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Product Interface Design for Complexity Management in Assembly Systems

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ABSTRACT Manufacturing firms are facing the challenge of minimizing variety-induced complexity in assembly systems. One of the effective approaches to complexity management is to reconfigure the assembly system by rearranging its assembly sequence. In order to rearrange an assembly sequence, a design-oriented approach is necessary because assembly is an activity of connecting parts through an interface between them. It means that the assembly sequence in production is restricted by the structure of interface connections in design. In this vein, this paper introduces a new design-oriented approach called *interface design* approach to complexity management in assembly systems. First, the mechanism of how the structure of interface connections affects assembly system complexity is identified. Then, an interface design framework is proposed for effectively finding an optimal interface structure and its assembly sequence to minimize assembly system complexity. For evaluating the complexity, the operator choice complexity index is adopted and modified for the interface design problem. In the case study, the framework is applied to the interface design problem by using industrial data of a plasma display panel (PDP) family from LG Electronics. The result of the study demonstrates that the assembly system complexity is significantly reduced by the proposed interface design framework.

INDEX TERMS Assembly system complexity, complexity management, design for assembly, interface design, mixed-model assembly line, product architecture.

I. INTRODUCTION

Manufacturing firms have been launching a variety of products to the market in order to meet diverse needs of customers. The trend of diversifying products is accelerating to target global markets and to achieve higher market share. For this reason, manufacturing firms construct mixed-model assembly lines to efficiently produce a variety of products. A mixed-model assembly line is a flow line capable of producing multiple products by assembling different kinds of module variants [1]. Mixed-model assembly systems has been recognized an effective strategy to handle the increased variety but it could create lots of difficulties to operators due to the increased the number of module variants [2]. Previous studies have demonstrated the situation in which high product variety causes poor performance of an assembly system through empirical observations and simulation [3], [4]. At this point,

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manufacturing firms are facing the challenge of minimizing variety-induced complexity in assembly systems while maintaining a variety of products.

Approaches to reducing variety-induced complexity in assembly systems can be classified into three categories: (1) the reduction of part variety, (2) the increase in process flexibility, and (3) the reconfiguration of an assembly system. The reduction of part variety is achieved by reducing product variety or commonizing parts [5]. The increase in process flexibility is implemented by investment in automated machines or multifunctional tools in order to effectively respond to changes by part variety [6]. The reconfiguration of an assembly system is to rearrange an assembly sequence using the delayed differentiation strategy [7]. Among the three approaches, the reduction of part variety results in a direct loss of sales and market share [8], and the increase in process flexibility requires an enormous investment cost for the extension of technologies, facilities, and tools [9]. Thus, this paper focuses on the third approach, the reconfiguration

of an assembly system, which accompanies relatively low cost and profit loss. Especially, this approach can be applied to mixed-model assembly lines capable of flexible response to variety, rather than reconfigurable assembly systems that adapt to change by rapidly changing their configurations.

When a firm rearranges its assembly system, it should be understood that an assembly sequence is constrained by the interface connection structure within a product architecture shared by a product family. This is because assembly is an activity of connecting parts through an interface between them [10]. In design, on the other hand, an interface is defined as a physical connection having a role of implementing functional interactions between parts [11]. Thus, a decision on how to implement functional interactions through interfaces in the design phase constrains assembly sequences in production. In this vein, the cross-domain relationship among functional interactions, interface connections, and assembly sequences should be clarified in order to manage complexity in assembly systems.

The goal of this paper is to propose a novel interface design approach to complexity management in assembly systems. The term *interface design* focuses on structuring interface connections, not designing specifications of an interface. First, the interface design problem is defined by showing the mechanism of how the structure of interface connections affects assembly system complexity. Then, an interface design framework is proposed for effectively identifying an optimal interface structure and its assembly sequence to minimize assembly system complexity. The operator choice complexity index [2] is adopted and modified to evaluate complexity in mixed-model assembly system and to solve interface design problem. Using the complexity index, an interface design framework is proposed for effectively finding an optimal solution among various alternatives by identifying feasible interface structures and possible assembly sequences. The framework provides one or more solutions that minimize assembly system complexity in various situations.

The structure of this paper is as follows. Section II reviews related works on assembly system complexity and design for complexity management. Section III defines the interface design problem, which is the main idea of the paper, and then section IV introduces a complexity index by modifying the operator choice complexity index in design viewpoint. Section V describes a problem to be solved in this paper, and proposes a framework to find an optimal solution. Then, section VI conducts a case study with real data of a plasma display panel (PDP) family by conducting scenario analysis, and finally, section VII concludes the paper.

II. RELATED WORK

A. ASSEMBLY SYSTEM COMPLEXITY

Variety is one of the major sources of complexity in assembly systems [6]. Previous studies have proved that high product variety negatively affects the performance of an assembly system, by conducting empirical observations and simulation

studies [3], [4]. In order to capture the complexity, research has been conducted for defining and measuring assembly system complexity.

One of the main streams of the research is to view and measure complexity in terms of Shannon's information entropy. Information entropy is a measure of unpredictability of elements that configures a system [12]. Frizelle and Woodcock [13] defined static and dynamic complexity based on the entropy calculation logic using the ratio of a state being occupied in a process. Similarly, Deshmukh *et al.* [14] introduced a static complexity measure, and analyzed it with respect to part similarity, system size, and design changes in job shop scheduling. Fujimoto *et al.* [15] proposed a methodology for evaluating structural complexities of an assembly system at different stages in assembly process design. Smart *et al.* [16] extended the dynamic complexity measure developed in previous research [13]. They redefined dynamic complexity as the expected amount of information needed to describe two different system states which are scheduled and unintended states. Modrak and Soltysova [17] introduced a new complexity measure that focused on finding a balanced system layout through a line balancing method.

While previously mentioned research has focused on operational states of assembly process, another major stream of the research, which is based on the operator choice complexity (OCC), has concentrated on the relationship between operator's performance and task uncertainty. Zhu *et al.* [2] first defined the OCC using an entropy function in order to measure the uncertainty in choice activities of an operator in a mixed-model assembly system. Hu *et al.* [18] extended the application scope of the measure from assembly systems to multi-echelon supply chains. After that, Wang and Hu [19] used the OCC index for layout design of an assembly line with parallel and hybrid configurations. Zhu *et al.* [20] formulated an optimization model for the sequencing problem of an assembly line using the index. Wang *et al.* [21] extended Wang and Hu's study [19] to general assembly lines with non-identical parallel stations by formulating a non-linear programming problem in order to identify an optimal system configuration. In recent studies on the OCC, Busogi *et al.* [22] proposed a sequence-based optimization model for the reduction of complexity.

On the other hand, research has also been continuously studied to capture the complexity by heuristic measures from various viewpoints. ElMaraghy and Urbanic [23], [24] developed a methodology for systematically modelling the three complexity measures which are product, process, and operational complexity indices based on the predefined complexity sources of a system. Zaeh *et al.* [25] introduced a multi-dimensional task complexity measure in a manual assembly line. The measure predicts the performance of an operator based on the three factors: task time, level of cognition, and similarity of tasks. Zeltzer *et al.* [26] defined complexity at the workstation level, and proposed statistical complexity models using survey data obtained at the workshops done with automotive manufacturers from Belgium and Sweden.

Mattsson *et al.* [27] combined three complexity causes, station design, work variance, and disturbance handling, into the perceived production complexity measure from an operator's perspective. Falck *et al.* [28] proposed a method for predictive assessment of manual assembly complexity based on criteria of high complexity and low complexity. Chang *et al.* [29] introduced a dynamic signal to build a more stable system by reducing the uncertainty caused by unmodeled dynamics and unmeasured states on switched systems.

In summary, many studies have been conducted to define and measure complexity in assembly systems. Although those studies have great contributions for capturing complexity in the production domain, there have been few studies on a design-oriented approach.

B. DESIGN FOR COMPLEXITY MANAGEMENT

A research stream called design for assembly (DFA) has been conducted by integrating both production and design viewpoints in order to manage complexity in assembly systems. Originally, DFA was implemented by providing guidelines to designers [30] for designing a product for an ease of assembly. Then, Boothroyd [31] proposed a DFA method for measuring the difficulty of assembly based on data from empirical observations. Rodriguez-Toro *et al.* [10], [32] presented the notion of complexity by categorizing it into component complexity and assembly complexity in terms of DFA methodology. The main idea of their work was that all complexities in assembly systems are affected by design activities. Samy and ElMaraghy [33] introduced a measure for product assembly complexity based on product attributes that cause difficulties of handling and insertion tasks in manual and automatic assembly. Afterwards, Samy and ElMaraghy [34] developed a matrix-based mapping method for identifying the relationship between product attributes and assembly system functions which are feeding, handling, joining, and transportation. Recently, Parmentier *et al.* [35] comprehensively reviewed the meaning of DFA, and guided how product designers support operators' cognition in assembly process.

In addition to physical attributes of a product, design strategies such as modular design and product architecture design have also been an important enabler for complexity management. AlGeddawy and ElMaraghy [36] proposed a hierarchical clustering (cladistics) technique to find an optimum granularity level of a modular product architecture in assembly process. Then, Samy *et al.* [37] applied the technique to find an appropriate granularity level for balancing two sources of complexity in an assembly system: equipment and layout. Since then, AlGeddawy *et al.* [38] integrated cladistics with both a matrix-based tool and the measure they introduced before [33] in order to balance modularity and complexity. Bonev *et al.* [39] developed a formal computer-aided system to support design of product family architectures covering the design and production phases. Keckl *et al.* [40] emphasized that product design and production are strongly connected, and then they proposed a methodology for identifying modularization potential of

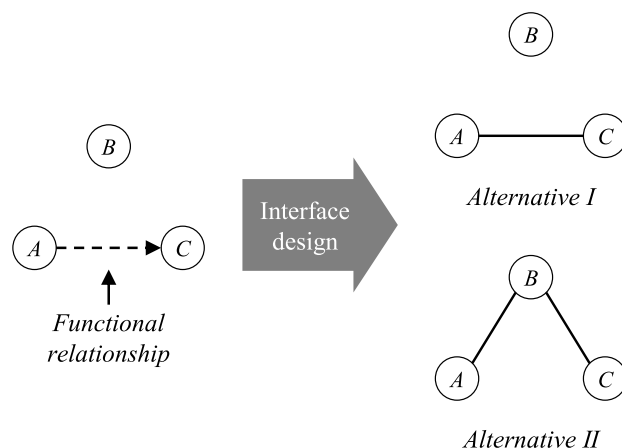


FIGURE 1. Interface design alternatives from a functional relationship.

products based on different production time at workstations. Alkan *et al.* [41] conducted experiments for investigating the link between perceived assembly complexity and product complexity in manual assembly process.

In conclusion, in design viewpoint, research has been done to manage complexity in assembly systems, however only a few studies have focused on product interfaces even though assembly process is affected by the structure of interface connections. In this regard, this paper focuses on product interfaces by showing the mechanism of how interface design affects assembly system complexity.

III. INTERFACE DESIGN

Interface design is defined as a problem of selecting an interface connection structure among feasible alternatives that are derived from functional relationships of a product. Fig. 1 shows a simple example of two design alternatives in which a functional relationship is realized. When a product has a functional relationship between modules (or parts) A and C, an interface can be built directly (*Alternative I*) or indirectly through module B (*Alternative II*). Selecting alternatives among several possible (alternative) options depends on the goals that a firm want to achieve. Since minimization of complexity in assembly systems is the major concern of firms, it would be addressed in this paper. Thus, *interface design* is redefined as a decision-making problem: an interface connection structure is determined for the minimization of assembly system complexity among design alternatives that satisfy functional relationships of a product.

A functional relationship and an interface need to be defined for clear explanation of the interface design problem. A *functional relationship* is defined as an interaction between elements in the functional domain [11]. Pimmler and Eppinger [42] categorized an interaction between functional elements into four different types which are spatial, energy, signal (information), and material. These four types of interactions are respectively identified when physical adjacency, energy transfer, signal exchange, or material exchange occur between two functional elements. An *interface*, in addition, is defined as a physical connection between modules implementing functional relationships [11]. A type of a physical

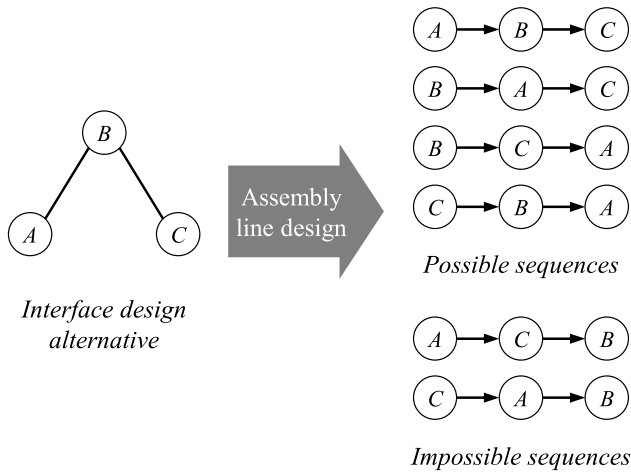


FIGURE 2. Possible assembly sequences from an interface structure.

connection varies depending on a type of an interaction. For example, a spatial interaction requires fasteners such as bolts or screws for mechanically connecting two objects, while a signal interaction is implemented by a cable or a wiring harness.

Extending the viewpoint from design to assembly systems, interface design is not only related to functional relationships, but also assembly sequences. In the production domain, an interface connection structure constrains a sequence of assembly process. An *assembly sequence* in this paper is defined as a list of modules in a specified order in the assembly line. Fig. 2 describes which assembly sequences are possible for an interface design alternative. When a product has two interfaces between A and B, and B and C, assembly sequences $A \rightarrow C \rightarrow B$ and $C \rightarrow B \rightarrow A$ are impossible, because module A and C can be connected to each other only through module B in the structure. It never happens that unconnected A and C except B flow on the assembly line. In this case, an interface connection structure is recognized as an enabler for changing an assembly order, and the alteration of an assembly order can lead to less complicated assembly systems. Thus, not just the satisfaction of functional relationships but also the constraints on assembly sequences should be matters to be considered.

Interface design is a problem of architecture-level design. It constructs an interface connection structure at the system-level design phase in the development process. When firms design a structure of a product family, most of the families have a limited set of alternatives of structures due to the existing design concepts. In practice, product families in the same industry have similar structures (e.g., automobiles, smartphones, and appliances). Thus, this paper involves certain assumption that the number of possible alternatives is limited by product concepts and characteristics in the interface design problem. Detailed constraints for decreasing the feasible solutions can be further considered during the detail design phase, but this paper considers the abstract level of constraints because the number of alternatives of interface connection structures is in a controllable range. Note that the

role of interface design is to connect interfaces in the physical domain considering functional interactions and assembly sequences in other domains, not to search for the detailed design space.

The overall scope of the interface design problem is described in Fig. 3. Interface design is related to multiple domains which are the functional, physical, and process (production) domain. Specifically, interfaces in the physical domain need to implement functional relationships in the functional domain, and at the same time, they constrain assembly sequences in the process domain. In addition, Interface design can improve assembly system complexity by changing assembly orders. In this vein, the approach to complexity management should not be a just simple approach from the production viewpoint, but a design-oriented approach from the cross-domain viewpoint. The next subsection will describe specific sources of assembly system complexity and introduces an index to measure the complexity.

IV. ASSEMBLY SYSTEM COMPLEXITY

A. OPERATOR CHOICE COMPLEXITY (OCC)

This paper focuses on the complexity induced from product variety. Manufacturing firms have been using mixed-model assembly lines to accommodate the increased variety. Fig. 4 shows a mixed-model assembly line. At each station, an operator assembles an input module into a subassembly which is a set of modules assembled at the previous stations, then at the end of an assembly line, a final product assembly is completed. In order to produce a variety of products, an operator at each station has to handle diverse module variants, not a single variant. In a mixed-model assembly line, the performance of operators who deal with diverse module variants has significant impact on the productivity of an assembly system [2]. Addressing this issue, Zhu et al. [2] proposed an index named *operator choice complexity* (OCC) that measures the amount of uncertainty in choice situations faced by operators. The index measures the average uncertainty of operators' choice tasks such as part, fixture, tool, and procedure choices.

The OCC index is based on Shannon's information entropy [12]. When the probability of each choice is p_m among M choices, the average uncertainty in a choice task is represented as the following form:

$$H(X) = H(p_1, p_1, \dots, p_M) = -K \sum_{m=1}^M p_m \log p_m \quad (1)$$

where K is a constant for adjustment depending on a function. In the formula, if a \log_2 function is selected, $K = 1$ and the unit of complexity is *bit* [2]. The function H calculates the average reaction time of an operator choosing an object of a task. Zhu et al. [2] justified that the information entropy is an effective measure for calculating the uncertainty in a choice task of an operator by the previous cognitive ergonomics studies. Among them, Bishu and Drury [43] found that average choice reaction time is direct proportion to the amount of

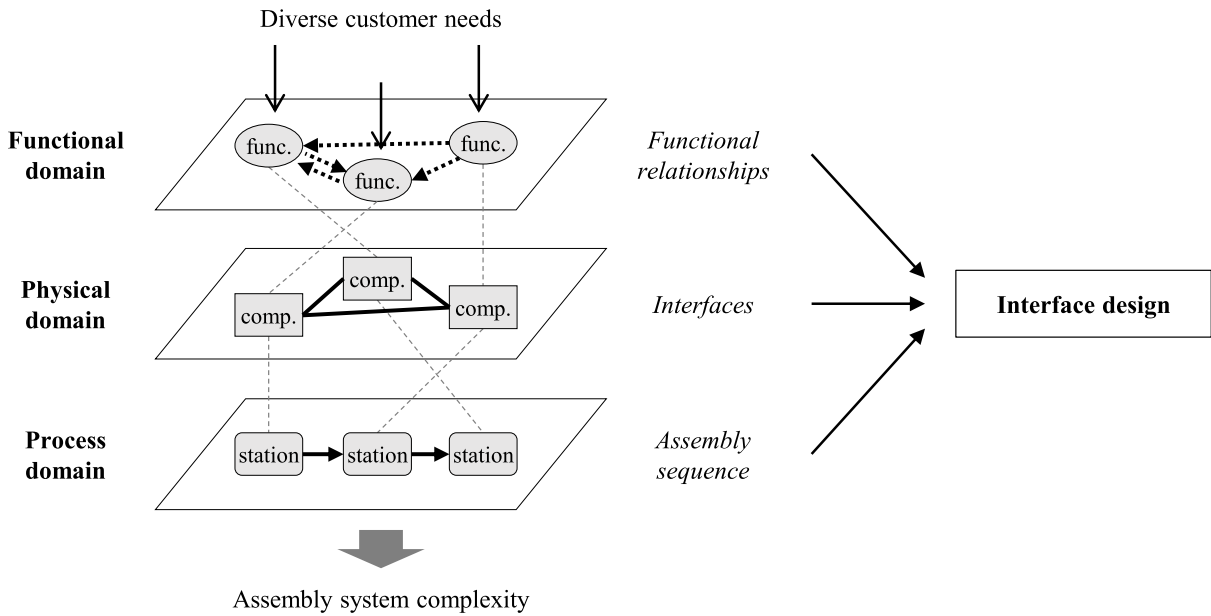


FIGURE 3. Interface design problem.

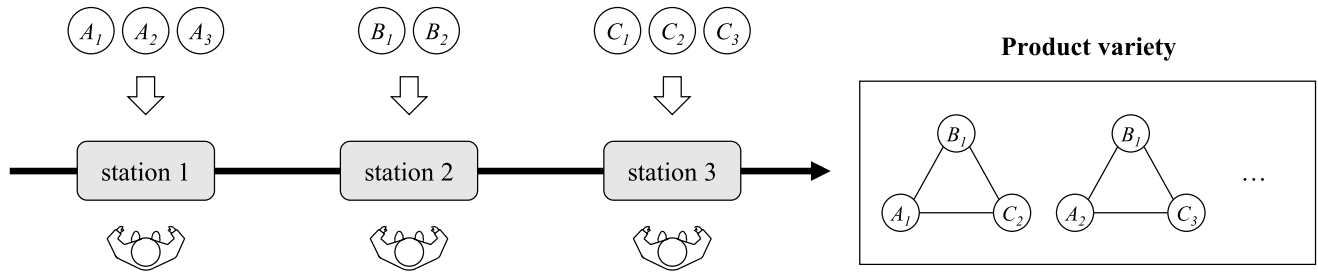


FIGURE 4. Mixed-model assembly line.

information contained in a task. They used a unit of bit as a measure for the amount of information calculated by the function H above.

Zhu *et al.* [2] extends the information entropy function in a single task to the station level to define the OCC. Types of tasks conducted in a station is identified as follows: part, fixture, tool, and procedure choice task. The complexity of station i is defined as the sum of the complexity of sequential tasks from 1 to J at the station:

$$C_i = \sum_{j=1}^J \alpha_{ij}(a_{ij} + b_{ij}H_{ij}), \quad \alpha_{ij} > 0, j = 1, 2, \dots, J \quad (2)$$

where α_{ij} is the weight indicating the relative difficulty of j th task in station i , a_{ij} and b_{ij} are the empirical constants revising the entropy measure to reaction time, and H_{ij} is the entropy function based on the appearance ratio of choice objects.

The station level complexity is then divided into feed complexity and transfer complexity depending on whether a task is propagated or not [2]. *Feed complexity* is related to choice tasks that cause the complexity only at the current station such as part and tool choices. *Transfer complexity*, on the other hand, is associated with tasks that affect the complexity of other stations such as fixture and procedure choices. In some cases, tool choice tasks may affect other stations.

The propagation concept of the complexity well describes a situation of cumulative increase in complexity at the end of an assembly line.

B. DESIGN-PERSPECTIVE ASSEMBLY SYSTEM COMPLEXITY

Since choice activities defined in Zhu *et al.* [2] cannot identify direct impact of interfaces on the complexity, a task in design viewpoint is redefined in this paper. For this reason, this paper concentrates on the physical elements of assembly while Zhu *et al.* [2] focused on the objects of choice activities such as part, fixture, tool, and procedure choices. Fig. 5 describes the three physical elements handled by an operator in a station. The elements are divided into an input module, a subassembly, and interfaces between them [44]. An input module is a module to be assembled at a station, and a subassembly is a set of modules that are assembled at the previous stations. Interfaces are physical connections between the input module and the subassembly at a station. Note that an input module can be connected to more than one module of a subassembly.

This shift of the perspective is based on the fact that the choice of assembly objects comes from the choice of design elements. Part choice tasks are related to the type of modules, and tool choice tasks are associated with the type of interfaces. Also, fixture choice tasks are related to the type of

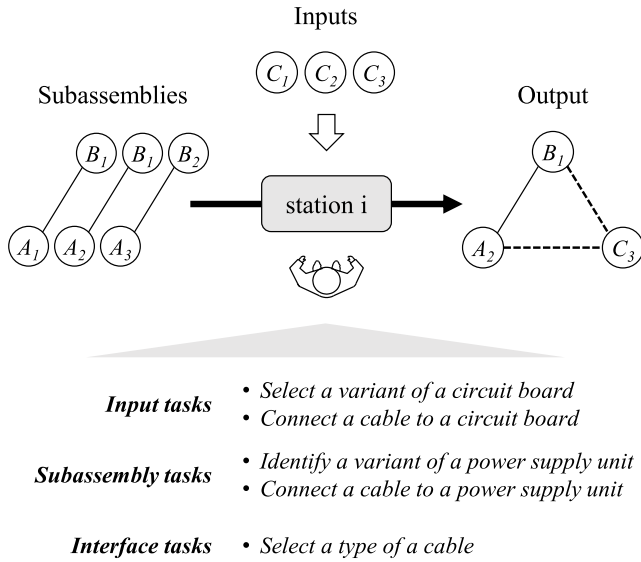


FIGURE 5. Assembly tasks at a station.

subassemblies, and procedure choice tasks are based on the type of subassemblies or interfaces. In this regard, this paper redefines choice tasks through design elements which are the main objects of assembly in design viewpoint.

Assembly tasks are then categorized with the three elements as listed on the bottom of Fig. 5. An *input-related assembly task* includes tasks to pick a module variant to be assembled and to choose an assembly process suitable for a variant. A *subassembly-related assembly task* consists of tasks to identify a module variant of a subassembly that needs to be connected with an input module. An *interface-related assembly task* contains tasks to choose a suitable interface type, and to prepare a tool for an assembly. For example, when there is a station assembling a circuit board (input module) to a power supply unit (subassembly) with a cable (interface), an operator first identifies a variant of a power supply unit (subassembly-related task), then selects a variant of a circuit board (input-related task) and a type of a cable (interface-related task), and finally connects a cable to a circuit board (input-related task) and a power supply unit (subassembly-related task).

With this viewpoint of assembly tasks, this paper attempts to measure complexity of a mixed-model assembly line. The *assembly system complexity* of a mixed-model assembly line is defined as the sum of station complexities generated at each station i . The equation is as follows:

$$C = \sum_{i=1}^I C_i \tag{3}$$

All assembly tasks are assumed to be independent of each other in this study. Zhu et al. [2] have defined the propagated complexity from the previous stations to the current station as transfer complexity. An operator at the end of the line, however, does not always do assembly tasks with high complexity. In addition, in design viewpoint, the complexity from the previous stations is propagated through various types

of subassemblies moved with the line. For this reason, this paper only deals with the station level complexity without distinction between transfer complexity and feed complexity defined in Zhu et al. [2].

The *station complexity* is calculated as the sum of task complexities that occur in a series of assembly tasks at a station. Task complexities are divided into three depending on the task types: input, subassembly, and interface-related assembly tasks. Then complexity of station i is stated as follows:

$$C_i = C_i^1 + C_i^2 + C_i^3 = \sum_{j=1}^{J_i^1} \alpha_{ij}^1 C_{ij}^1 + \sum_{j=1}^{J_i^2} \alpha_{ij}^2 C_{ij}^2 + \sum_{j=1}^{J_i^3} \alpha_{ij}^3 C_{ij}^3 \tag{4}$$

where C_i^1 , C_i^2 , and C_i^3 are the complexity of the three types of tasks respectively, and C_{ij}^k ($k = 1,2,3$) is the complexity of each task j at station i . J_i^k is the number of tasks included in each task type k , and α_{ij}^k is the weight parameter indicating the relative difficulty of a task. Since the difficulty of assembly tasks is one of the major sources of complexity as well as variety, it should be carefully considered. However, since this paper mainly focuses on managing variety-induced complexity rather than difficulties in assembly tasks, the difficulty is assumed as a weight parameter. The value of the relative difficulty can be obtained by information from the experienced difficulty or working time of each task. For simplicity, this paper assumes that all tasks are equally difficult, so the value of α_{ij}^k sets to 1.

Among the three types of the task complexities, the first term calculates complexity generated from input-related assembly tasks. This type of tasks requires different activities as a module variant to be changed, so the complexity measure is formulated by the probability of occurrence of each module variant for an operator. The probability of occurrence of a module variant is obtained from a production volume of a module variant. Complexity of task j is derived from the entropy function (1) as below:

$$C_{ij}^1 = -K \sum_{m=1}^{M_i} (v_{im}/V_i) \cdot \log_2(v_{im}/V_i) \tag{5}$$

where M_i is the number of variants of module i , v_{im} is a production volume of variant m of module i , and V_i is the total volume of all variants of module i .

On the other hand, complexity of subassembly-related assembly tasks is associated with module variants of a subassembly assembled at the previous stations. Tasks of this type vary depending on assembled module variants before in a subassembly. Subassembly-related tasks are greatly influenced by the assembly sequence since the sequence change influences the type of subassemblies, confusing an operator. As an input module is connected to a subassembly with a large number of interfaces, more tasks are required. If module i is connected with all modules (module 1, 2, ..., $i-1$) in a subassembly, there are at least $i-1$ number of subassembly-related tasks to do. Among $i-1$ number of modules in a

subassembly, when module l has one or more interfaces with input module i , complexity of subassembly-related task j is calculated as below. The probability of occurrence of a module variant is obtained from a production volume of variant m of module l :

$$C_{ij}^2 = -K \cdot I_{il} \sum_{m=1}^{M_l} (v_{lm}/V_l) \cdot \log_2(v_{lm}/V_l) \quad (6)$$

where M_l is the number of variants of module l , v_{lm} is a production volume of variant m of module l , and V_l is the total volume of all variants of module l . When there are multiple interfaces between module i and l due to diverse functional interactions, the complexity value is multiplied by the number of interfaces I_{il} .

Lastly, interface-related assembly tasks are affected by interface variants to be assembled. If an interface is not standardized, an operator has to choose an appropriate interface variant for the assembly. This type of tasks requires as many tasks as the number of non-standardized interfaces between an input module and a subassembly. Thus, complexity of interface-related assembly tasks is calculated using the same formula as (4) by substituting a production volume of a module variant with that of an interface variant. Since this paper assumes that a product family is designed based on the modular product architecture, it is also assumed that interfaces are standardized. For this reason, complexity of interface-related assembly tasks is regarded as zero ($C_{ij}^3 = 0$). Note that interface standardization is a major enable to reduce complexity by making assembly tasks identical, so it is the first consideration for manufacturing firms.

In summary, the assembly system complexity is represented as the sum of station complexities, and module variants assembled at the previous stations diversify tasks at the current station. Thus, in order to manage the assembly system complexity, decisions on an assembly sequence and an interface structure are important. When a firm tries to minimize complexity in the existing assembly system, they can find an optimal solution by reconfiguring its assembly sequence with redesigning interface structures of a product family. A framework for finding an optimal solution will be described at the next section.

V. A FRAMEWORK FOR AN OPTIMAL INTERFACE DESIGN

A. PROBLEM DESCRIPTION

The objective of this paper is to minimize the assembly system complexity by designing an interface structure and sequencing an assembly process for a product family. One important requirement for minimizing the complexity is that all products assembled in an assembly system must have the same interface structure. This is because when an assembly system accommodates various interface structures, more complexity is generated by unnecessary tasks such as part preparation, tool setup, structure identification etc. Thus, the problem assumes that all products in a family are designed with the same interface structure.

TABLE 1. Number of module variants in the PDP family.

Module	Name	No. of variety
A	panel	36
B	frame	17
C	y-sustain board	9
D	y-driver board	7
E	z-sustain board	7
F	control board	13
G	x-sustain board	12
H	heatsink	11
I	power supply unit	15

The problem covered in this paper is described in Fig. 6. Based on the given information of a product family plan and its functional relationships (top layer), interface design alternatives and possible assembly sequences are derived (middle layer), and then the assembly system complexity is calculated by each alternative (bottom layer). First of all, this paper assumes that a product family is designed based on the modular product architecture, so a product is regarded as composition of N number of modules. Each module i has M_i number of variants, and a product is created by a combination of module variants. For functional relationships, all products in a family have an identical function structure. Information on the four types of relationships, which are spatial, energy, signal, and material, can be obtained by function analysis tools such as the function structure diagram.

At the middle layer in Fig. 6, interface design alternatives are generated from the given information on functional relationships, and then possible assembly sequences for each alternative are generated. An interface design alternative for each functional relationship can be identified by designers' knowledge. Through the knowledge, a number of interface structures can be created at this stage. Assembly sequences also have a variety of alternatives depending on the constraints of assembling possibility. Operators' working conditions, assembly order in a product structure, or limitations of an assembly system could be the constraints.

Lastly, at the bottom of Fig. 6, a mixed-model assembly line is virtually constructed by each sequence of an alternative, and its complexity is calculated. An assembly line is considered as a single serial line of N stations. One module is entered at each station, and all assembly tasks are done manually by an operator. After an assembly line for an alternative is constructed, assembly tasks to be done at each station are arranged. Finally, the total complexity of an assembly line is obtained by calculating the complexities of all tasks and stations.

The objective of the problem is to find an optimal interface design alternative and assembly sequence to minimize

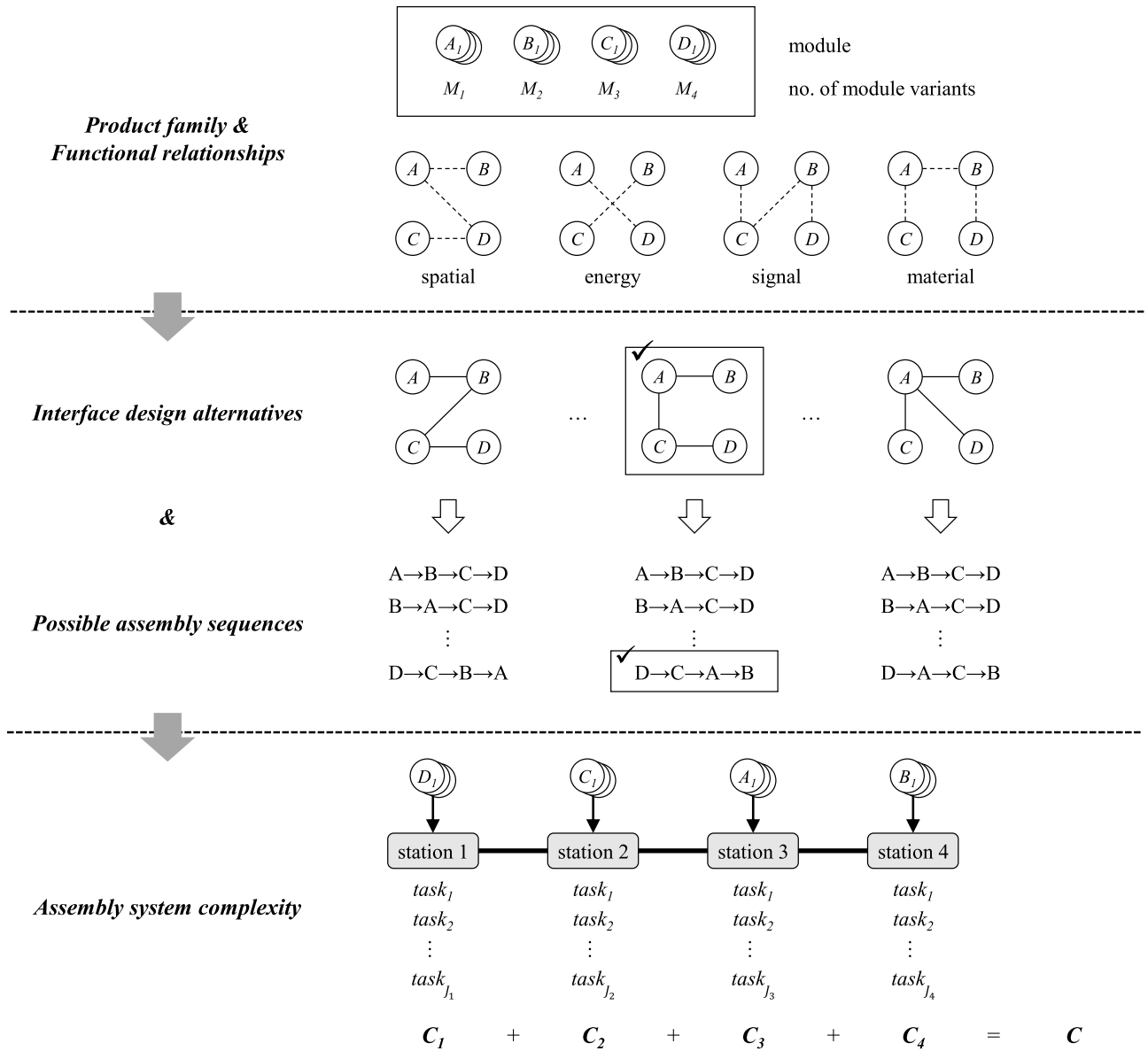


FIGURE 6. Problem description.

the assembly system complexity. The problem is stated as follows:

$$\begin{aligned}
 & \min_S \min_{\rho} C(S, \rho) \\
 & \text{s.t. } S = f(R) \\
 & \quad \rho = g(S)
 \end{aligned} \tag{7}$$

where S represents an interface structure, and it is constrained by functional relationships R of a product family. A function $f(R)$ represents the process of generating interface design alternatives with respect to functional relationships. This function involves the constraints on interface design. The term ρ is an assembly sequence derived from an interface structure S . A function $g(S)$ is used for describing the process of generating possible assembly sequences. Additionally, the

function can also include the constraints on assembling possibility. This optimization problem can be further modeled as specific formulations, but this paper focuses more on proposing a framework for the process of generating alternatives. The next subsection introduces a framework for identifying an optimal solution by generating all feasible alternatives to the problem.

B. INTERFACE DESIGN FRAMEWORK

Fig. 7 shows the interface design framework for identifying an optimal solution that minimizes the assembly system complexity. The framework is divided into three steps which are (1) the generation of interface design alternatives, (2) the derivation of possible assembly sequences, and (3) the evaluation of each alternative through the complexity index.

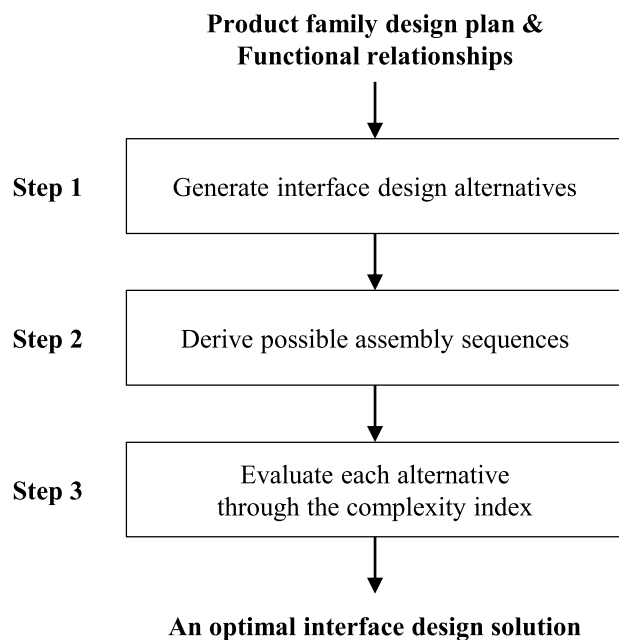


FIGURE 7. Framework for an optimal interface design.

The first step creates feasible alternatives of an interface structure that satisfy functional relationships of a product family. Decisions at this step include which types and what structure of interfaces would be designed for the four types of functional relationships which are spatial, energy, signal, and material. For example, when there is a signal interaction between two modules, a decision maker first decides whether to connect it with a cable or a wiring harness, and then determines whether to connect directly or indirectly via another module. At this time, it is significant for experts to consider the possibility of interface connection. If a signal connection should be designed only directly, alternatives with indirect connections can be removed. Thus, the use of information from accumulated design experiences of designers is essential for narrowing down the number of alternatives.

At the second step, possible assembly sequences are derived from each alternative of the interface design. When a product consists of N number of modules, the number of possible solutions for an assembly sequence is theoretically $N!$. The number of feasible solutions, however, can be significantly reduced by the constraints on assembling possibility. In the case of a vehicle, a frame, which is the skeleton of a product, must be the first to enter into an assembly line in order to connect other additional parts afterwards. Another example of the constraints is that a module located inside must be assembled before a module located outside. The number of possible assembly sequences can be greatly reduced by considering these constraints regarding precedence relationships of modules. Thus, in this step, it is necessary to list up the constraints for the assembly sequence by interviewing experts such as an assembly system manager or a system layout designer.

Finally, all alternatives are evaluated by using the assembly system complexity index, and compared with each other

under the given situation of a firm. Then, an optimal interface design solution and an assembly sequence are selected. The objective function of the problem is to minimize the complexity value. In this study, a full enumeration method is used for finding an optimal solution in given constraints from the first and second steps that reduce the range of feasible solutions. This method is suitable for small scale products such as a display panel in the case study. For a complex product such as an automobile, however, it can have extremely large feasible solutions. If there is no constraints for an interface connection, an interface can have $N!/e$ number of solutions where N is the number of modules. It gives $(N!/e)^M$ solutions when there are M interfaces in a product. Thus, in order to increase the practicality of the proposed framework, it is necessary to develop an algorithm to find a solution in a short time. Some algorithms, especially metaheuristics, can be developed to quickly identify an optimal solution, but the paper deals with the case having diverse practical constraints on interface connections and assembly sequences, so the development of a heuristic algorithm remains for future works.

The optimal solution of the problem can vary depending on situations a firm is facing. If a firm has a limited fund for complexity management, they need to consider both redesign cost for changing an interface structure and reconfiguration cost for changing an assembly system layout. For this reason, the optimal solution should be reviewed by considering firm's current situation with various constraints. Scenario analysis is conducted in the case study with respect to this issue.

VI. CASE STUDY: PLASMA DISPLAY PANEL (PDP) FAMILY

A. CASE DESCRIPTION

This paper uses industrial data of a plasma display panel (PDP) family from LG Electronics for a case study of the proposed interface design framework. A PDP is a device that displays moving images on the panel by using electrical discharges of plasma. A PDP, the core module of a television, is also produced as a final product. The overall structure of a PDP is shown in Fig. 8. It consists of a panel that displays images, a frame that supports all other parts, several boards that receive and process video signals, a power supply unit that supplies electrical energy, and a heatsink that protects the device from the heat. Each of parts is regarded as a module that independently performs its own function, and has several variants to compose a product of a product family. The PDP family has 66 different products, and Table I shows the number of module variants that comprise those products. Currently, 66 products are designed by the four interface structures in Fig. 9. Since the difference of structures is a main factor for the increasing complexity, the structures should be integrated into a single one.

The assembly line of the PDP family is a single serial line as shown in Fig. 10. The line is divided into nine stations which number is equal to the number of modules. At each station, one module is assembled with a subassembly on the conveyor line by an operator. Once all interfaces are

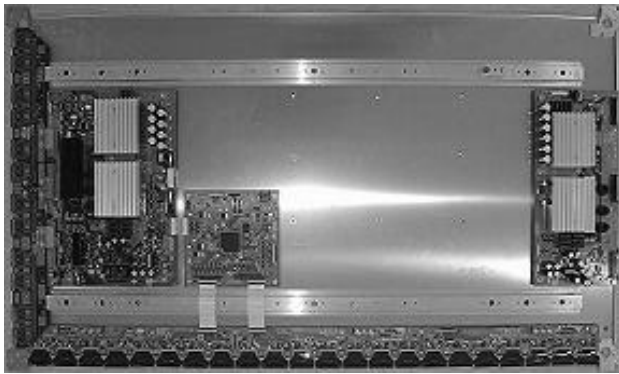


FIGURE 8. Plasma display panel (PDP).

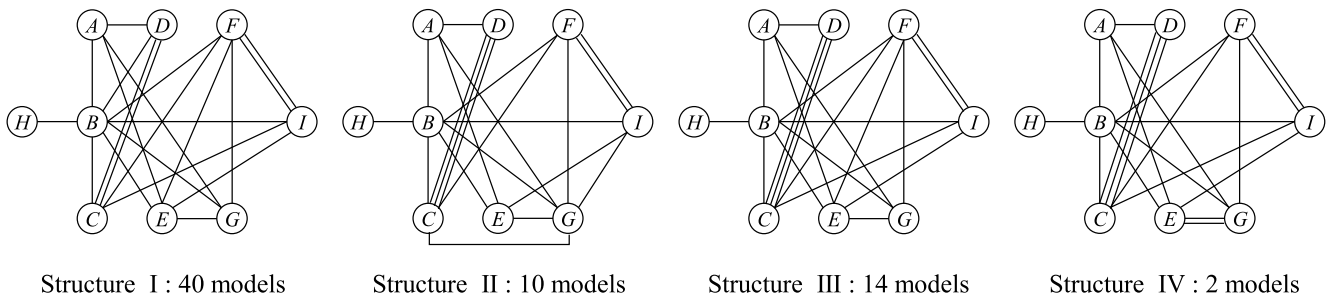
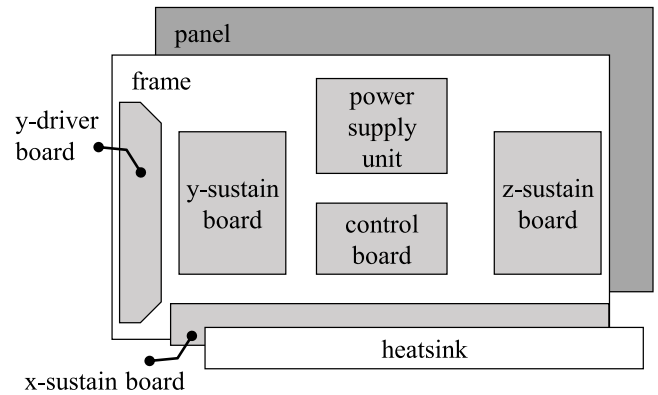


FIGURE 9. Current interface structures of the PDP family.

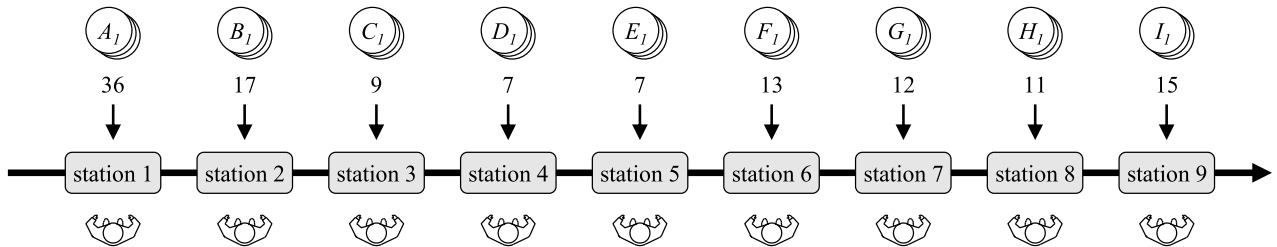


FIGURE 10. PDP family assembly line.

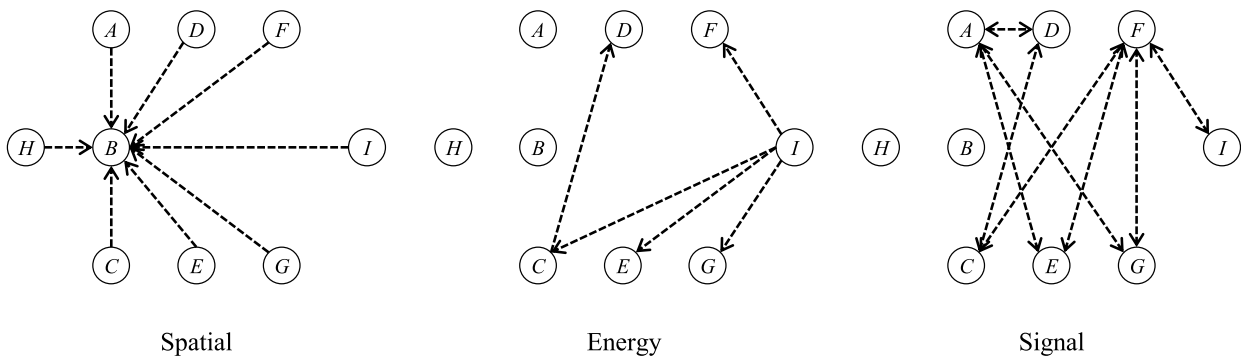


FIGURE 11. Functional relationships of the PDP family.

standardized, operators' tasks no longer are affected by the interface types. However the diversity of module variants and subassemblies decreases work efficiency in that it makes operators confused. In order to measure the complexity, a production volume of each module variant should be calculated from production volumes of all products. This case

study assumes that all products are assembled as the same production proportion.

B. GENERATION OF FEASIBLE SOLUTIONS

In order to generate feasible solutions for the interface design, we analyzed functional relationships of the PDP family.

TABLE 2. Scenarios for the interface design.

Scenario	Strategy		Required cost	
	Interface design alternatives	Assembly sequences	Redesign cost	Reconfiguration cost
1	Select a current structure	No change	Relatively low	-
2	Select a current structure	Change	Relatively low	High
3	Design a new structure	No change	Relatively high	-
4	Design a new structure	Change	Relatively high	High

TABLE 3. Scenario 1 result.

Interface design alternatives	Current structure I	Current structure II	Current structure III	Current structure IV
Interface structure				
Assembly sequence	ABCDEFGHI			
Minimum value of complexity	114.99	114.07	113.30	113.30

TABLE 4. Scenario 2 result.

Interface design alternatives	Current structure I	Current structure II	Current structure III	Current structure IV
Interface structure				
Optimal assembly sequences	DCFEGIBAH DCFEGIBHA DCFGEIBAH DCFGEIBHA	DCGEFIBAH DCGEFIBHA DCGFEIBAH DCGFEIBHA	DCFEGIBAH DCFEGIBHA DCFEIGBAH DCFEIGBHA	DCFIEGBAH DCFIEGBHA
Minimum value of complexity	103.21	102.97	102.44	102.65

Fig. 11 is the result of three types of interactions that the PDP family has. Material interactions were not identified because a PDP is not worked with material flow, but energy and signal flows. From the interview with experts, we found that there are total 21 functional relationships between modules. For the three types of interactions, some constraints exist with regard to the interface design. The constraints are listed as follows:

1) Constraints on spatial interactions

- All modules must be connected.

- A panel, a heatsink, and boards must be directly connected to a frame.
 - Only a y-driver board can be indirectly connected to a frame through a y-sustain board.
- 2) Constraints on energy interactions
- A y-driver board must be directly connected with a y-sustain board.
 - A control board must be directly connected with a power supply unit.

TABLE 5. Scenario 3 result.

Optimal interface design alternatives	
Assembly sequence	ABCDEFGHI
Minimum value of complexity	<u>111.13</u>

- Energy interactions between modules should be designed via a control board.

3) Constraints on signal interactions

- An x-sustain board, a y-driver board, and a z-sustain board must be directly connected to a panel.
- A y-driver board must be directly connected with a y-sustain board.
- Signal interactions between modules should be designed via a y-driver board.

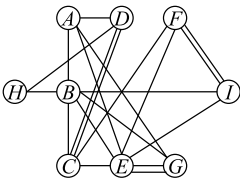
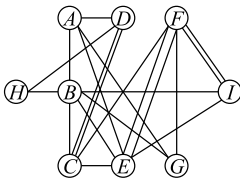
The numbers of feasible interface design alternatives for each type of interactions are 25, 16, and 9 respectively. The alternatives can be generated by a combination of the three interface structures, so the number of feasible interface design alternatives is 3,275. With this result, we generated

all possible assembly sequences by each alternative for the complexity measurement.

C. SCENARIO ANALYSIS

Based on the generated alternatives, scenario analysis was conducted for different situations that can be faced in practice. As shown in Table 2, the scenarios are divided into four cases depending on whether to develop a new interface structure or not, and whether to reconfigure an assembly sequence or not. Developing a new interface structure is more expensive in terms of redesign cost than integrating the existing structures to the current one. In addition, changing the assembly sequence requires additional cost for reconfiguration of the assembly system. It may be impossible for a firm to change interface structures or to reconfigure its assembly system due to various practical reasons. For this reason, this paper

TABLE 6. Scenario 4 result.

Optimal interface design alternatives	I	II		
Interface structure				
Optimal assembly sequences	DCEFGHIBA DCEFIHGBA DCEGHFIBA DCHEFIGBA DCEFGIHBA DCEGFHIBA DCEHFGIBA DCHEGFIBA DCEFHGIBA	DCEGFIHBA DCEHFIGBA DHCEFGIBA DCEFHIGBA DCEGHFIBA DCEHGFIHBA DCEHGFIBA DHCEFIGBA DCEFIGHBA DCHEFGIBA	DCEFGHIBA DCEFIHGBA DCEGHFIBA DCHEFIGBA DCEFGIHBA DCEGFHIBA DCEHFGIBA DCHEGFIBA DCEFHGIBA	DCEGFIHBA DCEHFIGBA DHCEFGIBA DCEFHIGBA DCEGHFIBA DCEHGFIHBA DCEHGFIBA DHCEFIGBA DCEFIGHBA DCHEFGIBA
Minimum value of complexity	<u>99.50</u>	<u>99.50</u>		

conducted this scenario analysis to find optimal solutions for each situation.

The first scenario is to unify the four different structures into one of them without changing the assembly sequence. In this case, redesign cost is relatively low because a current interface structure is selected, and reconfiguration cost is not to be considered. This scenario is suitable for the case when a firm has limited fund, or a huge cost is required for the development a new interface structure, and the change of the assembly process. There is no need for process change, operator relocation, or assembly tool change, while the redesign cost is needed for changing the interface structures to the same one. Table 3 shows the minimum value of complexity when the interface structures are unified into one of the four current structures. When the current interface structure III or IV are selected among the four, the complexity value is minimized to 113.30.

The second scenario is to change an assembly sequence while unifying the interface structures into the existing one. In this scenario, reconfiguration cost of the assembly sequence is additionally incurred compared to the scenario 1. This scenario is appropriate when the reconfiguration cost is not burdened for a firm. The cost includes expenses of process change, operator relocation, and assembly tool change. Table 4 lists optimal assembly sequences in each existing interface structure that minimize the complexity. When the structure III is selected, the complexity value is minimized to 102.44, and four optimal assembly sequences are identified. Figuring out which one is better sequence is not treated in this study, but an appropriate solution should

TABLE 7. Summary of the results.

Scenario	Result	
	Minimum value of complexity	Compared ratio
1	113.30	114%
2	102.44	103%
3	111.13	112%
4	<u>99.50</u>	<u>100%</u>

be selected considering the amount of efforts (e.g., cost) to reconfigure the assembly system.

The third scenario is to develop a new interface structure without changing the assembly sequence. This case does not require reconfiguration cost for changing the assembly system, but needs redesign cost for development of a new interface structure. In order to find an optimal solution, we evaluated all 3,275 of feasible interface structures. Among all of the solutions, 18 optimal solutions are identified as shown in Table 2. If a firm selects a new interface design among those 18 solutions, the complexity value can be reduced to 111.13.

The last scenario is to develop a new interface structure, and to simultaneously change the assembly sequence to a new order. This scenario has a high degree of freedom in decision-making, so a firm can consider all possible solutions of an interface structure and an assembly sequence. On the other

TABLE 8. Summary of the results.

Criteria		Interface design approach	OCC-based approach [19]-[22]	DFA approach (task difficulties) [10], [32]-[34]	DFA approach (granularity levels) [36]-[38]	DFA approach (production time) [40]
Design phase	System-level design	●			●	●
	Detail design			●		
	Process design	○	●	○	●	○
Decision level	Product variety	●	●		○	●
	Product architecture	○		○	●	
	Modularization				●	●
	Component design			●		
	Interface structure	●				

●: mainly considered
○: partially considered

hand, a firm should consider both relatively high redesign cost for developing a new interface structure, and reconfiguration cost for modification of the order in assembly. Thus, this case is suitable for a firm that can afford to change both of them. Among all feasible solutions of an interface structure and an assembly sequence, the result for optimal solutions is shown in Table 4. When a firm selects a new interface structure I or II, the complexity value is minimized to 99.50 with 18 optimal assembly sequences listed in Table 6, respectively.

D. DISCUSSION

This paper proposes a strategy for reducing complexity by changing an interface structure in the design phase with reconfiguring the sequence of an assembly line in the production phase. The effect of the strategy was studied by the scenario analysis, and Table 7 summarizes the results of the four scenarios. As shown in the table, we identified that the assembly system complexity is minimized to 99.50 in scenario 4, which allows both the development of a new interface structure and the reconfiguration of an assembly sequence. The physical meaning of the result is that the average choice reaction time is reduced by the ratio from the current state (higher than 113.30) to 99.50 comparing all scenarios. In addition, the result means that the complexity can be reduced while keeping the current product family as well as the assembly system without losing money from the reduction of the product variety or the investment on the assembly system. The result, however, have not been compared with the costs of redesign and reconfiguration, so further analysis must be conducted by comparing the costs to the reduced complexity that represents the reaction time. Instead, it is expected that the solutions within the scenarios described in the previous subsection will be effective because they were compared with other alternatives under the same conditions.

By comparing the results, scenario 2 and 4 with the change of the assembly sequence have complexity values of 11-2% less than scenario 1 and 3, respectively. This supports the previous studies that complexity can be reduced by the delayed differentiation [2]. In addition, in the comparison of scenario 1 and 3, the complexity values differ by 2% depending on the choice of an interface design alternative, even if the assembly sequence is fixed. Although its difference is less than the effect of a sequence change, the result shows that the choice of an appropriate interface structure has significant impact on the reduction of complexity. Thus, it would be effective for manufacturing firms to manage complexity by extending the managerial area to the design phase, rather than restricting it to the production phase.

Among the design-oriented approaches, the interface design approach proposed in this paper is novel in that it manages assembly system complexity by changing the structure of interface connections. Table 8 summarizes the differences between the interface design approach and others. Firstly, the interface design approach enables to manage complexity during the system-level design phase early in the development process. The DFA approach considering task difficulties [10], [32]-[34], on the other hand, can manage complexity at the detail design, and the OCC-based approach [19]-[22] focuses on the process design phase which can only control the layout or sequence of an assembly system. Other DFA approaches regarding granularity levels [36]-[38] or production time [40] deal with the system-level design phase, but decision levels of those research focus on a product architecture, modularization or a component design rather than an interface structure. At this point, this paper has a different contribution from other approaches in that it proposes a new approach for complexity management by changing a connections structure of interfaces among possible structures.

The framework proposed in this study can be helpful for a firm to make decisions for reducing complexity in various situations. Depending on a situation that a firm is facing, there may be some restrictions on changing an assembly system or an interface structure e.g. limited fund, assembling possibility, or the feasibility of an interface structure. The interface design framework can accommodate these constraints to find an optimal solution. This study showed it through the scenario analysis by reflecting various situations, but for each scenario, more than one optimal solution was obtained. This is because we assumed that all tasks had the same difficulty, and all products had the same production volume. Thus, if a firm applies different level of task difficulties and production volumes to the framework, they will be able to find a unique solution that suits a firm's situation.

VII. CONCLUSION

This paper proposed a novel interface design approach to complexity management in assembly systems from the design-oriented perspective. First, we defined the interface design problem by showing the mechanism of how interface design affects assembly system complexity. Then, an index for the assembly system complexity was introduced from the design-oriented viewpoint by modifying the operator choice complexity index. Finally, an interface design framework was proposed for identifying an optimal solution by generating all feasible solutions of interface structures and assembly sequences. In the case study, the framework is applied to the interface design problem by using industrial data of a plasma display panel (PDP) family from LG Electronics. The result of the study demonstrates that the assembly system complexity is significantly reduced by the interface design framework.

The contribution of this paper is that it proposes a novel complexity management strategy only by redesigning interface structures without loss of market share or investment in assembly technologies. In particular, the paper is significant in that it changes the perspective of complexity management from production to design. Manufacturing firms can be helped by this study to find out which alternative is suitable for their situation among various interface structures and assembly sequences. Furthermore, a firm can notice that unifying interface structures of a product family is an important key to reduce complexity in assembly systems.

There are also several limitations and future works. First, the assumptions in this study need to be additionally considered and relaxed. The problem in this paper used some assumptions such as interface standardization, identical level of task difficulties, and the same production volume of products. These should be mitigated in future works depending on a situation that a firm is facing. Especially, in terms of task difficulties, there are many critical factors that affect assembly system complexity as well as variety, thus additional consideration must be required. Second, future works need to formulate an optimization model and to develop its solving algorithm. This paper proposed a framework for

finding an optimal solution, but building an optimization model with practical constraints including the cost considered in the scenario analysis will be more useful for a firm to obtain an optimal solution quickly. In addition, the development of an algorithm will be able to cover complex products such as an automobile as well as small scale products. Various types of layout in assembly system is the last issue to be considered. This paper only considered a single serial assembly line, but future works will extend an assembly line to various layouts such as parallel lines or a reconfigurable system.

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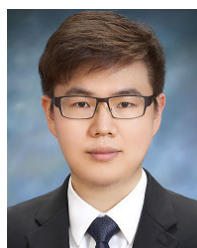
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