece's CAD model. Therefore, the vision module is unnecessary for the realisation of the basic welding functionality for the robotic welding system. SMEs can choose such unnecessary module by considering its development cost and their financial resources.

- Class **Common module** and class **Specific module**: the modules of robotic manufacturing systems can be generally divided into two types, i.e., common modules and specific modules. Common modules are the modules required in different robotic manufacturing systems, such as the control module, power supply module, movement modules, etc., while the specific modules are used to achieve specific manufacturing tasks, such as the welding module of the robotic welding system, the cutting modules of the automated cutting system. In Fig. 2, the **generalisation** relationship is adopted to represent the relationship between the class **Module** and the classes **Common module/Specific module**.

- Class **Component**: Fig. 2 clarifies the relationship between the terms of module and component because both of them play an important role for the configuration design, but they are often confused by designers. For example, the switch, the power transmission line, the transformer, etc., are the basic components of a robotic manufacturing systems, but none of them can be called as "modules". However, the power supply sub-system composed by the aforementioned components can be considered as a module, because according to the definition of Gu et al., modules are the cluster of components, in which the interactions of components are maximised [66]. The relationship between classes **module** and **component** can be depicted by the **aggregation** relationship in UML, which is represented as a hollow diamond shape in Fig. 2.

- Class **Component Document**: designers usually have several alternative combinations of components provided by different component suppliers to realise the function of one module. The class **Component Document** is proposed to store the information related to the components provided by different component suppliers, such as the logistics, supplier location, price, delivery time, etc.

- Considering the information stored in the classes **module** and **component**, designers can select their preferred modules or components from the list of possible choices. The selection process is essentially a multi-attribute decision-making problem. The operation **configuration()** contained in the class **architecture** is therefore defined as a smart search algorithm based on the multi-attributes decision-making model to help designers to select the most suitable combination of modules or components. The proposed multi-attributes decision-making model is composed of two sub-models, a deviation model and a similarity model. Hence, it has two metrics for evaluation as compared with other mono-metric models using "distance-based" evaluation. Another advantage of this model is that it is more suitable to deal with vector-represented solutions in the discretised solutions space. For more details of the multi-attributes decision-making model, the interested readers are referred to [55].

3.1.2 Representation of interfaces in template model

The interface is defined in the paper as the logical or physical relationship through which two modules (or two components) interact with each other. Fig. 2 also presents the modelling principles of the interface:

- Class **Interface**: **Type** and **Configuration** are proposed as two main attributes of the class **Interface**. The attribute **type** represents the transfer information occur through one interface. One enumeration type is created to detail the attribute **type**, in which four different types of transfers, i.e., **geometric**, **energy**, **control** and **data**, are presented. The attribute **configurat**ion describes which two modules (or two components) are linked by the interface. The operation **compatibility()** contained by the class **Interface** is used to test the interface compatibility in order to guarantee the different modules (or components) to integrate correctly. For the details of the compatibility rules and its implementation in computer-aided design platform, interested readers are referred to [67].

- Class **Port**: the port refers to the primary location through which one module (or component) interacts with other modules (or components), and every interface links two modules (or components) through the ports. Therefore, the relationship between the class **port** and the class **component** or **module** is the whole/par relationship and can be represented as the composition relationship, which is graphically rendered as a filled diamond shape in UML. The attribute **direction** of the class **Port** signifies the direction of the information transferred through the port, and an **enumeration** type is used to represent the direction of the information (i.e., in, out and in/out).

- Class **Port Document**: the class **Port Document** is used to store the documents describing the port, such as the parameters or the brief description. The attributes **value**, **maxValue**, **minValue** and **unit** are used to express the value or the interval of the value and its unit of the port's parameter, such as the input voltage, output power, etc. However, sometimes the value of the port's parameters may not be accurately determined during the early design phase, and designers can just roughly describe the information related to the port. In this case, the attribute **portDescription** is proposed to store such brief description.

- Relationship between the class **Interface** and the classes **Module/Component**: one module or component can be decomposed into several components or sub-components linked by interfaces. Therefore, the classes **Module/Component** can be the aggregation of class **Interface** or class **Component**. Moreover, when refining the system architecture during the design process, designers can also decompose one interface into several sub-components and sub-interfaces, so the class **Interface** can be also an aggregation of the class **Component** and itself.

The implementation of the proposed template model of robotic flexible manufacturing systems in an open collaborative design platform is illustrated in Fig. 3, and such open collaborative design platform allows the collaboration among designers, SMEs, and components suppliers during the design process. Designers specify and store their existing design solutions in the common module and specific module bases by instantiating the classes **Common module** and

Specific module of the proposed template model; therefore, the basic information relating to each module, such as basic working principle and cost, can be stored in the open design platform. The configuration and compatibility rules, specified as operations in the classes **Interface** and **Module**, are stored in the configuration rule and compatibility rule bases, from which designers can obtain the design rules or constraints that designers must follow when assembling modules or components to robotic flexible manufacturing systems. The template base is considered as the key part of the open design platform. Through reading the basic information relating to modules of each proposed template stored in the template base, SMEs can select the system templates from the template base with their preferences. By considering the selection results, designers propose the possible components (or component combinations) which can fulfil the required functionality of modules and make the component list. After receiving the component list, component suppliers provide the information relating to each component, such as the logistics, supplier location, price, delivery time, etc., by instantiating the classes **Component** and **Component document** and store such information in the component base. After evaluating the alternative components and their combination, designers can therefore select suitable components among various alternatives to achieve an ideal combination; thus, the final architecture of the required flexible manufacturing system can be achieved.

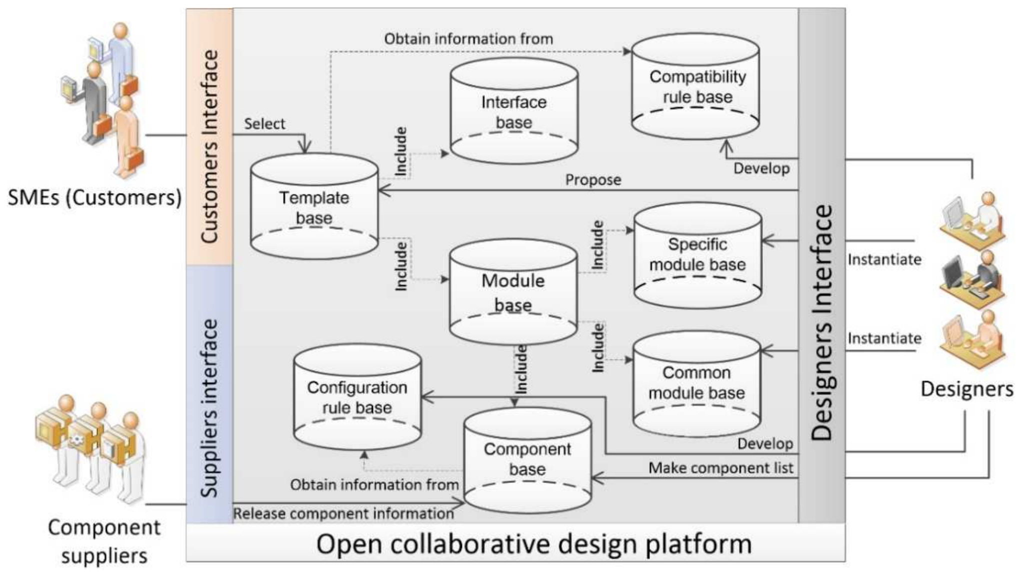

Fig. 3 Implementation of proposed template model in an open collaborative design platform

3.2 Design approach for robotic flexible manufacturing systems

Based on the proposed template model, the technology process of the SME-oriented design approach for robotic flexible manufacturing systems is illustrated in Fig. 4. The details of each step will be presented as follows:

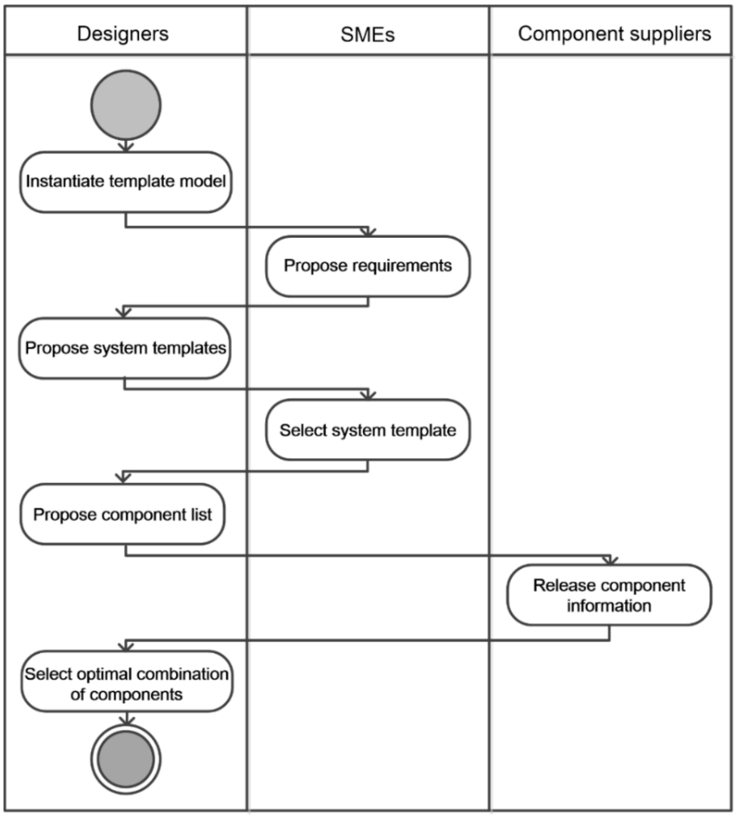

Fig. 4 Technology process of SME-oriented design approach for robotic flexible manufacturing systems

(1) Instantiation of template model: designers' existing technology accumulation play an important role for developing robotic flexible manufacturing system, since previous successful design experiences can greatly help designers to reduce the development lead-time, cost and risk. The proposed template model provides designers with an effective support to represent the basic information of existing modules in structured forms. Designers should firstly classify their existing design solutions into common modules and specific modules, and then define them in structured forms by instantiating the template model.

(2) Proposition of customer requirements: SMEs propose their requirements in this step. However, the manner in which designers capture customer informal design requirements is not merely a mathematical or technological challenge, but a complex social process [53]. Therefore, the iterations still exist between customers and designers in order to understand customer expectations.

(3) Proposition of system template: after analysing customer requirements, designers can put forward several design solutions based on previous successful design experiences. Candidate templates of the required robotic manufacturing system can be therefore obtained by configuring existing modules and checking the compatibility of the interfaces between modules. Sometimes, some specific modules may be required by customers to achieve special manufacturing tasks, but they may not be contained in the module base. In

this case, designers can update the module base by adding new instances of the specific modules required by customers.

(4) System template selection: in this step, SMEs can select the configuration of modules by their own. Due to the lack of basic engineering knowledge, the SMEs can check the basic working principle and the cost of each module, and the technologies to achieve the functionality of each module is encapsulated in a black box. They can choose the suitable configuration according to their design requirements and financial resources. The flexibility in design can be therefore achieved because even though the customers change their requirements or put forward new requirements, designers can always propose a new configuration of modules with a few changes.

(5) Proposition of component list: after SMEs select their ideal system template, designers should further decompose the modules of the selected template into components. However, the required functionality of one component can be achieved by one or more solutions. Therefore, the designers should propose a component list which contains different component alternatives, from which designers select the most suitable combination.

(6) Release of component information: the components suppliers can be industrial robot companies, automatic device manufacturers, or even designers themselves. Components suppliers are required to release the information related to components, such as logistics, supplier location, price, delivery time, and other lifecycle issue in the open design platform by instantiating the proposed template model.

(7) Selection of optimal combination of components: various candidates of one component may be provided by different components suppliers; therefore, designers should evaluate the performance of combinations of different possible alternative components and select the optimal one based on multiple criteria.

In this section, the authors present the details relating to the SME-oriented design approach for robotic flexible manufacturing systems. The template model is considered as the key part of the design approach, which provides different views for both designers and customers. Based on the template model, the process of the design approach is described, bridging the gap between the customer requirements and the designers' design solution.

The flexibilities in design and customisation for the implementation of robotic flexible manufacturing systems in SMEs can therefore be achieved by adopting the proposed design approach. On the one hand, various templates of the robotic flexible manufacturing system are proposed by designers according to their existing technology accumulation; therefore, the previous successful design experiences can greatly reduce the development time, cost and risk. On the other hand, the proposed design approach provides a means by which customers can choose and decide the architecture of their required manufacturing system according to their design requirements and financial resources, so that the possible misunderstanding of customer requirements by designers can be avoided at the beginning of the design process. In summary, the design approach based on the template model is proposed to support the design process of robotic manufacturing systems in a collaborative way, in which costumers and designers define the architecture of the system together. The applicability of the proposed design approach for robotic flexible manufacturing system is demonstrated by industrial design cases in the following section.

4. Case study

The case study selected for demonstrating the application of the proposed design approach is the industrial projects carried out in the authors' research team for two SMEs. The authors' research team in the School of Mechanical Engineering utilises its advanced engineering experiences to provide reliable industrial automation solutions with an eye to the robotic flexible manufacturing to satisfy industrial manufacturing requirements of different customers.

According to the proposed design approach, the design team firstly classifies their existing modules into common and specific modules (Fig.5(a)), represents them in structured forms by instantiating the proposed template model (Fig.5(b)), and stores them in the module base (Fig.5(c)).

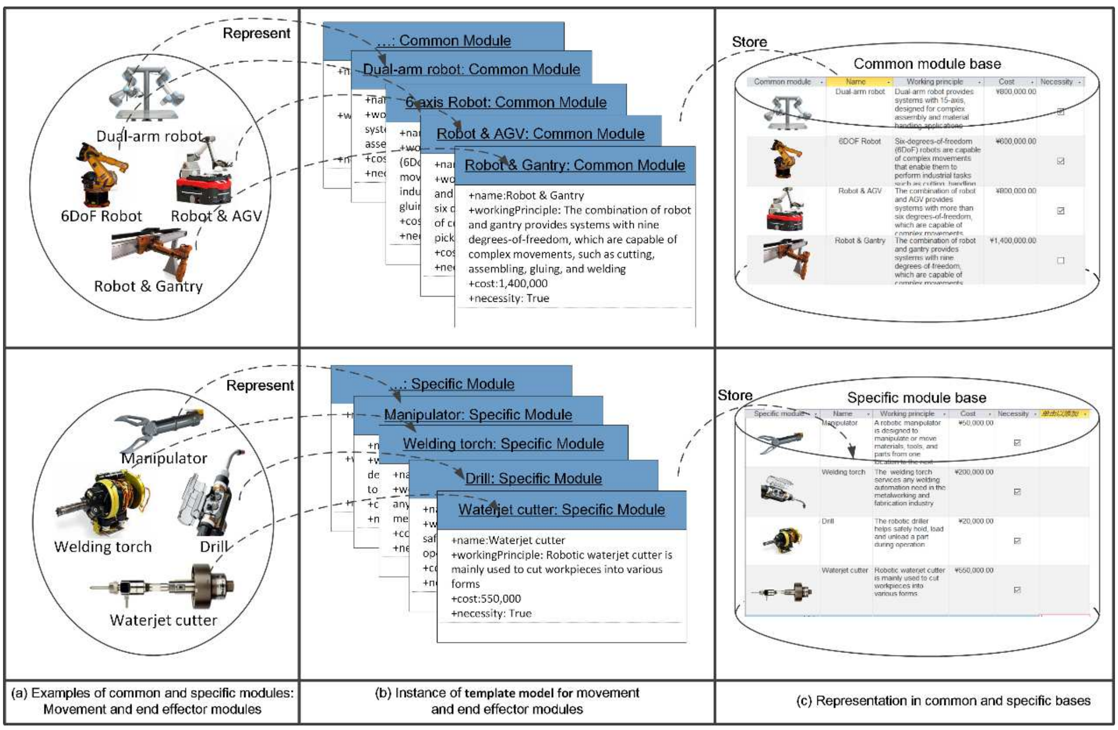

Fig. 5 Classification, representation and storage of existing modules

The authors' design team is required by two SMEs of different industrial manufacturing domains to develop two robotic manufacturing systems. The SME A is a superhard material company in Xi'an (an inland city of China), and it needs an automated ceramic matrix composite materials (CMC) cutting system to cut workpieces made of CMC materials into various forms, according to different industrial uses. The SME B is a shipbuilding company in Shenzhen (a coastal city of China), which requires the authors' design team to develop a robotic manufacturing system for robotising welding tasks.

The authors' design team captures the design requirements of the automated CMC materials cutting system and robotic welding system, and then propose several candidate templates of the required manufacturing system by selecting existing modules from the module base and checking the compatibility of the interfaces between modules (Fig. 6).

Fig.6 (a) shows the proposed architecture of the two robotic manufacturing systems. The main modules are represented as blue boxes, while the interfaces among modules are represented in purple. The details relating to the proposed architecture of the two robotic manufacturing systems is presented as follows: supported by the position detection module (CM^7) which can detect the welding seams (or the cutting shapes), the off-line program sub-system (CM^2) generates the collision-free trajectory. Executing the off-line program, the control module (CM^4) enables the movement module (CM^1) to move the end effector module (SM^1) to the starting point of the welding seams (or the cutting shapes). Fig. 6 (b) illustrates solutions selected from the module base by designers for the proposed common and specific modules.

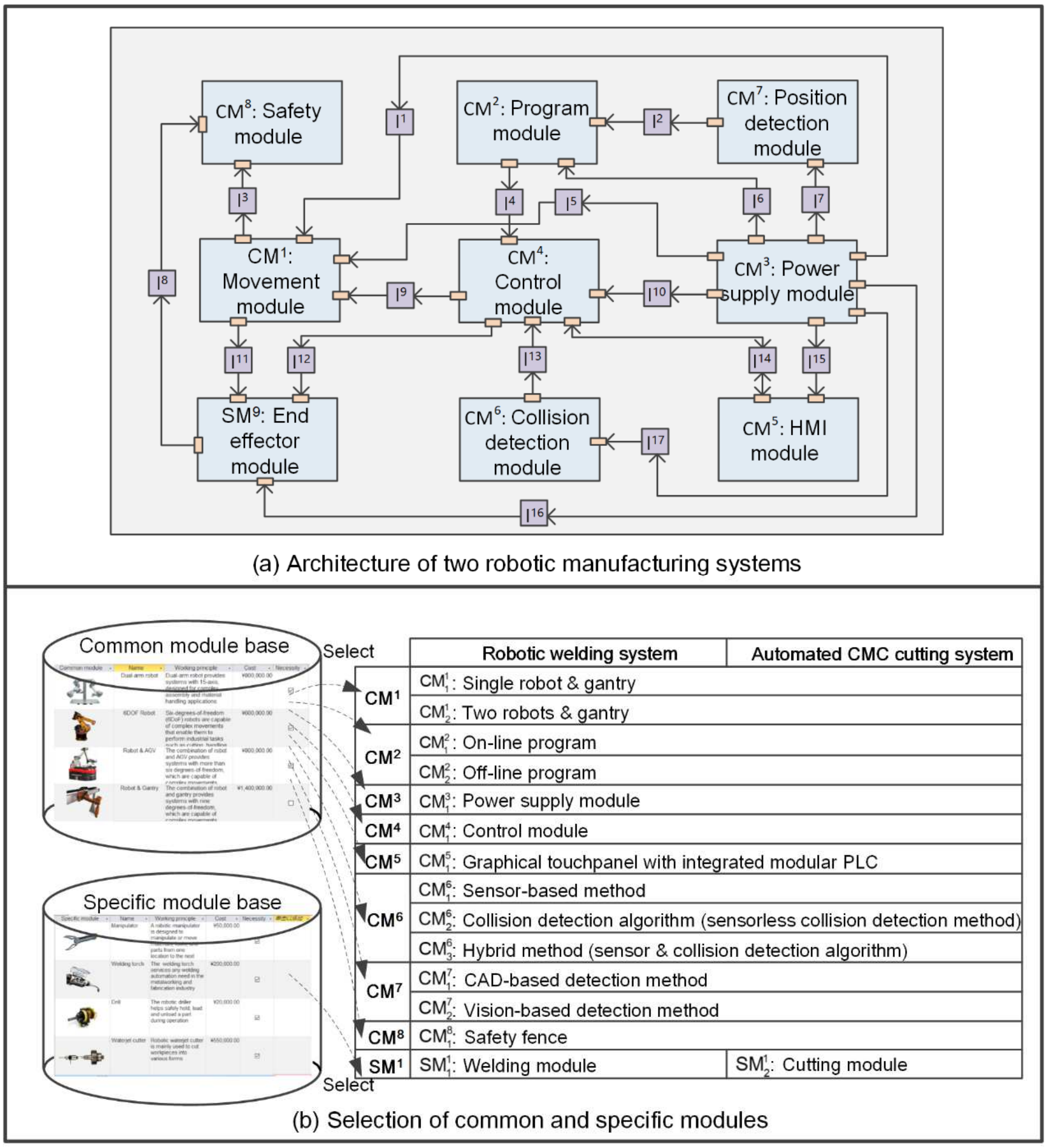

Fig. 6 Proposition of system templates for two manufacturing systems

By reading the basic information relating to each module stored in the open design platform, the customers can have a general idea about the basic working principle of each module and estimate the cost of the entire system. Table 3 presents the customers' template selection results of two manufacturing systems.

Table 3 Template selection results of two manufacturing systems

Module	Robotic welding system	Automated CMC cutting system
CM^1	CM_2^1: Two robots & gantry	CM_1^1: Single robot & gantry
CM^2	CM_2^2: Off-line program	CM_2^2: Off-line program
CM^3	CM_1^3: Power supply module	CM_1^3: Power supply module
CM^4	CM_1^4: Control module	CM_1^4: Control module
CM^5	CM_1^5: HMI module	CM_1^5: HMI module
CM^6	CM_3^6: Hybrid method	CM_3^6: Sensor-based method
CM^7	CM_2^7: Vision-based detection method	CM_1^7: CAD-based detection method
CM^8	CM_1^8: Safety fence	CM_1^8: Safety fence
SM^1	SM_1^1: Welding module	SM_2^1: Cutting module

Considering the template selection result, designers further decompose the modules of the selected template into components. Table 4 illustrates the design alternatives for each component of the robotic welding system.

Table 4 Components and their alternatives - example of robotic welding system

Selected module of robotic welding system	Components of each module	List of alternative components
CM_2^1	M^1: Robot	M_1^1: Yaskawa AR1730
		M_2^1: KUKA KR16-2C
	M^2: Servo-motor	M_1^2: Bosch Rexroth MSK061C-0300-NN-S1-UG1-NNNN
		M_2^2: Delta ECM-E2M-D11315RS0
	M^3: Linear motion rail	M_1^3: THK HSR-35B
	M^4: Linear bearing	M_1^4: THK LR50130
	M^5: Gearbox	M_1^5: SHXTM ZF80
	M^6: Other mechanical parts of gantry	M_1^6: Local machining company
CM_2^2	M^7: Off-line program	M_1^7: Proposed by authors' research team
CM_1^3	M^8: PLC power supply unit	M_1^8: SANTAK Rack3KS
	M^9: Cables	M_1^9: Local cable manufacturer
CM_1^4	M^{10}: Robot controller	M_1^{10}: KUKA KR C4
		M_2^{10}: Yaskawa YRC1000
	M^{11}: Gantry controller (programmable logic controller - PLC)	M_1^{11}: BECKHOFF C6930
		M_2^{11}: SIMATIC S7-400
CM_1^5	M^{12}: Graphic touchpanel with integrated modular PLC	M_1^{12}: SIMATIC HMI KTP400
		M_2^{12}: BECKHOFF CP6942-0001
	M^{13}: Robot control panel	M_1^{13}: KUKA SmartPAD holder
		M_1^{14}: Yaskawa Smart Pendant
CM_3^6	M^{14}: Collision detection algorithm	M_1^{14}: Proposed by authors' research team
	M^{15}: Collision avoidance sensor	M_1^{15}:TBi KS-2 Safety-off mechanism
		M_2^{15}: iCAT ABIROB W cpl
CM_2^7	M^{16}: Camera	M_1^{16}: Baumer XC100
		M_2^{16}: Cognex CIC 2000
	M^{17}: Image reconstruction algorithm	M_1^{17}: Proposed by authors' research team
CM_1^8	M^{18}: Safety fence	M_1^{18}: Local machining company

SM_1^1	M^{19}: Welding machine	M_1^{19}: Panasonic YD-500GP5
		M_2^{19}: KempArc SYN 500
	M^{20}: Welding torch	M_1^{20}: ABIROB W500
		M_2^{20}: TBi RM 82W-22
	M^{21}: Welding seam tracking system	M_1^{21}: Intelligent Laser IL-UNI seam tracker
		M_2^{21}: DIGI-LAS/MDL Laser joining head

Following the step in which designers propose the list of alternative components, the components suppliers are required to provide the information relating to each alternative (Fig.7(a)) and store the information in the open design platform by instantiating the proposed template model (Fig.7(b)). Then, designers evaluate the performance of combinations of different possible alternative components and select the optimal one based on multiple criteria. Criteria to evaluate each combination are proposed by designers according to the system constraints, such as physical size, weight, operation simplicity, etc., and the level of request on component suppliers, such as price, delivery time, confidence level, etc. To evaluate these alternatives and select the most suitable combination, a smart search algorithm based on the multi-attributes decision-making model is proposed and stored in the configuration rule (Fig.7(c)). According to the proposed algorithm, designers can obtain the best combination as: $(M_2^1, M_1^2, M_1^3, M_1^4, M_1^5, M_1^6, M_1^7, M_2^8, M_1^9, M_2^{10}, M_1^{11}, M_2^{12}, M_2^{13}, M_1^{14}, M_1^{15}, M_1^{16}, M_1^{17}, M_1^{18}, M_2^{19}, M_2^{20}, M_1^{21})$. Fig.7(d) illustrates the architecture of robotic welding system and its final selection of components.

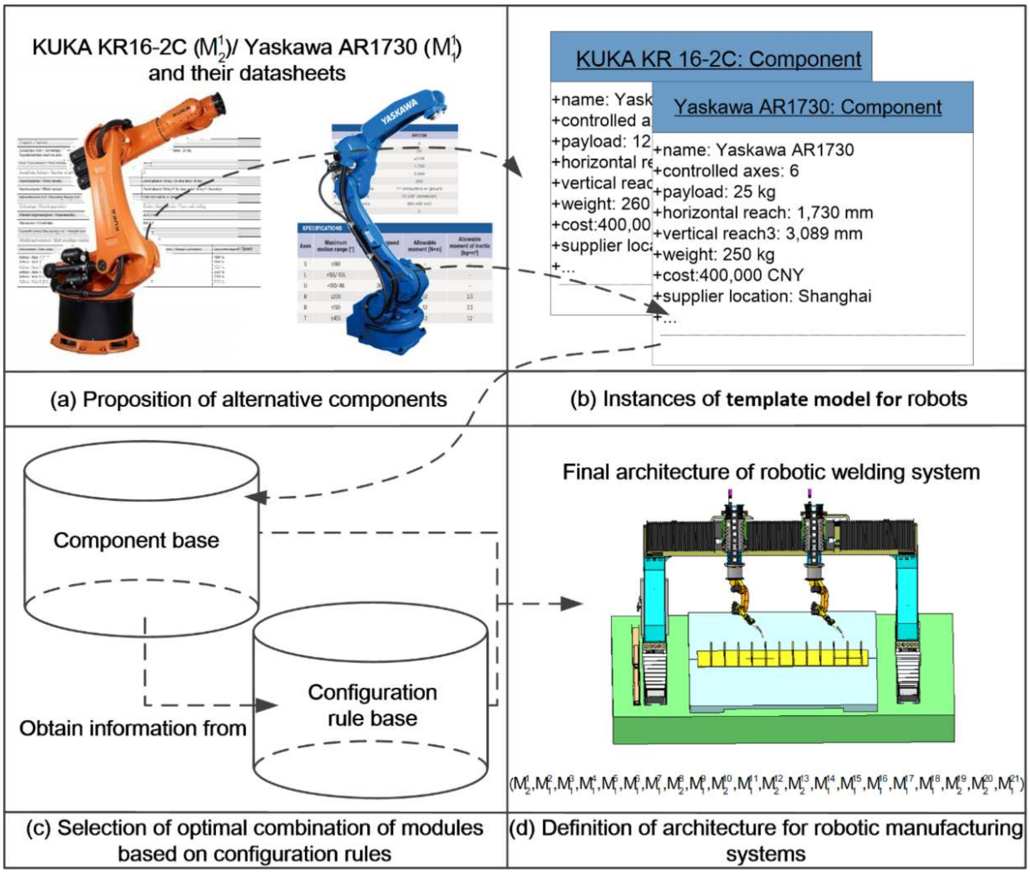

Fig. 7 Component information representation and final component selection - example of robotic welding system

5. Discussion

Considering the challenges of the implementation of robotic manufacturing systems in SMEs, the authors present an SME-oriented flexible design approach in the paper. The proposed method provides the following advantages:

- Firstly, as to the solution to the conflict between development cost of flexible manufacturing systems and financial burdens of SMEs, the proposed design approach provides designers with a template to define the basic architecture of manufacturing systems. Moreover, the template offers designers the possibility to rapidly switch the development of one manufacturing system to another (i.e., configurable product family), so that the development cost can be greatly decreased.

- Secondly, the authors propose the design approach in which SMEs can configure the manufacturing system through selecting modules among various alternatives by their own. In this design approach, the template selection and system configuration are not only completed by the professional designers, but also by the SMEs according to their own needs, thus solving the conflict between professional designers and non-professional SMEs.

However, although the authors' research team have applied the proposed design approach successfully in industrial design cases, several perspectives for future research based on this approach are still recommended.

- Continuously growing pressures of increasingly complex market demand companies to develop new strategy to deal with various needs of customers with acceptable quality and affordable cost by considering the socio-economic context of the targeted market. In this new challenged context, frugal innovation theory is put forward by different authors. Frugal innovation is defined as an innovation strategy to create significantly more value by minimising the use of resources such as energy, capital, and time [68]. Therefore, frugal innovation provides the SMEs with a compact physical architecture and more degree of freedom of movement for agile production, which can deal with mass customisation production despite financial, technological, material or other resource constraints. In fact, the design approach in the paper is proposed with respect to one of the basic principles of frugal innovation theory, that is, selecting the suitable alternative components respecting the requirements from regional markets. The authors' research team has already begun the research on the configuration design for defining product architecture and production network to reach frugality goals [69]. However, in order to achieve frugal innovation for robotic manufacturing systems, there are still a lot of further studies to be carried out in the future.

- Although SMEs play an important role in the global economy, however, they are also considered as a significant source of pollution. A report completed by the Commission of the European Communities points out that SMEs are responsible for 64% of the overall environmental impact in the European Union, including greenhouse gas emissions [70]. In

China, more than 80% of SMEs have environmental pollution problems and account for 60% of the total pollution in the country [7]. Therefore, "dematerialisation" becomes a new development trend for SMEs. In other words, how to aid SMEs in creating non-physical service that provide users with the same level of satisfaction as the physical product with an inherently lower environmental burden has attracted increasing attention from both academia and industry. The proposed design approach in the paper can help designers to design robotic manufacturing systems for SMEs to produce physical products. However, it cannot fully support the service design for SMEs. Therefore, large amount of efforts is still required to propose a novel approach to help SMEs to develop both physical product and non-physical service.

- Successful development projects require accurate cost defining. Cost estimations predict the resources and their costs required during the development process of robotic manufacturing systems, which helps designers to satisfy customer requirements within the approved budget. However, defining the development cost is a difficult task. On the one hand, the development process can be affected by various risks, so it is significant to build allowances into cost estimations. Risk identification and allocation of contingency reserves are the most common approaches. On the other hand, even considering all risks when estimating the development cost, the estimation may still contain some degree of uncertainty. Therefore, the estimates should be overestimated rather than underestimated, and designers should establish tolerance levels for cost deviation. Although various cost estimating software and different development cost estimating methods have been developed to help designers to define the development cost, however, providing an accurate cost estimates is still a challenging issue, which not only demands estimating techniques, but also requires designer experiences. Interested readers are referred to [71] for more information about the techniques relating to the cost estimation.

- Future work should also focus on the implementation of the proposed design approach in an expert home-made PLM system. Even though the authors' research team has developed a design platform based on 3DEXPERIENCE of Dassault Systèmes to help designers partially achieve the automated design for mechatronic systems [52]. However, large amount of efforts is still required by the development of an expert system which can realise the automated conceptual design process for robotic manufacturing systems as well as more complex interdisciplinary system design problems in a life cycle view.

• Conclusion

Considering the challenges of the implementation of robotic manufacturing systems in SMEs, the authors present an SME-oriented flexible design approach in the paper. The main contributions of the work lie on the following two levels. From the designers' perspective, the proposed design approach provides designers with a template to aid them in defining the basic architecture of robotic manufacturing systems, which offers designers the possibility to rapidly switch the development of one manufacturing system to another, so that the flexibility in design can be therefore achieved because even though the customers change their requirements or put forward new requirements, designers can always propose a new configuration of modules with a few changes. Therefore, the development lead-time and cost can be greatly decreased. From the customers' perspective, the authors propose the design approach in which SMEs can configure the manufacturing system through selecting modules among various alternatives by themselves according to their design requirements and financial resources, thus solving the conflict between professional designers and non-professional SMEs and reaching the goal of flexibility in customisation.

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