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Investigating product innovation pathway from a modular standpoint: A case study of large aircraft assembly line

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ABSTRACT

Product innovation is a robust approach for enterprises to acquire and maintain a competitive edge. In order to support the development of enterprise product innovation, it is essential to establish an innovation pathway. Grounded in a modular perspective and considering the product innovation process, this study segments the process into product demand analysis, product module partitioning, product innovation opportunity recognition, and product innovation design. Consequently, an integrated product innovation pathway is constructed by incorporating relevant innovation theories and methodologies, encompassing the innovation process, theory, and methods. The feasibility and efficacy of this research are validated through a case study of a large aircraft assembly line, indicating that this approach effectively bolsters product innovation development and holds practical significance.

1. Introduction

Innovation represents the primary driving force for development and the strategic pillar for constructing a modern economic system. From a business development standpoint, product innovation is a crucial strategy for enterprises to obtain and maintain a competitive advantage [1]. As product innovation evolves, continuous innovation has gradually emerged as a predominant development trend. By continuously innovating, enterprises can enhance their competitive advantage and achieve surplus profits [2,3]. To actualize continuous innovation, enterprises must establish a robust innovation support mechanism and devise a product innovation pathway that guides the realization of product innovation.

Product innovation is a creative activity carried out by enterprises in production practice. It refers to the creation of a new product or the innovation of the functions of a new or old product. According to different classification standards, product innovation also takes different forms. According to the different organizational innovation methods, product innovation can be divided into independent innovation, cooperative innovation [4], and introduced innovation. According to the degree of innovation, product innovation can be divided into breakthrough innovation and incremental innovation [5]. Amid an increasingly competitive market landscape, product innovation is characterized by pronounced uncertainty, substantial complexity, and high costs [6]. These factors contribute to a high failure rate for product innovation, hindering its development to a certain extent. In order to cope with market competition and demand, product innovation requires a shorter development cycle, a more flexible design method, and a lower design cost. Under these

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conditions, product innovation based on a modular perspective emerged as the times required.

Product innovation from a modular perspective is a process that starts from the perspective of system composition, uses decomposition and combination methods to achieve modular decomposition of products, and reconstructs products through the systematic combination of modules. Based on this method, the product is decomposed into different modules. R&D personnel can arrange and combine the modules to find the maximum number of combination solutions from the limited modules, find the appropriate combination, and shorten the development cycle. At the same time, the individual use, reuse, and repeated testing of modules also dramatically reduce the cost of product innovation. Therefore, in product innovation, products can be divided based on modular thinking. On this basis, innovation theories and methods are combined to build product innovation paths, enhance product innovation capabilities, promote product innovation development, and accelerate product innovation.

The remainder of this paper is organized as follows: Section 2 reviews existing product innovation research and examines the application of modular methods in constructing product innovation pathway. Section 3 establishes a product innovation pathway by incorporating the product innovation process, innovation theories, and innovation methodologies, subdividing the process into product demand analysis, product module partitioning, product innovation opportunity recognition, and product innovation design. Section 4 employs a case study of a large aircraft assembly line to validate the research's feasibility and effectiveness through innovative design. Section 5 puts forth relevant recommendations and measures from the perspectives of product module partitioning, product innovation opportunity recognition, and product innovation design. Finally, Section 6 concludes the paper, analyzes the research limitations, and outlines future research directions.

2. Literature review

Product innovation refers to enterprises' imaginative activities within their production practices. At present, research on product innovation primarily emphasizes aspects such as influential factors and inventive design approaches. Regarding the influential factors, numerous academics have delved into both external and internal elements. For example, what impact do enterprise agglomeration [7], enterprise technical capabilities, and product usage costs [8] have on product innovation? In terms of inventive design approaches, certain studies highlight the origins of demand for product innovation design. These investigations typically employ information-based, data-driven methodologies, gathering user requirements as a foundation for creative design [9–11]. Alternatively, other research focuses on the execution of product innovation design, predominantly employing the TRIZ theory. Some research focuses on the realization of product innovation design, mainly through TRIZ theory. For example, the TRIZ method can identify critical issues in the product process and carry out product innovation [12]. Combine QFD and TRIZ methods [13] or combine human-computer interaction (HCI) with TRIZ [14] to achieve technological innovation in new products.

Furthermore, several scholars have investigated product innovation pathway throughout the product innovation process. Jaimovich [15] emphasized the continuous effects of process innovation and product innovation on product revenue growth, suggesting that only when both elements achieve a virtuous cycle can product revenue consistently increase. Chen et al. [16] examined how developing nations should contemplate their unique innovation factors while selecting the most efficacious product innovation pathway within intricate innovation systems. Li et al. [17] introduced an innovative design procedure based on TRIZ and patent evasion, enabling the identification of issues and the construction of solutions utilizing patent evasion techniques. Kumar et al. [18] constructed a technology patent citation network for mobile payment services using patent citation data, analyzing the technological trajectory of mobile payment systems.

Amidst industrial specialization and inter-enterprise division of labor, modularization has gained prominence. In general, products can be subdivided into various modules, each serving a distinct function and manufactured by different enterprises. Enterprises can reduce knowledge and technical barriers through modular partitioning, facilitating product innovation [19]. Consequently, a product innovation pathway can be devised based on modular principles. Initially, the automotive industry broadly applied modular thinking, considerably promoting the sector's product innovation progress [20,21]. Later, numerous academics conducted extensive research on modular product innovation pathway, applying their findings to other industries. Sun and Lau [22] proposed a modular product design system and product development roadmap, validating the presented model with survey data from the electronics and electrical sectors. Wang and Shu [23] introduced a modular-based innovation process for products, wherein the modular product architecture acts as a liaison between a company and its suppliers, finding applications in manufacturing firms. Bai et al. [24] analyzed demand and conflict issues within modular structure design, employed fuzzy clustering algorithms to divide functional modules, and utilized design matrices to scrutinize the coupling relationships between modules, ultimately fostering product innovation.

In summary, current research on product innovation mainly focuses on factors influencing innovation and product innovation design, while relatively fewer studies concentrate on product innovation pathway. Most of these studies merely analyze the process of product innovation, without integrating innovation theories and methods to construct a scientifically sound and comprehensive product innovation pathway. Therefore, it is not easy to systematically support the development of enterprise product innovation activities. Moreover, as the industrial division of labor gradually moves towards specialization, modularization has been widely applied across various industries and can effectively support product innovation. Based on this, this paper adopts a modular perspective, utilizing modular theory and methods to divide products. By integrating internal and external factors to identify product innovation opportunities and implementing innovative designs, this paper ultimately constructs a product innovation pathway that supports continuous product innovation.

3. Implementation mechanism of product innovation path from a modular perspective

3.1. Product innovation path construction

In building a product innovation path, it is necessary to conduct modular division based on structure and function based on product demand analysis. Moreover, it explores the internal and external factors, identifies product innovation opportunities, and carries out innovative designs. On this basis, combine innovation theories and methods to obtain product innovation paths to achieve continuous product innovation. The path is shown in Fig. 1.

As can be seen from Fig. 1, the product innovation path can be divided into three aspects: process level, theoretical level, and methodological level. The process level mainly involves the product innovation process, which consists of product demand analysis, product module division, identification of product innovation opportunities, and product innovation design. Among them, product demand analysis is the input for product innovation. In a complex and ever-changing market environment, grasping current and future product demand is the basis for product innovation. The product module division is the key to product innovation. Based on product needs, by introducing a modular perspective, products can be divided into relatively independent and combinable modules to identify product innovation opportunities and carry out product innovation design. The identification of product innovation opportunities is the focus of product innovation. Directions for product function and structure improvement can be discovered by effectively identifying internal and external product innovation opportunities. Simultaneously, the importance of product innovation opportunities can be ranked to determine the research and development focus, maximizing user satisfaction. The product innovation design part is the core of product innovation. In this stage, the main focus is on realizing product requirements and functions. According to the innovation opportunities, innovative designs are carried out, and the innovative product is ultimately obtained based on the formation of

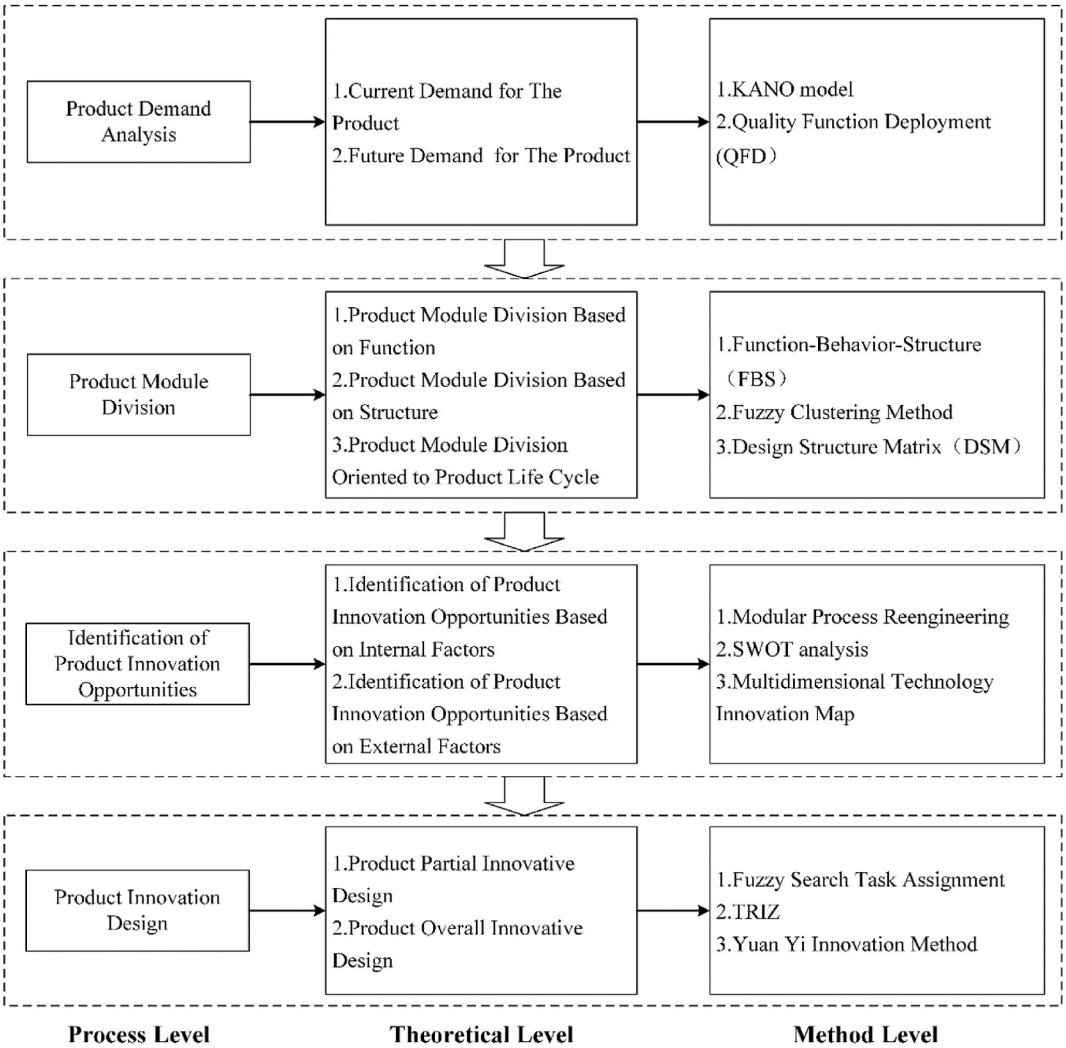


Fig. 1. Product innovation path.

product innovation schemes.

The theoretical level mainly involves the relevant theories in each process. Product demand analysis can be divided into the current demand for the product and the future demand for the product. Product module division can be divided into function-based, structure-based, and product lifecycle-oriented module division. Identification of product innovation opportunity can be divided into external innovation opportunity and internal innovation opportunity identification. Product innovation design can be divided into product partial innovation design and product overall innovation design.

The methodological level mainly involves the methods that may be used in each workflow process. In the product demand analysis process, there are methods such as KANO model, quality function deployment. In the product module division process, there are methods such as Function-Behavior-Structure (FBS), fuzzy clustering, and Design Structure Matrix (DSM). In the identification of product innovation opportunities process, there are methods such as modular process reorganization, Porter's Five Forces model. In the product innovation design process, there are methods such as fuzzy search task allocation, TRIZ theory.

3.2. Product demand analysis

The accurate acquisition and analysis of product needs is the basis and essential link of product innovation. Depending on the time span, product demand can be divided into the current demand for the product and the future demand for the product. The current demand for products is mainly driven by upgrades based on user needs to gain a competitive advantage. The future demand for products is no longer limited to meeting user needs. However, it is based on future goals and technology development to meet users' future demands and even lead and create user needs.

In product demand analysis, the first is to explore product innovation needs from market trends and user feedback based on user needs [25]. The second is to promote product improvement and iteration based on technological development to meet user needs. In the specific implementation process, user needs can be obtained through fuzzy cognitive maps and KANO models, and user core needs can be determined through methods such as QFD and AHP [26]. For product technology development, technology development trends can be obtained through text mining and big data analysis based on patents, papers, user reviews, and other information [27,28]. Finally, the future development needs of the product are analyzed through technological development trends.

3.3. Product module division

Product module division is mainly based on combining product requirements and product module division methods to divide the product into modules. When dividing product modules, depending based on division, product module division methods can be categorized into three types: function-based module division, structure-based module division, and product lifecycle-oriented module division.

Function-based module division methods mainly divide product modules according to the sub-functions realized by the product, generally requiring the establishment of a product function system. By performing functional decomposition and analysis of the product, clustering methods are used to obtain various product modules, with common methods including Function-Behavior-Structure (FBS), fuzzy clustering, and K-means clustering [29]. Structure-based module division methods mainly divide product modules based on the physical structure of the product. Such division methods are generally relatively simple. Modules can be divided according to the product BOM, and the Design Structure Matrix (DSM) can be used to represent the relationships between components [30]. Product lifecycle-oriented module division methods start from aspects such as product function, structure, and materials to achieve multiple goals such as maintainability, recyclability, and upgradability for product modular division. This type of division method is often based on the DSM method and expands upon it, describing the strength of relationships between row and column elements while indicating whether elements are related, and introducing heuristic algorithms for solving classification to obtain product modules.

3.4. Identification of product innovation opportunities

After the product module division, innovation opportunities can be identified based on the divided modules, generally classified into external and internal innovation opportunity identification [31,32].

For external innovation opportunity factors, analysis can be conducted from the market environment and industry technology [33]. From the market environment perspective, the Porter's Five Forces Model can be used to analyze the market competition environment, and SWOT analysis can identify product strengths and weaknesses, thus determining the direction of product innovation. From the industry technology perspective, patent mining and multidimensional technology innovation maps can be used to collect cutting-edge technology information in the industry domain and identify product innovation opportunities through patent mining and analysis.

For internal innovation opportunity factors, introducing product modularization thinking has led most single products to be produced and manufactured by multiple companies, reducing the knowledge barriers between enterprises. Therefore, when identifying product innovation opportunities, internal innovation opportunities can be considered, identifying product innovation opportunities from aspects such as module knowledge sharing [34], reduction of technical barriers between modules, and modular process reorganization.

3.5. Product innovation design

In the product innovation design stage, the product is innovatively designed mainly based on the key innovation opportunities discovered. According to the scale of innovation and the degree of impact of innovation on the system, product innovation design can be divided into overall and partial innovation. Among them, overall innovation pursues new solutions and focuses on the proposal of new plans or new ideas. Through it, the entire technical system undergoes qualitative or partial qualitative changes, and product updates and iterations are achieved [35]. Partial innovation focuses on improving details, aiming to make small-scale improvements or adjustments on the original basis, reflected in the continuous improvement of existing products.

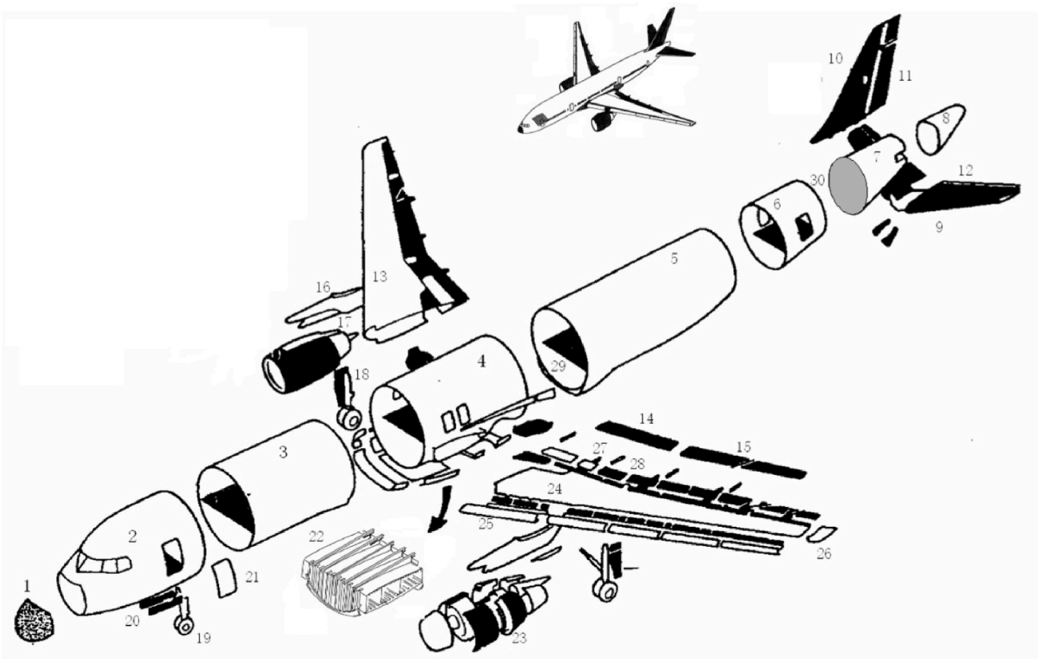
Product partial innovative design mainly starts from the current product needs and conducts feature and functional analysis of the product according to the needs. At this stage, the commonly used method is TRIZ theory [36], which is used to design the functional structure of the product and finally form a product innovation design plan [37]. However, in the process of product iterative development, the innovative value of the product is crucial. It is difficult to adjust and optimize product components comprehensively, the relationship between elements, and the overall structure of the product through partial innovation alone [38]. In this regard, through overall innovation, the overall product system can be oriented, combined with the future needs of the product, to achieve the upgrade and iteration of the overall product function.

From a modular perspective, product innovation design combines partial and overall innovation to form a product design system. The product structure and functions are divided through a modular approach, and local innovations are carried out for corresponding modules based on current product needs. On this basis, issues such as task decomposition, resource allocation, and conflict coordination between multiple modules are considered, and overall innovation is carried out for the future needs of the product. In this way, we can realize the continuous iteration of partial and overall innovation and ultimately achieve continuous product innovation.

4. Analysis of innovation path for large aircraft assembly line

4.1. Demand analysis of large aircraft assembly line

Large aircraft highly integrate national industrial civilization and advanced information technology. The research and development of large aircraft can drive economic growth and lead to scientific and technological progress, with a significant industrial



1-radome	2-nose	3-front fuselage	4-mid fuselage	5-center rear fuselage front section
6-center rear fuselage rear section	7-rear fuselage	8-tail	9-hirao	10-vertical tail
11-rudder	12-elevator	13-outer wing box	14-trailing edge flap	15-aileron
16-fairing	17-engine suspension	18- main landing gear	19-front landing gear	20-landing gear door
21-hatch	22-central wing	23-engine nacelle	24-outer wing panels	25-leading edge slat
26-winglet	27-flap slide	28-spoiler	29-cabin floor	30-rear pressure frame

Fig. 2. Schematic diagram of the structure of the large passenger aircraft.

clustering and industry radiation effect. The schematic diagram of the aircraft structure is shown in Fig. 2.

As mass production increases, establishing an advanced large aircraft assembly line is crucial for meeting current demands and accelerating future production. Current assembly lines feature automated hole-making, drilling and riveting, fuselage joining, mobile assembly, integrated testing, and digital measurement. As large aircraft production continues to grow, new assembly lines and technologies must be introduced to maintain their technological advantage in the long term.

Considering the strong global demand for large aircraft in the next 20 years, new assembly lines are necessary. Technological improvements in automation, flexibility, and intelligence are needed to enhance efficiency and product quality while reducing human interference. Reduce the manufacturing cost of large passenger aircraft while improving the quality of large aircraft and enhancing product competitiveness. Therefore, from all aspects, the large aircraft assembly line needs to be innovated to increase the large aircraft assembly production capacity and introduce new technologies and equipment to ensure the progressive nature of the large aircraft assembly line.

4.2. Modularization of large aircraft assembly line

The large aircraft assembly line consists of processing equipment, measuring equipment, assembly tools, and work platforms, involving numerous complex components. Innovating in this area is a complicated systems engineering task. Modularization can help by dividing the assembly line into relatively independent and combinable modules, making it easier to implement each module and identify innovation opportunities.

Using the Function-Behavior-Structure (FBS) model, the assembly line can be divided into modules. F represents technical functions, B represents implementation behaviors, and S represents structural forms. The FBS model maps from the functional domain (F) to the behavioral domain (B) and from the behavioral domain (B) to the structural domain (S), enabling the modularization of the large aircraft assembly line, as shown in Fig. 3.

Fig. 3 shows that the large aircraft assembly line is mainly designed to achieve the production of large aircraft, which can be divided into two major functions: component assembly and final assembly. Specific actions need to be taken for different purposes to achieve these functions, and the corresponding product structures are obtained through the decomposition process. To achieve the component assembly function, actions such as nose filling, fuselage joining, wing filling and installation, vertical tail assembly, horizontal tail assembly, wing-body mating, and door assembly are needed, and their corresponding structures are represented in the form of workstations, platforms, and type frames. To achieve the final assembly function, actions such as internal body filling, installation of the entire aircraft system components, system debugging, interior and engine installation, horizontal measurement, and final inspection are needed, and their corresponding structures are wire laying and installation workstations, piping and equipment installation workstations, system function testing workstations, interior and engine installation workstations, and final inspection workstations.

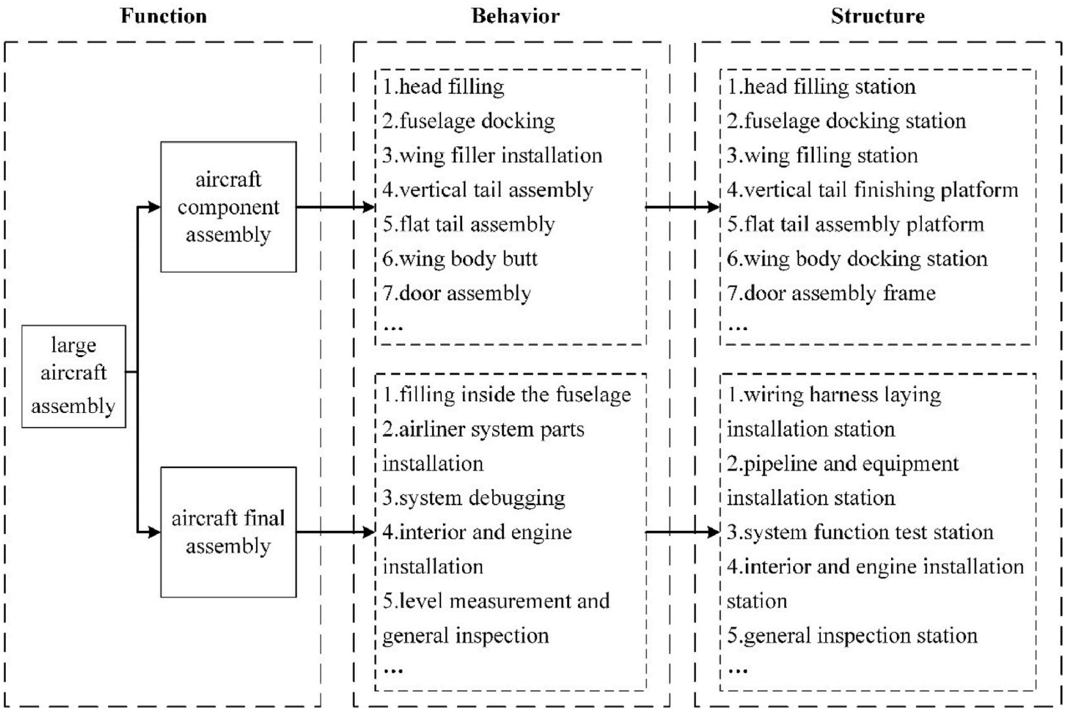


Fig. 3. Module division of large aircraft assembly line.

4.3. Identification of innovation opportunities for large aircraft assembly line

After the module division of the large aircraft assembly line, innovation opportunities can be identified internally by effectively utilizing and recombining the resources of the enterprise and each module to form a collective resource advantage, which is conducive to identifying innovation opportunities and achieving innovation for the large aircraft assembly line. Firstly, knowledge sharing can be achieved among the entities. Through mutual feedback between the entities, existing knowledge resources can be integrated to form collective knowledge and thus explore innovation opportunities. Secondly, on the basis of knowledge sharing, the cost of knowledge acquisition can be effectively reduced, thereby lowering technical barriers and facilitating technological breakthroughs to discover innovation opportunities for the large aircraft assembly line. Thirdly, in the process of resource integration, business processes can be optimized and restructured to reduce costs and enhance the product competitiveness of the large aircraft assembly line.

In addition, innovation opportunities for the large aircraft assembly line can also be explored by considering external factors such as market environment, industry technology, and user needs.

In terms of the market environment, a SWOT analysis can be conducted to analyze the large aircraft assembly line. In terms of strengths, there is a high demand for large aircraft, which requires constructing a large aircraft assembly line. In specific applications, the vast popularity of automated fuselage joining equipment, as well as technologies such as automated drilling and digital measurement, demonstrates a relatively advanced level of technology. In terms of weaknesses, there is currently a high level of manual participation in the large aircraft assembly line, and ensuring quality control and stability is difficult. In terms of opportunities, as the market competition enters the era of big data, digitization will become a development pathway for modern large aircraft manufacturing, which can accelerate the development of the large aircraft assembly line through digital means. In terms of threats, foreign competitors have strong capabilities, and the large aircraft assembly line has a high degree of automation integration, leading to high assembly quality and efficiency.

In terms of industry technology, the relevant technologies for the large aircraft assembly line mainly focus on fuselage joining,

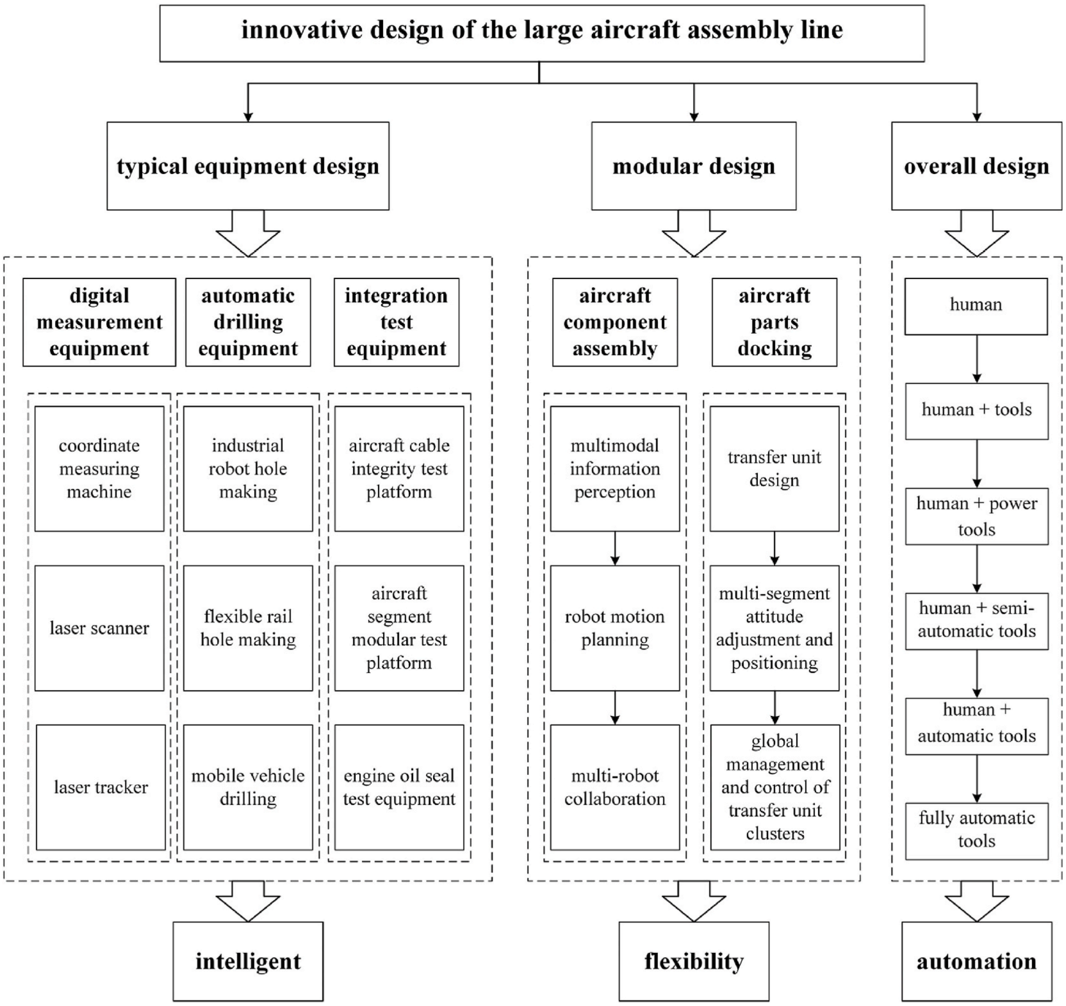


Fig. 4. Innovative design roadmap for large aircraft assembly line.

collaborative assembly, digital measurement, functional testing, logistics construction, and intelligent control. From a modular perspective, innovation opportunities for the large aircraft assembly line can be identified by establishing clear construction goals through multi-entity collaboration, analyzing the necessity of technological improvements, and exploring the direction and possibility of technological development.

In terms of user needs, the users of the large aircraft assembly line are mainly large aircraft manufacturing enterprises. Through research, the following requirements of the enterprises have been identified: first, capacity improvement. With the rapid recovery of the aviation market, there is a huge demand for large passenger aircraft. Therefore, there is an urgent need to increase the production capacity of large passenger aircraft assembly lines. Second, advanced technology. Generally, civil aircraft have a service life of several decades and the aircraft assembly process is complex with numerous parts. Therefore, it is vital to maintain advanced technology and stay caught up for a long time. Third, cost reduction. Cost is an essential factor affecting enterprise operations. Effective cost reduction can improve enterprise economic efficiency, form a cost advantage, ensure the sustainable development of enterprises, and promote product technology improvement and quality enhancement.

In summary, the main demands for the large aircraft assembly line are capacity improvement, advanced technology, and cost reduction, which can be achieved through knowledge sharing between enterprise entities and modules, lowering technological barriers, exploring the direction and possibility of relevant technology development, and achieving automation, flexibility, and intelligence of the large aircraft assembly line.

4.4. Innovative design of large aircraft assembly line

In response to the development needs of the large aircraft assembly line, innovative designs are conducted in three aspects: typical equipment design, modular design, and overall design. In terms of overall design, the large aircraft assembly line is innovatively designed according to the increasing automation rule in TRIZ theory, enhancing its automation level. In modular design, focusing on component assembly and component joining, multi-machine collaborative assembly is realized during component assembly, and flexible assembly is achieved during component joining, improving the flexibility of the large aircraft assembly line. In terms of typical equipment design, taking the digital measurement, automatic hole making, and integrated testing as examples, the intelligent upgrade of the large aircraft assembly line is realized through its innovative design. The specific design route is shown in Fig. 4.

4.4.1. Typical equipment design of large aircraft assembly line

In the typical equipment design stage of the large aircraft assembly line, digital measurement, automated hole-making, and integrated testing equipment are used as examples. Through innovative design, the intelligence of related equipment is enhanced.

Digital measurement is a technology that enables automatic, fast, and precise measurement of key component features under computer control and processes the data based on the digital model definition. It is the foundation for various tooling structures in the large aircraft assembly line. For digital measurement equipment, coordinate measuring machines, laser scanners, and laser trackers are introduced to form a collaborative measurement network with complementary advantages and data fusion, achieving interconnectivity between 3D digital information and the assembly process.

Mechanical connections are the main connection method in large aircraft assembly. During the installation of numerous fasteners, a large number of high-quality rivets or bolt holes must be processed on various layered structures, requiring high efficiency and accuracy in hole-making. Industrial robot hole-making systems, flexible rail hole-making systems, and mobile vehicle-mounted hole-making systems are introduced to improve hole-making precision and efficiency in the large aircraft assembly line.

For integrated testing equipment, firstly, a complete aircraft cable integrity testing platform is built, developing visual inspection terminal equipment based on digital twin technology, achieving intelligent and efficient cable installation detection in large aircraft and enhancing the detection level of technology. Secondly, a modular testing platform for partial sections is established, allowing modular process testing such as pipeline cleaning pressure resistance, cable conductivity, and flight control functionality tests for sections like wings. Thirdly, engine oil seal testing equipment and fuel cleanliness online detection platforms are introduced for special large aircraft testing requirements to enable data monitoring and improve testing efficiency.

4.4.2. Modular design of large aircraft assembly line

During the modular design stage of the large aircraft assembly line, the focus is on component assembly and component joining stages. Multi-machine collaborative assembly is implemented in the component assembly process, such as flexible joining, enhancing the flexibility of related modules in the large aircraft assembly line.

In the component assembly stage, addressing the diverse types, complex shapes, and significant size differences of large aircraft components, various types of robots are introduced to solve compatibility issues effectively. This reduces reliance on site conditions and tooling while allowing for capacity expansion and layout adjustment based on production demands. The implementation process involves: 1) adopting multi-modal information perception technology to collect visual, joint angle, and force information and integrating these into a full-state perception model for robots; 2) realizing robot motion planning and control in complex scenarios based on collected information; and 3) focusing on the coordinated control of multi-robot systems, achieving harmony among humans, robots, and the environment during large aircraft component assembly.

In the component joining stage, traditional fixed large aircraft assembly lines cannot meet the needs of flexible capacity adjustment and rapid tooling switching. To address this, a mobile platform is introduced for posture adjustment and flexible joining between sections, improving production efficiency. The process involves: 1) designing mobile units based on AGVs and positioning sensors; 2) implementing collaborative transportation of multiple mobile units, adjusting their transport paths in real-time to accommodate complex environments, achieving high-precision, fast, stable, and safe collaborative transportation of complex large components; 3) efficiently and precisely adjusting the posture and positioning of multiple sections, enabling parallel posture adjustment and joining using automatic positioning by mobile units; and 4) realizing full-domain management and control of mobile unit equipment clusters, implementing real-time data and algorithms to achieve full-domain management and control of mobile units based on actual large aircraft assembly line scenarios.

4.4.3. Overall design of large aircraft assembly line

The automation levels of different module structures vary during the overall design stage of the large aircraft assembly line. The innovation is mainly achieved through the increasing automation rule in TRIZ theory. For modules at the stage of human + power tools, they mainly evolve towards human + semi-automatic tools, such as wiring harness installation stations and pipeline equipment installation stations in the general assembly process. The assembly conditions and process are complex in wiring harness laying and pipeline installation, with manual labor dominating, severely affecting assembly efficiency. To address this issue, semi-automatic tools can be introduced for human-machine collaboration, such as introducing AR technology for visual guidance and assisting cable connections, laser projection technology for assisting wiring and pipeline installation, and intelligent sensing technology to ensure high-quality detection.

For modules with human + semi-automatic tools, the evolution towards human + automatic tools is needed, such as fuselage and wing-body joining stations during component assembly. Operations like hole-making, posture adjustment, and component joining involve manual labor, affecting efficiency and quality. Solutions include introducing robots for automated drilling and riveting, AGV-based automatic hole-making systems for high-precision hole-making, and using laser radar for environmental perception. Digital measurement and multi-section parallel posture adjustment improve fuselage joining efficiency.

For modules with human + automatic tools, the evolution towards fully automatic tools is necessary, such as system function tests and final inspection stations in the final assembly. Current testing equipment operates independently with low integration, hindering efficiency improvement. Building a testing platform enables full electronic testing processes, incorporating natural language processing for keyword-based test cases, and automating testing processes. Integrating digital twin, IoT, and big data technologies creates digital production lines for intelligent management and control.

4.5. Analysis of innovation effects on large aircraft assembly line

After innovatively designing the large aircraft assembly line, it is necessary to analyze the innovation effects to promote continuous innovation. Introducing new technologies, equipment, and processes in the large aircraft assembly line leads to advanced technology, improving automation, flexibility, and intelligence while meeting production capacity needs.

From the perspective of typical equipment innovation effects, the intelligent improvement of the large aircraft assembly line has been achieved. For digital measurement equipment, three-coordinate measuring machines, laser scanners, laser trackers, and other equipment are introduced to build a collaborative measurement network. The complementary advantages and data fusion of multiple measuring instruments are realized, and the interconnection of three-dimensional digital information and assembly processes is achieved. For automated hole-making equipment, industrial robot hole-making systems, flexible guide rail hole-making systems, and mobile vehicle-mounted hole-making systems have been constructed. It can replace manual, repetitive work, greatly improve the hole-making efficiency, and stabilize the hole position accuracy and hole-making quality. For integrated test equipment, a full-machine cable integrity test platform was built, which can reduce the full-machine cable test time from 5.5 days to 3 days. A segmented modular test platform has been built, which can save 2–3 days for each aircraft assembly while ensuring the consistency, completeness, and traceability of the test. Engine seal testing equipment was built to improve efficiency and significantly reduce testing costs.

Judging from the innovation effects of related modules, the flexibility of the large aircraft assembly line has been improved. In the component assembly stage, by introducing various types of robots, humans, robots, and the environment are coordinated to achieve multi-machine collaborative assembly. In the component docking stage, by building a transfer unit and introducing flexible guide rails, flexible docking and hole making of large parts of large passenger aircraft can be achieved to meet the needs of flexible equipment scheduling.

Judging from the overall innovation effect, based on the increased automation rules of TRIZ theory, the automation level of the large aircraft assembly line has been improved. Through the introduction of related power tools, semi-automatic tools, and automatic tools, the proportion of automated assembly has gradually increased. It can realize automatic drilling and riveting, automatic hole making, automatic fastener installation, automatic grinding, and other operations, significantly improving assembly efficiency.

5. Discussion

This study constructs a dynamic circular path for product innovation based on a modular perspective, starting from the current product status and combining product demand analysis, product module division, product innovation opportunity identification, and product innovation design processes to support enterprise product innovation. In each stage of product innovation, it is necessary to consider various factors in combination with practical situations to achieve product innovation ultimately.

(1) Accurate acquisition of product requirements is the basis and essential link of product innovation. In the product demand analysis stage, first, we must grasp the actual needs in product diversification, customization, and personalization. At the same time, the needs are classified. For example, the Kano model can be used to classify the needs into basic needs, expected needs,

and exciting needs to ensure the pertinence of product needs. The second is to balance the contradiction between users' diverse needs for products and limited corporate development resources. Build an apparent product demand ranking strategy to maximize user satisfaction with the product. The third is to build a product demand forecast framework based on product status and technology development trends. Forecast demand for the future to ensure that products maintain market competitiveness in the long term.

(2) The modular method effectively controls the product development cycle and cost, with module division as its foundation. In the product module division stage, the first step is to combine product structure and function, describe the relationship between components in a matrix, and build a quantitative information model of the product to ensure the scientific nature of product module division. The second is to determine the product module division method. Combining product characteristics and the applicability of different categories of methods, select appropriate methods or models to ensure the rationality of product module division. The third is to conduct product module division and evaluation. For the product module division scheme, evaluation criteria and indicators are constructed, including product stability, assembly complexity, and maintenance complexity. On this basis, the final product module division plan is determined to ensure the reliability of the product module division plan.
(3) Product innovation opportunity identification is crucial for maintaining a competitive edge and catching up with industry leaders. In this stage, first, external environments such as the market, industry technology, and user needs are considered. Second, the relationship between product functions, behaviors, and structures is analyzed, and the technological elements are recombined or optimized to explore product innovation possibilities. Third, identified product innovation opportunities are discussed and evaluated, ensuring their effectiveness, scientific nature, and feasibility.
(4) Product innovation is essential for gaining and maintaining a competitive advantage, with product innovation design as a critical aspect. In this stage, first, relevant theories are applied, such as the TRIZ theory. Second, patent knowledge is utilized to explore product innovation schemes and avoid patent infringement. Third, innovation scheme evaluation and implementation are carried out, collecting expert opinions and selecting the final innovation scheme for implementation.

6. Conclusion

Considering the product innovation process, innovation theories, and innovation methods, this paper adopts a modular perspective to divide the product innovation process into product demand analysis, product module division, product innovation opportunity identification, and product innovation design. A product innovation path is constructed by combining relevant theories and methods. Through the evolution and iteration of the product innovation path, continuous innovation can be effectively supported while integrating innovation theories and methods into the process, providing theoretical support for enterprises and enhancing the scientific and rational nature of product innovation.

Furthermore, based on the constructed product innovation path, this paper uses a large-scale aircraft assembly production line as an example to validate its effectiveness. Through the innovation process, including status analysis, module division, innovation opportunity identification, innovation design, and innovation effect analysis, the assembly production line's automation, flexibility, and intelligence have been improved. The case study demonstrates the practical significance of the proposed product innovation path.

However, there are some limitations in this study. The division of the innovation process is relatively broad and not detailed enough. Future research will consider this point, delve deeper into the product innovation path, and improve its applicability and operability.

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Data availability statement

No data was used for the research described in the article.

CRediT authorship contribution statement

Huyi Zhang: Writing - original draft. **Lijie Feng:** Validation. **Jinfeng Wang:** Conceptualization, Writing - review & editing. **Tiancong Zhu:** Methodology. **Lecheng Jin:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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