

Research Article

Research and Analysis on Assembly Methodology for the Fusion Blanket System

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In the development process of the blanket system, assembly design is quite important, and suitable systematic methodologies are required. As we know, the CFETR machine and the associated fusion components are not usually mass-produced large-scale products, but highly customized machines which are still in the design phase. Appropriate assembly methodology plays an important role in fulfilling the function of the fusion machine. This paper has investigated some universal assembly methods for similar complex products. Two preferred methods of design-for-assembly (DFA) and product-process hierarchical modeling (PPHM) have been analyzed and improved taking the fusion blanket system as a study case. The overall process of the blanket system was studied including the stages of design, assembly, and overview of the blanket system hierarchy structure. The two newly proposed methods aim to clarify a probably feasible assembly method for the blanket system, though it is still in the engineering design stage. Case studies of the two favorable assembly methods can be good references to demonstrate and analyze the advantages of DFA and PPHM for decision-making in each product development phase.

1. Introduction

Although about 80% of the energy needs currently depend on fossil fuels [1], the search for reliable and sustainable alternative energy sources has become increasingly urgent due to the reduction of the reserves and the environmental sustainability. Fusion energy is in principle anticipated as the ultimate energy source with the features of security, inexhaustibility, and environmental friendliness [2]. The Chinese fusion engineering test reactor (CFETR) is the next Chinese magnetic confinement fusion device to solve critical issues on the road to fusion energy exploitation [3]. It is a large machine involving many subjects during its design and construction. As one of the most important components, the blanket system has to accomplish the functions of tritium self-sufficiency, heat extraction, and neutronic shielding. The integration assembly of the blanket system involves the assembly design of the blanket modules, back plates, and supporting system, as shown in Figure 1. The blanket module

is composed of the tungsten armor, the first wall (FW), stiffening plates, caps, cooling tubes, manifolds, and breeding zones (BZ). As for so many subsystems, the design and assembly involve high complexity, many uncertainties, and replaceable maintenance, especially in the design stage. Thus, there is an urgent need to investigate an applicable method for rapid assembly which should be considered during the present design stage and the future manufacturing stage.

Literature works on the exploration of rapid assembly methods for similarly complex large-scale devices are reviewed. Through this literature, the methods that are probably applicable for the fusion components and systems are selected. The focus of this paper is on the exploration of an applicable assembly method for fusion components and systems. Section 2 presents the literature investigation of the rapid assembly methods of different complex systems. In Sections 3 and 4, two selected methods were analyzed taking the fusion blanket system as a study case. A discussion is also given.

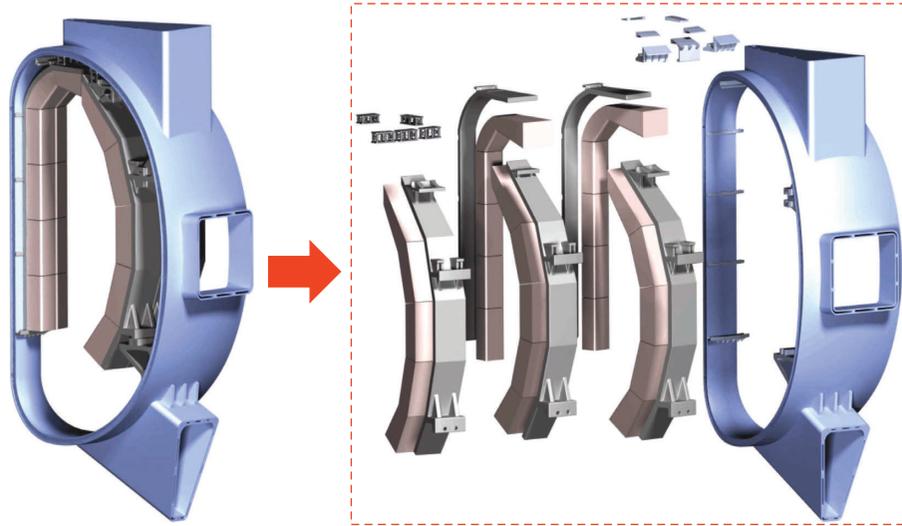


FIGURE 1: An exploded view of the CFETR blanket system.

2. Methods Investigation

Widespread attention has been paid to the assembly process of complex machines, especially for those working at severe and challenging environments. The assembly process is carried out according to the specified technical requirements of the assembling machine. Qualification is to be made by debugging and inspection. Some assembly methods for complex machines are presented in this section. A comparison of different methods has been made to select applicable assembly methods.

With the development of the state-of-the-art technologies of the Internet of Things, cloud analysis, and big data analysis of smart manufacturing and assembling, the demand for cyber-physical integration has been researched widely. As one of the preferred means of such integration, an advanced technology of the digital twin (DT) method [4, 5] is proposed and developed in the fourth industrial revolution. The method is used to analyze the association of the digital model and physical model especially for complex products such as satellites, missiles, and aircraft. DT is the real-time interaction and feedback mechanism research between information space and physical space. It is a key enabling technology applied in smart assembly. The integration of the assembly process between information space and physical space can facilitate the relevant technical and management personnel to timely grasp the assembly information and solve the encountering problems. For years, design-for-assembly (DFA) methodologies have been widely studied [6, 7]. DFA is an integrated methodology focusing on the key aspects of the assembly during the design phase. The design stage is an iterative and long process during the development of the complex machine. This method takes into consideration each stage covering component and product design, simulation, and evaluation for assembly performance improvement. The fundamental objective of DFA is to minimize the number of assembly operations and thus reduce assembly time and costs. The product-process hierarchical modeling (PPHM) method for complex

assembly is a useful tool for the design and assembly of complex products [8]. By making out the hierarchy modeling process of the blanket, the system is quite beneficial to the assembly process development for complex products. The investigated methods which are probably applicable were concluded in Table 1. Through comparison, DFA and PPHM were improved and analyzed based on the blanket system. Integrated research of the two methods was carried out in Section 3.

3. Assembly Analysis for the Blanket System

The blanket is one of the most critical components of the CFETR tokamak machine [9, 10]. Assembly is a critical process in the development of the fusion blanket. All the composing components of the blanket system need to be assembled to fulfill the functions of tritium breeding and extraction, heat removal, and neutron shielding. The applicable assembly method and system for the blanket system can be very beneficial in terms of cost, efficiency, maintenance, and manufacturing. The whole process of the product is shown in Figure 2. The two probably applicable methods for the blanket system assembly were analyzed and discussed.

CFETR machine is not usually a mass-produced large size product but a highly customized machine which is still in the design phase. According to the authors in [11], the conceptual design of the CFETR was completed in 2017, and the Chinese government has approved to proceed with the engineering design of CFETR, and the project started on December 2017. The process of the conceptual design, detailed engineering design, and the envisaged manufacturability evaluation was presented and concluded in Figure 2. In this figure, BS stands for the blanket system, BZ stands for the breeding zone, EM stands for electromagnetic, CS stands for the cooling system, and MF stands for manufacture. It is important to highlight that the design and assembly process has been divided into three design and assembly stages surrounding the assemblability. The first is the early

TABLE 1: Advantage and disadvantage analysis of the assembly methods.

Method	Advantages	Disadvantages
DT	It is a multidisciplinary method integrating the VR and AR technologies which has considerable advantages in information interaction between the physical world and the digital world, especially in the smart assembly of complex products.	DT is still in its infancy; its application scope is limited to the operation and maintenance, service stage of digital workshop, and production line, and it is less applied to the design, manufacturing, and assembly of product parts in the manufacturing industry.
DFA	Overall monitoring and evaluation of each stage are done during the design phase for assembly ability. It is strongly advantageous if used during the first phases of the conceptual design machine.	In the conceptual design stage, the design and assembly data cannot be used and applied when the most important product decisions are made.
PPHM	Facilitates the design of the various components of the blanket.	The decomposition of the products is very important with a detailed numbering process. If the final design or assembly has been changed from the decisions, this method will be costly

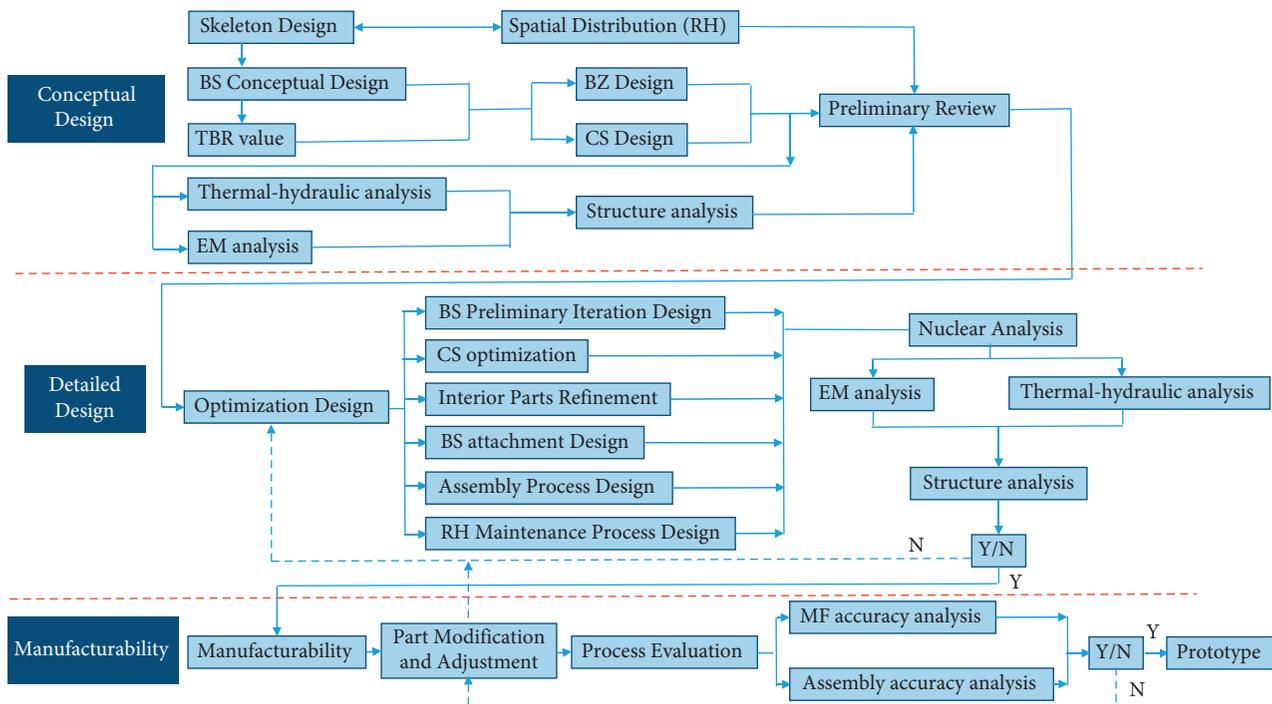


FIGURE 2: An approach for the blanket system assembly flow diagram.

conceptual design phase, the second is the detailed engineering design phase, and the third is the manufacturability of the consisting parts and the accuracy analysis of the prototype. It is worth mentioning that the optimization process is an iteration process for performance evaluation of the blanket system design due to the fact that product design has a strong influence on the final product manufacturing and assembly processes.

3.1. Method of Newly Proposed DFA. As discussed in Section 2, DFA methodologies can be strongly advantageous because its development focused on key aspects of assembly during the design phase. However, applying DFA methodologies to those large-sized products which are highly customized but not usually mass produced is quite challenging [7]. This paper proposes the new DFA assembly methodology which adapts and merges the investigated DFA methodologies

including each stage during the design related to the final assemblability and applies it to the CFETR blanket system assembly design. There is an improvement in the proposed DFA in this paper to accommodate the fact and real condition of the CFETR blanket system. The assembly workflow and process have taken the overall design and assembly into consideration including the preliminary conceptual design, iterations of optimizations, and the final manufacturability assessment. The overview of the blanket system decomposition based on DFA is shown in Figure 3.

It is worth noting that the three phases (the conceptual design phase, the detailed engineering design phase, and the manufacturability of the consisting parts) of the DFA approach are mutually coupled and interrelated which needs a repeatedly iteration process to reach the next step arrangement. Every two phases of the design and manufacture are closely linked. Based on DFA methodology, the CFETR blanket module assembly can be decomposed into tungsten

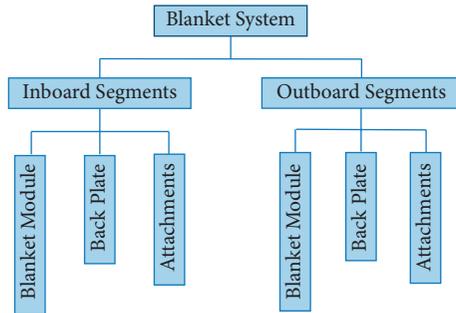


FIGURE 3: Blanket system decomposition for DFA.

armor (1), first wall (2), stiffening plane (3,4), ribs (5), cooling tubes (6), manifold (7), and CAPs (8,9). The assembly process of the DFA methodology is shown in Figure 4.

3.2. Method of the PPHM method. The investigated product-process hierarchical modeling (PPHM) method has been improved and applied to CFETR blanket system assembly analysis. The aim of this method is to make assembly development much more standardized, systematic, and efficient. This newly proposed approach integrates the blanket system's hierarchical structure and its assembly process into two critical steps. One step is to make out the overview hierarchy structure of the analytic target blanket system which is quite important for the second assembly process design. The second step is to make out the assembly process of the subsystems according to the important decisions. The overview of the blanket system hierarchy structure after decomposition is shown in Figure 5.

A clear hierarchical structure of the product can serve as a valuable foundation for the development of the assembly manufacturing process as different decomposition processes of a product can mean various assembly sequences and flows. In the case of the CFETR blanket system assembly, the blanket system was decomposed into three main components, the blanket module, back plate (BP) structure, and supporting system. Each component can also be decomposed into several hierarchical components in the next hierarchy structure. Three components also have a corresponding assembling sequence. The blanket module needs to be assembled on BP, and BP will be assembled on the supporting structure. One important objective of the assembly is to join the components together to fulfill the design and engineering requirements. Moreover, an assembly manufacturing sequence is usually opposite to the product decomposition process if a specified decomposing method has been decided. We take the blanket module as a study case. The detailed assembly sequence of the typical blanket module is shown in Figure 6.

4. Multidimensional Evaluation of Blanket with DFA and PPHM

The design of the blanket and decisions made at the design stage are major factors in determining the cost of installation. During the design phase, in addition to the

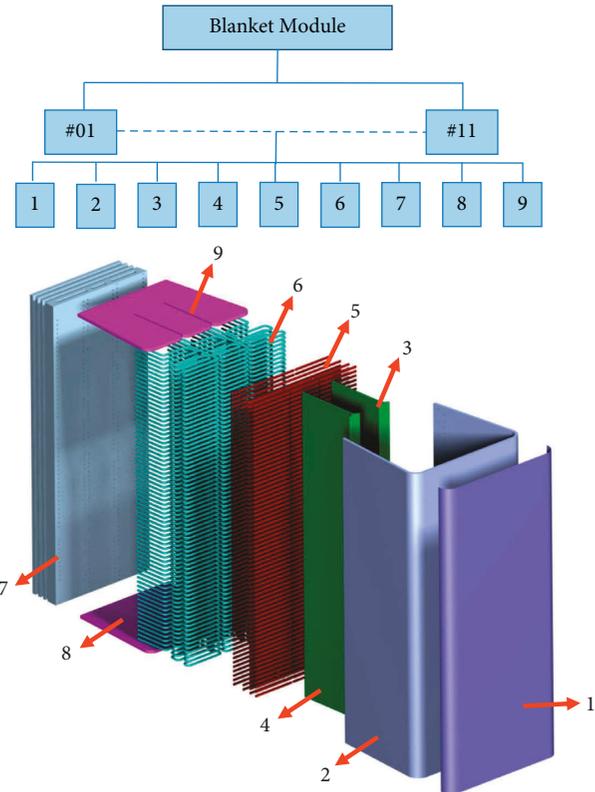


FIGURE 4: The blanket module for DFA.

functionality of the blanket, other factors can be considered to optimize the design and reduce the final cost of the blanket system assembly. In general, the main focus is on facilitating assembly, minimizing the number of parts or variability, and allowing other issues to be considered, such as replaceability. The basic goal is to minimize the number of assembly operations, thereby reducing assembly time and cost [6]. A calculation method for the final cost is proposed. A comprehensive assembly index [12] is given, which is composed of multiple parameters, such as maintenance, time, logistics (transportation, packaging, etc.), assembly, and manufacturing. Collaborative engineering and multi-dimensional analysis methods are used to carry out the research on the assembly performance of the blanket system. For multidimensional analysis, three methods are mainly used: advantage and disadvantage evaluation, overall efficiency evaluation, and economic evaluation [13].

4.1. Analysis of Advantages and Disadvantages. Advantages and disadvantages of PPHM and DFA assembly methods are listed in Table 2. The DFA method improves assembly efficiency by reducing the number of operations, while PPHM achieves the final product by completing step-by-step assembly of complex parts. Regardless of the DFA or PPHM method, processes such as positioning, clamping, joining, and welding are essential in the blanket assembly process. Due to the small number of assembly times of DFA, the number of parts' disassembly puts forward extremely high requirements on the manufacturing and assembly process.

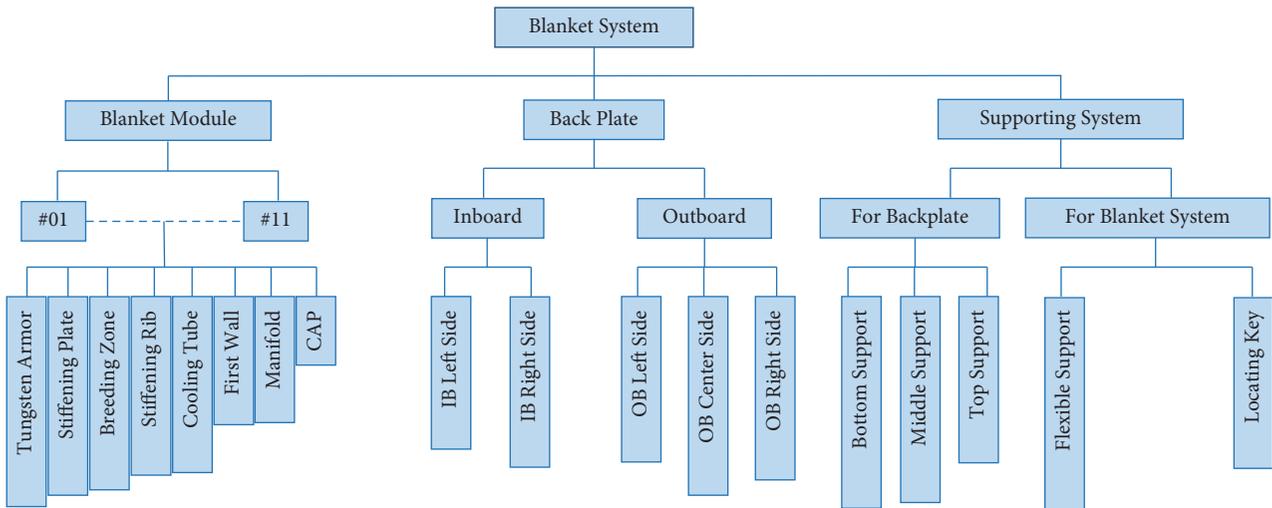


FIGURE 5: The overview of the blanket system hierarchy structure.

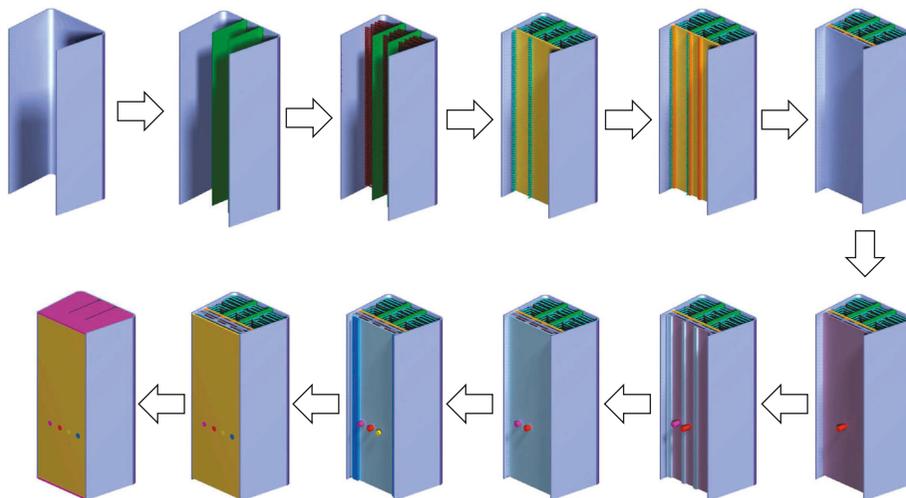


FIGURE 6: The scheduled assembly sequence of the blanket module.

TABLE 2: Advantages and disadvantages of PPHM and DFA assembly methods.

	PPHM	DFA
Advantages	High frock efficiency Easy to be connected Easy to position Easy to weld	Less number of parts Less tooling steps Less number of welds Less number of fixtures Easy to be connected
Disadvantages	More number of parts More tooling steps More number of fixtures	Low frock efficiency Hard to position Hard to weld Complex tooling of fixtures Need more auxiliary tools

During the design phase, the assembly process does not need to be considered too much until the part design is completed. The PPHM mainly simplifies the assembly of complex parts. Through the principle of multiple disassembly, the complex and difficult-to-assemble parts are disassembled to obtain an efficient assembly process. Therefore, this method needs to

fully consider the disassembly of parts in the design process. The number of parts is large, but the difficulty of parts' assembly is low. For the PPHM method, the complex component is decomposed into many simplified parts and should be assembled independently. Thus, there is more space and less difficulty for the assembly of the parts, such

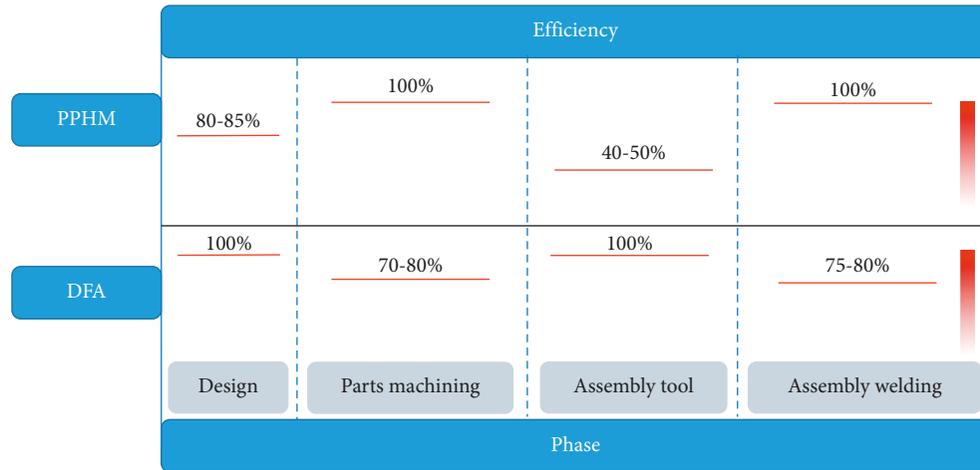


FIGURE 7: The efficiencies of the two assembly methods (experience-based reference values).

as easy to connect, easy to find the correct position, and easy to weld. The manufacture of the simplified parts is easier than the complex component, and the frock efficiency (time cost of processing and assembly) is improved greatly at the same time. On the other hand, the greater the number of parts for the PPHM method, the more the tools for assembly processing. The DFA method is just the opposite.

4.2. Efficiency and Cost Evaluation. The design, manufacture, and assembly process of the blanket system are all included in the overall assembly efficiency. A good product design can greatly improve assembly efficiency and reduce the amount of clamping and positioning during the assembly process. Therefore, the efficiency of the design and manufacturing processes should also be considered, and the assembly is divided into three parts: positioning, clamping, and welding [14]. When comparing the two methods of PPHM and DFA, if one of the methods is efficient, it is assumed to be 100%, and the other method is evaluated based on experience and so on. Figure 7 shows the efficiencies of the two assembly methods during design, fabrication, and assembly.

The difference between the two methods in the assembly process of blanket modules is mainly reflected in the complex assembly between CT and MF, while there is no significant difference in assembly between FW, SP, and W-titles. The main difference is that the PPHM assembly method divides the MF into multiple pieces to achieve simple assembly, while DFA mainly designs the MF into one piece to simplify the assembly process. In the design stage, the DFA method mainly improves the overall efficiency by reducing the number of assembly times, while the PPHM method completes the assembly by dividing complex parts. Therefore, the design of DFA is relatively easy than the PPHM method. Assuming that the design efficiency of DFA is 100%, the PPHM assembly method mainly divides MF into multiple pieces to achieve simple assembly. The number of the designed parts of the PPHM method is about 1.2 times than that of DFA, and the design efficiency is about 80–85% of DFA. PPHM divides the MF into multiple parts, which

greatly reduces the manufacturing difficulty. The positioning and manufacturing holes can also be easily found and realized. However, the DFA method is very difficult to process the complete MF parts, and the positioning manufacturing requires extremely high machinery tools and high-level operations. Therefore, the manufacturing efficiency of DFA is 70–80% of PPHM while PPHM is considered to be 100%. For the assembly process, more tools are needed for the PPHM method than for the DFA due to multiple pieces divided by MF. The number of tooling of PPHM is about 2 times than that of DFA. The tooling efficiency is 40–50% for PPHM, and for DFA, it is assumed to be 100%. The connection of the various parts of the blanket is mainly completed by welding, and the number of integral parts in the DFA method is slightly smaller than that in the PPHM method. But the part welding of the DFA method is more difficult than the PPHM method, and the main welding difficulty is reflected in the multiple welding of the pipeline. Therefore, the welding efficiency of the PPHM method is recorded as 100%, and the efficiency of the DFA welding method is estimated to be 75–80%.

In the process of design, manufacture, and assembly, the process division and the use of fixtures, tools, and time costs of the two methods are obviously different. Therefore, evaluating the cost of the two methods has a certain reference value for future blanket design and assembly [15], listed in Table 3. It is mainly divided into three aspects: material, energy, and the manufacturing level. The materials are divided into direct materials and auxiliary materials. The direct materials are consumables of parts, and auxiliary materials are consumables, fixtures, and auxiliary tools in the process of manufacturing. The energy cost mainly refers to the electric energy, labor, and others in the overall manufacturing process. The manufacturing level refers to the requirements for the level of the factory. The higher the index, the higher the level of complex assembly the factory can achieve. Assuming that the original cost of parts is 1, other consumptions in the process of manufacturing and assembly are accumulated on the basis of the original cost accordingly. The PPHM method requires more materials than the DFA method. The initial evaluation of the material

TABLE 3: The cost evaluation of two methods.

Methods	Material consumption	Assembly tools	Assembly energy	Factory level
DFA	1.3–1.4	1.8–1.9	1.2–1.5	2.9–3.5
PPHM	2.1–2.3	1.1–1.3	1.3–1.6	1.1–1.2

consumption of the DFA method is 1.3–1.4, and the PPHM method is 2.1–2.3. The consumption of auxiliary materials mainly refers to the consumables of fixtures and positioning devices in assembly tooling. Compared with the PPHM method, the DFA method has fewer assembly steps and fewer tooling fixtures. Assuming that the assembly tooling cost of other parts is 1 except for the MF part, the cost of comprehensive auxiliary material consumption is accumulated on the remaining parts. In DFA assembly, the assembly tooling of MF has a complex structure and high cost, which is recorded as 1.8–1.9. In the PPHM assembly, although the MF is composed of multiple parts, the tools are relatively simple, and the cost is about 1.1–1.3. Energy costs mainly refer to logistics (transportation, packaging, etc.) and electricity costs. The fewer parts and the fewer assembly times mean lower energy costs. If the energy cost of blanket assembly is 1 without additional cost, the assembly energy cost of DFA is 1.2–1.5, and the energy cost of PPHM is 1.3–1.6. The complexity of the blanket parts and the factory level determines the manufacturing cost. In general, the more complex the parts are, the higher the manufacturing level is required. The more precise the tools are required, the higher requirements are needed for the factory. The DFA method has higher requirements on assembly tools and means. However, the PPHM method is divided into a large number of parts, which is relatively easy to assemble and has lower requirements on the factory level. The cost of the factory-level requirements of the PPHM method is initially estimated to be 1.1–1.2, and the cost of the DFA method to the factory-level requirements is 2.9–3.5.

5. Discussion and Results

5.1. Discussion. Two assembly methodologies adapted to the complex products and machines have been analyzed and used to carry out the case study of the fusion blanket system for CFETR. DFA is a widely used method that can cover the assemblability consideration during the design phase including the preliminary design stages. A detailed product process of the CFETR blanket system was presented and analyzed based on this method. The process includes the firstly conceptual design arrangement, the further detailed design task division and arrangement, and the manufacturing process which covers the whole product development process. However, the method is certainly very meaningful unless the important decisions were changed. If the important decision is changed, the adjustment will be made accordingly. As for the PPHM method, it helps provide a clear recognition of the overall hierarchical framework of the studied case which can also promote the design variety and modularity. This method also helps demonstrate an adaptable product decomposition process. With different hierarchical decomposition, the blanket

system will be decomposed into several first-layer parts, some second-layer parts, and so on. Clear structure decomposition plays an important role in the hierarchical modeling design and the assemblability evaluation.

The two assembly method case studies of the blanket system presented here are good examples to demonstrate and analyze the advantages of the DFA and PPHM methods for decision-making in each product development phase. The assembly analysis and application of the case studies allow the product development teams, designers, and managers to deliver the best solution for product quality improvement.

The assembly of the blanket is a complex project, and the methods of assembly are also different. The above mainly discusses the assembly evaluation of the blanket under the two methods of DFA and PPHM. By comparing the two methods of blanket assembly, it is found that DFA assembly has low complexity, low material cost, high assembly difficulty, and a high level of assembly factory requirements; PPHM has more parts, low assembly difficulty, and low requirements for the factory level but high material cost. In general, DFA is more efficient, but it is also expensive. PPHM is relatively inefficient but is also low in cost. We can choose a suitable assembly method according to the actual situation and comprehensive consideration.

5.2. Results. The aim of this paper is to explore the adaptable assembly methodologies for a comprehensive analysis of the affecting aspects in the preliminary conceptual design phase to the manufacturing phase of complex product development. A proper method can help designers and engineers select a more effective design solution. According to the investigated assembly methods of similar complex products and machines, two adapted assembly methodologies have been analyzed and used to carry out the case study of the fusion blanket system of CFETR due to its high complexity, demanding interfaces, and replaceable maintenance requirements.

Two assembly methods were analyzed taking the fusion blanket system as a study case. Design-for-assembly is a useful method to master the overall process of the blanket system design. The overall design to manufacturing process has been set out for the blanket system which can give a deeper understanding of each developing phase of the blanket. The new hierarchical product-process modeling method can help the designers and the engineers make out about each hierarchical structure and its consisting parts. Moreover, it is proactive to consider the assembly hierarchical process in the product conceptual design phase to optimize the process feasibility, costs, and manufacturability because there are possibly different assembly processes and sequences from different perspectives for the same product.

Different decomposing sequences could lead to different assembly processes. This newly proposed approach integrates the blanket system hierarchical structure and its assembly process in two critical steps. Overall, the assembly methods selected for the blanket system are used to fulfill the design and engineering requirements. If these two methods can be applied to the blanket system, they will become meaningful references for similar fusion components in the future. However, a step forward would be to consider the other comprehensive interesting and development-related aspects such as the cost and environmental impacts. That would be one of the things to do in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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