Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 55-2 (2022) 475–480

Conceptual Design of Intelligent Manufacturing Equipment Based on a Multi-source Heterogeneous Requirement Mapping Method

Bo Wu[a,b], Wu Zhao[a,b*], Huicong Hu[c], Ying Liu[d], Junjie Lv[e]

[a] School of Mechanical Engineering, Sichuan University, Chengdu, 610065, China
[b] The Innovation Method and Creative Design Key Laboratory of Sichuan Province, Sichuan University, Chengdu, 610065, China
[c] Department of Design, Harbin Institute of Technology (Shenzhen), Shenzhen, Guangdong, 518000, China
[d] Institute of Mechanical and Manufacturing Engineering, School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK
[e] State-Grid Sichuan Electric Power Company Tianfu New Area Power Supply Company, Chengdu, 610041,China

*Corresponding author. E-mail: zhaowu@scu.edu.cn

Abstract: Intelligent manufacturing equipment constitutes important prerequisite and foundation for processing and manufacturing. In its conceptual design process, functional determination based on customer needs (CAs), intelligence demands (IDs) and manufacture constraints (MCs) is the prerequisite and basis for subsequent design work. As these various requirement information becomes more complex and mixed, a practical design method will improve the design efficiency of this type of problem. Although research on requirement acquisition and transformation methods has been intensively studied, this problem is still difficult to solve by traditional methods due to the multi-source heterogeneous characteristics of requirement information. To overcome this problem, a requirements mapping methodology is proposed to decompose and transform multi-source heterogeneous requirements and map them to different functional knowledge (FK). Multi-source design requirements are categorized by different objectives such as manufacturing, customer, and intelligence, and these heterogeneous information is analyzed by the decomposition method corresponding to them. The conceptual scheme (CS) is derived through a four-step selection process: requirement set (RS) determination, FK mapping, knowledge combination, and scheme evaluation. The prototype design and an experimental study of a brand-new intelligent folding gantry crane is conducted. The results show that the proposed method can not only improve the design efficiency of intelligent manufacturing equipment, but also reduce the repetitive work in the detailed design stage.

Copyright © 2022 The Authors. This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

Keyword: Product design; Collaborative design; Intelligent manufacturing.

1. INTRODUCTION

In recent years, the development of a new generation of information technology has brought new opportunities for industrial transformation to the manufacturing industry. As the foundation of the manufacturing industry, intelligent manufacturing equipment (IME) plays an important role in the transformation. IME refers to various types of manufacturing equipment with functions such as prediction, decision-making, control, and execution (Fu 2014), which mainly include high-end CNC machine tools, advanced assembly equipment, intelligent measurement and control devices, and so on. At present, the requirement for intelligent manufacturing equipment has become more accessible but also more complex due to the expansion of data (Wan 2018). Because in the conceptual design process of IME, not only the customer needs should be considered, but also the important information of the manufacturing process and the emerging intelligent demands should be put on an equal footing. And the information from a wide range of sources is often unstructured and irregular expression, which also brings challenges to the designer's work.

The researcher's goal is to establish a conceptual design framework based on the multi-source heterogeneous requirement mapping relationship, and generate a suitable design scheme based on the complex requirement information in the conceptual design stage. Under the guidance of this framework, multi-source design requirements are categorized by different objectives such as manufacturing, customer, and intelligence, so that various requirements and constraints are fully considered in the design stage. Through the mapping between requirements and functions, functions and functional knowledge (FK), multiple sets of alternative conceptual design schemes are formed. The framework adopts a multi-source heterogeneous requirement mapping method to improve the design efficiency of equipment and improve the degree of satisfaction of equipment to various requirements. Taking the conceptual design of intelligent folding gantry crane as an example, the feasibility of the proposed method is demonstrated.

2. RELATED WORK

2.1 Customized product concept design process

In order to enhance product innovation capabilities and shorten the design cycle, customized products have become the main development trend of the market (Liang, H. at al. 2004). The process of customized product conceptual design is the process of analysing functional requirements and generating product scheme (Zheng, H. 2018). Researchers have proposed some classical design methods such as empathic design and modular

2405-8963 Copyright © 2022 The Authors. This is an open access article under the CC BY-NC-ND license.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2022.04.239

design. Osório (2019) developed a method that will minimize the energy cost for a customized design of a quasi-stationary CPC-type collector. Zhang (2020) proposed a complex electromechanical system with a recessive inheritance mechanism to cope with the complexity of the system caused by increased requirement. In addition, our research team took a brand-new friction-wear testing machine (Guo, X. 2021a) and hard rock coring system (Guo, X. 2021b) as examples to study the conceptual design method of the product.

However, these related studies have not yet involved the research of intelligent manufacturing equipment, so it is still necessary to study the design methods of such important basic equipment.

2.2 *Requirement analysis and transformation*

In the era of big data the sources of information have become more numerous, which also increases the access to requirement. It is clear that requirement is not just from customers today, but is driven by multiple sources. Hellmuth (2020) studied the requirement from digital building models for factory building conversion. Chu (2016) proposed that manufacturing can be used as a tool to improve the design of the product, and discussed the importance of manufacture constraints on product design.

In addition, the requirements from different sources are often heterogeneous. To better exploit these requirements, Chen (2020) proposed a novel ontology-based requirement verification method to solve the problems; Wang (2019) integrate heterogeneous data sources into a holistic consideration in the proposed graph-based requirement acquisition framework.

Previously, the concept of multi-source heterogeneity was often found in the field of data information, but with the expansion of information, the requirement information has become complex and mixed. The analysis method of multi-source heterogeneous requirements in conceptual design should be further investigated.

3. FRAMEWORK

This paper proposes a requirement mapping method that supports IME conceptual design, which mainly includes four steps: requirement set (RS) determination, FK mapping, knowledge combination, and scheme evaluation. The framework of this method is shown in Fig. 1. In this framework, the conceptual design process starts with multi-source heterogeneous requirements and ends with conceptual scheme generation. A requirement decomposition rule is proposed, which provides a basis for decomposing complex requirements into requirement units. A transformation means is proposed to establish a mapping relationship between the structured expression RS and the function requirement (FR). Using the mutual combination of functional knowledge, multiple sets of conceptual design schemes are generated to meet the requirements. Finally, the dual evaluation criteria of economic index and technical index are adopted to select a more reasonable conceptual scheme. The framework refers to the FBS and Axiomatic Design (AD), forming a requirement-function-structure design process. On the basis of the method shown in Fig. 1, Section 4 explains the IME conceptual design process and method in detail through the introduction of principles and theory.

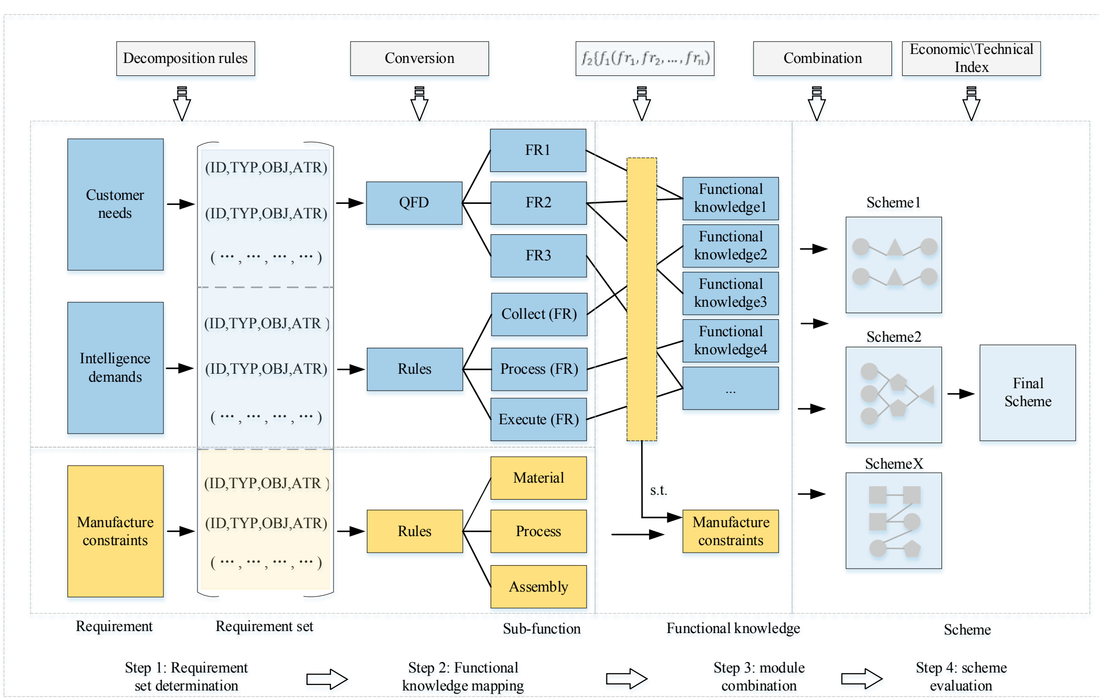

Fig. 1. A requirement mapping framework for conceptual design

4. METHODOLOGY

4.1 Multi-source requirement analysis

In the axiomatic design theory, the design process is divided into customer domain, functional domain, physical domain and process domain. The elements in the customer domain are customer needs/attributes, which are the needs of Customer. In view of the particularity of intelligent manufacturing equipment, we believe that in addition to customer needs, there are many other sources of requirement information, of which manufacture constraints and intelligence demands are extremely important (Fig. 2). The three types of requirement information need to be analysed in detail in order to provide basis and constraints in subsequent design tasks.

Customer needs (CAs): customer needs refer to the customer's needs for intelligent manufacturing equipment in terms of function, performance, price and other aspects. This information directly comes from the customer, reflecting the object of design research and the problem to be solved, and it plays an important role in guiding the development, design and even the structure of the equipment (Sun 2020). The customer needs obtained in this paper are represented by a set of CAs, $\mathrm{CAs} = \{CA_1, CA_2, CA_3, \ldots, CA_n\}$.

Intelligence demands (IDs): intelligence demands are the requirements put forward by customers for the intelligence of products. Kiritsis (2011) define intelligent products as systems with different intelligence levels that include functions such as sensing, memory, data processing, reasoning, and communication. That is to say, intelligence is mainly reflected in the imitation of human eyes, hands, brain and other functional organs by the product. Therefore, the demand for intelligence can be decomposed according to the level of intelligence, and the decomposition mode is relatively fixed. We expresses intelligence demands with set IDs, $\mathrm{IDs} = \{ID_1, ID_2, ID_3, \ldots, ID_n\}$.

Manufacture constraints (MCs): manufacture constraints refer to the requirement information from the manufacturing side. As equipment for manufacturing other products, the design process of intelligent manufacturing equipment should have the materials, geometry and topology of manufacturing being considered (Würtenberger 2018). Taking aero engine processing equipment as an example, aero engine components have many special and extreme requirements for processing equipment duo to the characteristics of materials and structures, so these technical requirements should be considered in the conceptual design stage of processing equipment. We use set MCs to represent manufacture constraints, $\mathrm{MCs} = \{MC_1, MC_2, MC_3, \ldots, MC_n\}$.

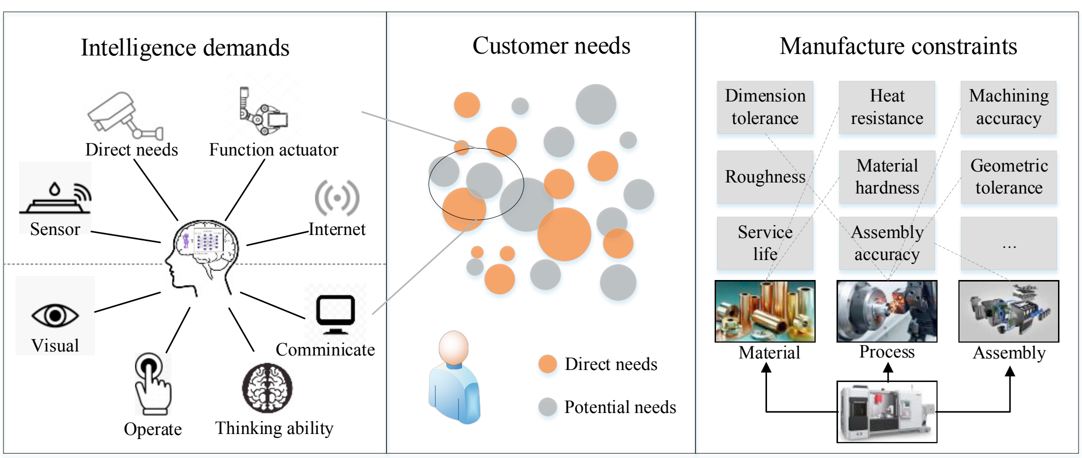

Fig. 2. Analysis multi-source heterogeneous requirement consisting of CAs, IDs, MCs

4.2 Conversion of heterogeneous requirement

In addition to having different sources, the requirements also have non-standard and unstructured characteristics. This paper refers to the concept of requirement unit proposed by Sheng (2015), and decomposes the requirements into the smallest unit that cannot be further subdivided. The decomposition process of heterogeneous requirements can be represented as:

$$RS = \{RU_1, RU_2, RU_3, \ldots, RU_4\} \tag{1}$$

Where RU stands for requirement unit and RS denotes the requirement set consisting of requirement units. In order to effectively call the requirements information in the subsequent mapping process, the requirement unit is standardized and structured as:

$$RU = \{id, type, objective, attributes\} \tag{2}$$

In the above formula, id represents the index number of RU, $type$ represents the type of RU, $objective$ represents the object of the requirement information, and $attributes$ represents the specific technical attributes. The formulation of RU decomposition rules refers to the independent axioms and information axioms of AD theory, and is improved according to the actual characteristics of intelligent manufacturing equipment.

1. *Rule of Independence:* The information carried between RUs should be independent of each other without interference.

2. *Rule of minimum information:* requirement should be divided into the smallest unit that cannot be further subdivided, that is, the amount of information contained is the least.

3. *Rule of similarity merging:* Similar requirement units should be merged.

4. *Rule of semantic consistency:* RUs should correspond to requirements and be consistent with requirements in meaning.

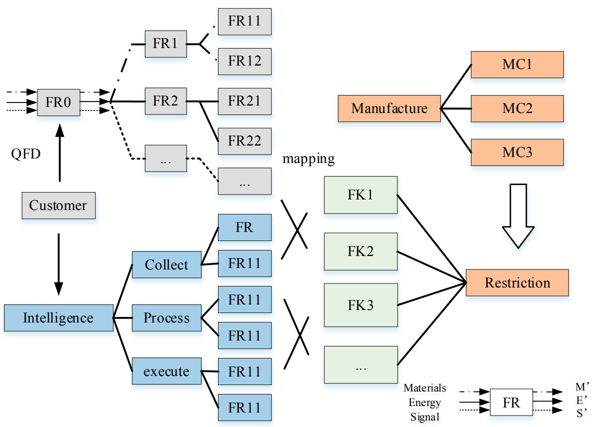

Fig. 3. Conversion of heterogeneous requirements to function requirement

Quality Function Deployment (QFD) can effectively analyse and integrate requirement information and function requirements (Hauser 1988), and its core is a binary matrix of house of quality (HoQ) for requirement conversion.

The requirement unit and its importance constitute the left end of the HoQ, and its importance rate can be determined by the analytic hierarchy process (AHP). At the top of the house of quality are the technical features or functional attributes of the equipment. They are described by engineering language to express the specific requirements of the equipment. There may be mutual obstruction, mutual promotion, or non-correlation between the requirement unit and the functional attributes, and the correlation matrix representing the mapping relationship is established through these correlations.

For the entire equipment system, the performance of the function is that the system has the characteristics of transforming materials, energy and signal (Pahl 2007). In order to reduce the complexity of the equipment design, the functional flow-based representation method (Al-Fedaghi 2016) is used to gradually decompose the functions corresponding to the RU. Functional flow includes material flow, energy flow and signal flow. As the flow branches and spreads, the function is gradually decomposed into more detailed sub-functions, and the specific conversion process is shown in Fig. 3.

Due to its characteristics, intelligence demands can adopt a fixed decomposition mode, which can be decomposed according to the classification of collection function, processing function and executive function. Manufacturing constraints are mainly some parameterized conditions of processing feedback. We express them in the form of ‘objective+ attribute’, and these MCs plays a restrictive role in the mapping relationship between function requirement and functional knowledge.

4.3 Mapping between functional knowledge and functions

Functional knowledge describes the basic elements that are necessary to implementation of sub-functions. A single functional knowledge may be related to multiple function requirements, and the realization of some functions requires the collaboration of multiple functional knowledge. Therefore, there is a many-to-many mapping relationship between functional knowledge and function requirement (Fig. 4).

Set $\{fk_1, fk_2, fk_3, \ldots, fk_n\}$ represents the functional knowledge FK, and set $\{fr_1, fr_2, fr_3, \ldots, fr_n\}$ represents the decomposed equipment function requirement FR, then the mapping relationship between the functional knowledge and the function requirement can be expressed as follows:

$$FR \rightarrow FK : (fk_1, fk_2, \ldots, fk_n) = f_1(fr_1, fr_2 \ldots, fr_n) \quad (3)$$

Since the constraints of manufacture requirements need to be considered in the mapping process, these constraints are expressed by the function f_2, and the mapping relationship can be expressed as:

$$FR' \rightarrow FK' : (fk'_1, fk'_2, \ldots, fk'_n) = f_2\{f_1(fr_1, fr_2, \ldots, fr_n) \quad (4)$$

The different combinations of these functional knowledge can meet the function requirements in different realization forms, which makes intelligent manufacturing equipment have specific functions, structures and levels.

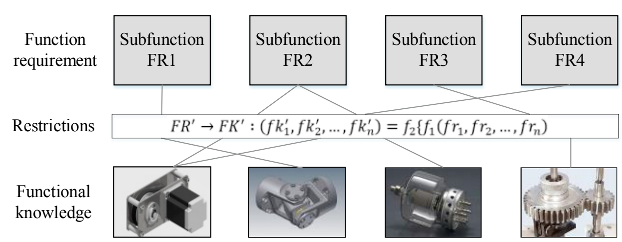

Fig. 4. Function requirements-functional knowledge many-to-many mapping process

4.4 Scheme evaluation

Since there are multiple combinations to achieve the design goals, this paper uses the technical index and economic index to score each scheme. A high economic index indicates that among the alternatives, this option is the most economical; a high technical index indicates that the alternative is the best technical option.

Assuming that there are n alternative design schemes, the technical index of scheme i is equal to the proportion of the technical score of this scheme in the total technical scores of all schemes:

$$TI_i = \frac{TS_i}{\sum_{i=1}^{n} TS_i} \qquad (i = 1,2, \ldots, n) \qquad (5)$$

The economic index of the scheme i is equal to the proportion of the economic score of this scheme in the total economic score of all schemes:

$$EI_i = \frac{ES_i}{\sum_{i=1}^{n} ES_i} D \quad (i = 1,2,\dots,n) \tag{6}$$

Where ES_i and EI_i respectively represent the economic score and economic index of the i-th scheme.

Under different design situations, the importance of economy and technology of the scheme is different. Therefore, the weighted geometric average of technical index and economic index is used as the evaluation basis of the scheme:

$$Wgn_i = \sqrt{\alpha EI_i \times \beta TI_i} \qquad (i = 1,2,\dots,n) \tag{7}$$

Where Wgn_i represents the weighted geometric average value of the i-th scheme, α represents the economic weight of the scheme, and β represents the technical weight of the scheme$(0 < \alpha < 1, 0 < \beta < 1)$.

5. CASE STUDY

5.1 Case introduction

Gantry crane is an important lifting and transporting machinery, which is widely used in workshops, warehouses and other places. Fig. 5 shows a brand-new intelligent folding gantry crane. However, in a complex environment with limited space, cranes are greatly restricted in terms of size, power, accuracy, etc. Therefore, in order to ensure that the crane works normally in a restricted environment, it is necessary to refer to the multi-source heterogeneous requirements in the conceptual design process.

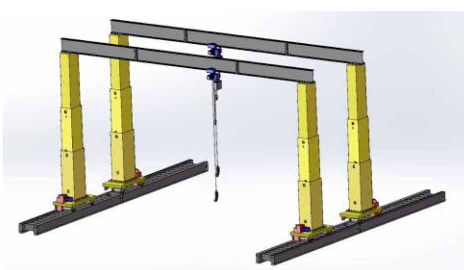

Fig. 5. A brand-new intelligent folding gantry crane

The gantry crane mainly includes telescopic mechanism, walking mechanism and load-bearing beam. Among them, the telescopic mechanism is an important part of the crane and the main component that supports the load-bearing beam. Its capacity is critical to the performance of the crane under different working conditions. Based on the above analysis, this article conducts further research on the telescopic mechanism.

5.2 Research and analysis

The reason for using the telescopic mechanism in folding gantry crane is that the telescopic mechanism can freely adjust the vertical height while supporting the weight of the beam, which is conducive to working in a space-constrained environment. According to the proposed framework, the requirements of the telescopic mechanism are analyzed and transformed. Limited by the user's professional knowledge, most CAs fall under the requirement for equipment functionality; IDs are decomposed according to the three categories of collection, processing, and execution to facilitate subsequent detailed design. For telescopic mechanism, MCs are important constraints. The working environment has restrictions on the overall size and telescopic size. The load weight of the crane puts forward requirements on the strength of the telescopic mechanism, and the accuracy of the lifting also affects the conceptual design of the telescopic mechanism. The partial decomposition results are shown in Table 1:

Table 1. Decomposition results

Type	RS	FR	FK
CAs	{01,Functional,Pillar,Dimensions can be adjusted}	Telescopic	Slide rail
	{02,Functional,Telescopic arm, Auxiliary telescopic}	Guide	Guide sleeve
IDs	{01,Functional,Additional modules, Position detection}	Collect	Sensor
	{02,Functional,Additional modules, Error judgment}	Process	Neural network
MCs	{01,Strength,Plug pin, Yield limit≤70Mpa}	——	——
	{02,Strength,Telescopic arm, Maximum stress≤540Mpa}	——	——

According to the above analysis, several combinations of telescopic mechanisms have been proposed, and the most suitable one has been selected based on economic and technical evaluations. As shown in Fig. 6:

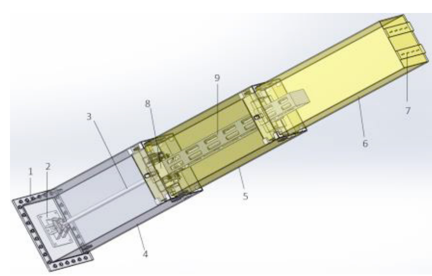

Fig. 6. Single-cylinder latch-type telescopic mechanism

The researchers used ANSYS Workbench to perform dynamic and static analyses of the scheme, including the response of the structure under static loading of the telescopic mechanism and the modalities of the telescopic arm under vibration conditions. The results are shown in Fig. 7.

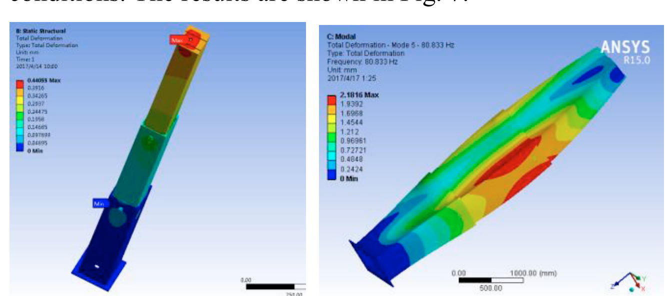

Fig. 7. Total deformation nephogram and modal analysis of telescopic mechanism

According to the mechanical analysis, the maximum stress value of the mechanism $\sigma_2 = 286.42$Mpa. Yield limit $\sigma_s =$

$540Mpa$ .The maximum stress value is less than the manufacturing constraint, so the strength meets the requirements. The local extrusion stress $\sigma_2 = 63.1Mpa$, which is less than the manufacturing constraint 70MPa, which further verifies the reliability of the scheme.

6. CONCLUSIONS

Intelligent manufacturing equipment provides various tools and equipment for the industry. It is the cornerstone and cradle of the entire industrial system. As the requirements become more complex and mixed, it is necessary to study the multi-source heterogeneous requirement mapping method in the conceptual design process of IME. In the present study, a framework are proposed to support the conceptual design of IME, which are mainly divided into 4 steps: (1) requirement set determination, including the decomposition of multi-source requirements and the formatted expression of heterogeneous requirements. (2) FK mapping, when the requirements are converted to function requirements, match the appropriate functional knowledge for FR according to the mapping relationship. (3) FK combination, different functional knowledge combinations can produce multiple alternative design scheme. (4) scheme evaluation, according to economic index and technology index evaluates the alternatives and selects a scheme that is more suitable for the environment. To demonstrate its feasibility, a case study of a brand-new intelligent folding gantry crane is presented. Results have shown that this method can improve the efficiency of IME design. This method considers important manufacturing requirements in the conceptual design stage, and can reduce repetitive work in the detailed design stage. In addition, the establishment of the FK knowledge base and the iteration of the scheme are the future study goals.

ACKNOWLEDGES

This work was partially supported by a National Key Research and Development Project of China (2018YFB1700700), two projects from the Sichuan Science and Technology Program (2021YFH0151).

REFERENCES

Al-Fedaghi, S. (2016) Design functional decomposition based on flow, *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC),* 2693-2698.

Chen, R., Chen, C.H., Liu, Y., & Ye, X. (2020). Ontology-based requirement verification for complex systems. *Advanced Engineering Informatics,* 46, 101148.

Chu, W.S., Kim, M.S., et al. (2016). From Design for Manufacturing (DFM) to Manufacturing for Design (MFD) via Hybrid Manufacturing and Smart Factory: A Review and Perspective of Paradigm Shift. *International Journal of Precision Engineering and Manufacturing-Green Technology,* 3(2), 209–222.

Dimitris Kiritsis. (2011). Closed-loop PLM for intelligent products in the era of the Internet of things. *Computer-Aided Design,* 43(5), 479-501.

Fu, J.Z. (2014). Development status and trend of intelligent manufacturing equipment. *Journal of Mechanical & Electrical Engineering,* 31(8), 959-962.

Guo, X., Zhao, W., Hu, H., Li, L., Liu, Y., Wang, J., & Zhang, K. (2021). A smart knowledge deployment method for the conceptual design of low-carbon products. *Journal of Cleaner Production,* 321, 128994.

Guo, X., Liu, Y., Zhao, W., Wang, J., & Chen, L. (2021). Supporting resilient conceptual design using functional decomposition and conflict resolution. *Advanced Engineering Informatics,* 48, 101262.

Hauser, J. R. (1988). *The House of Quality,* 63–73. Harvard Business Review, Boston.

Hellmuth, R. (2020). Method for requirements elicitation and traceability in a factory building conversion. *Procedia Manufacturing,* 51, 943–952.

Hou, L., Tang, R., Xu, Y. (2004). Review of theory, key technologies and its application of modular product design. *Chinese Journal of Mechanical Engineering,* 40(1), 56-61.

Osório, T., Horta, P., Collares-Pereira, M. (2019). Method for customized design of a quasi-stationary CPC-type solar collector to minimize the energy cost. *Renewable Energy,* 133, 1086–1098.

Pahl, G., Beitz, W. (2007). *Engineering design: A systematic approach,* Springer, London.

Sheng, Z., Wang, Y., Song, J., & Xie, H. (2015). Customer requirement modeling and mapping of numerical control machine. *Advances in Mechanical Engineering,* 7(10), 1-11.

Sun, H., Guo, W., et al. (2020). Dynamical mining of ever-changing user requirements: A product design and improvement perspective, *Advanced Engineering Informatics,* 46, 1474-0346.

Wan, J., Li, J., Hua, Q., et al. (2020) Intelligent equipment design assisted by Cognitive Internet of Things and industrial big data. *Neural Computing & Applications,* 32, 4463-4472.

Wang, Z., Chen, C. H., Zheng, P., Li, X., Khoo, L. P. (2019). A novel data-driven graph-based requirement elicitation framework in the smart product-service system context. *Advanced Engineering Informatics,* 42, 100983.

Würtenberger, J., Reichwein, J., & Kirchner, E. (2018). Using the potentials of additive manufacturing by a systematic linkage of the manufacturing process to product design. *Proceedings of the DESIGN 2018 15th International Design Conference,* 1465–1476.

Zheng, H. (2018). The Solving Process of Conceptual Design for Complex Product Based on Performance Evolution. *Journal of Mechanical Engineering,* 54(1), 214.

Zhang, P., Nie, Z., Dong, Y., Zhang, Z., Yu, F., & Tan, R. (2020). Smart concept design based on recessive inheritance in complex electromechanical system. *Advanced Engineering Informatics,* 43, 101010.