INTRODUCTION TO OPERATIONS ARCHITECTURE FOR
COMPLEXITY MANAGEMENT IN PRODUCT DESIGN AND
OPERATIONS

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Abstract
Manufacturing firms have been trying to develop high variety of products to cope with continuously changing customer requirements in marketplace. However, the demand for high variety of products generates inefficiencies which is called complexity (or complexity cost) in operations. Although some studies tried to see the complexity in overall viewpoint, the relationship between design and operations phase is not structurally taken into account. In this paper, operations architecture (OA) is introduced which is a tool for describing the structure and the relationship between design and operations phase to manage the variety-induced complexity. Using the OA, complexity sources considered at the previous studies are newly classified based on the four domains in the architecture. From the result of classification, the authors identified that the complexity sources are not only staying in a domain but propagating their impacts to other domains. Then, applicability of the OA is discussed showing three applications.

Keywords: Complexity, Product architecture, Design engineering, Operations architecture

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1 INTRODUCTION

Manufacturing firms have been trying to develop high variety of products to cope with continuously changing customer requirements in marketplace (Pine, 1993). Nowadays, the trend of mass customization and personalization grows, since technologies such as data mining and social network analysis are progressed to access to personalized data (Kumar, 2007). However, the demand for high variety of products generates inefficiencies which is called complexity (or operations complexity) to the manufacturing firms to operate manufacturing systems, assembly systems and supply chains (Hu et al., 2011). Especially, variety-induced complexity among various concepts is generated from the design phase where engineers design a set of products and is “propagated” to operations phase to give bad influence generally on operations such as production (manufacturing and assembly systems) and procurement (supply chains) (ElMaraghy et al., 2012).

In academia, many studies were conducted to define the complexity. They concentrated on specific areas in operations such as variety of manufacturing tools, tasks, and processes in assembly systems and supply chain structures (ElMaraghy and Urbanic, 2003; Zhu et al., 2008). However, these studies have limitation in that they did not consider the design phase in which the complexity is fundamentally generated from the variety. Although some studies tried to see the complexity in overall viewpoint (ElMaraghy et al., 2012; Fujimoto et al., 2003; Hashemi et al., 2013), the relationship between design and operations phase is not structurally taken into account. Figure 1 shows the mechanism of variety propagation from design to operations phase. The propagated things in both domain are all potential complexity sources. The purpose of this paper is to structure the relationship of the design and operations phases and to show the complexity management frame based on the structure of the relationship between complexity sources as shown in Figure 1.

In this paper, operations architecture (OA) is introduced which is a tool for structuring the relationship of complexity sources in design and operations phases. Through the OA, complexity sources which were considered from the previous studies are effectively classified and three applicable areas of the OA are introduced to emphasize applicability for the manufacturing firms. In Section 2, the concept of the OA is introduced defining each domain in the architecture. Section 3 explains complexity sources from the previous studies and classifies them based on four domains of the architecture. Section 4 briefly describes the applicability of the OA in the perspective of the complexity management frame. The last section summarizes the paper and refers some studies already done or in progress by the authors.

![Figure 1. Mechanism of variety propagation](image-url)

2 OPERATIONS ARCHITECTURE

This section introduces the OA which is a tool that describes the relationship between the variety from the design phase and the complexity sources residing in the operations phase. The complexity sources in operations including sources from manufacturing systems, assembly systems and supply chains are tightly linked to product architecture which is determined in design phase. Thus, decisions in the design phase affect diverse areas in operations. Therefore, the relationships between elements of variety in the
design phase and elements of complexity sources in the operations phase should be clarified through the OA.

Figure 2 describes the product architecture (PA) which is already defined in the previous research and the OA which is newly defined in this paper. Ulrich (1995) defined the PA as the relationships between functions and physical components. Suh (2001) denoted functional domain considers “what we want to achieve” and physical domain determines “how we want to achieve it”. Likewise, the OA consists of two domains which are operational domain and configurational domain. The operational domain determines “what we have to operate” and the configurational domain designs “how we have to operate it”. While the PA is a reference for helping engineers design a set of products, the OA is a tool to support process design and operations control in production stage. Thus, the OA needs to cover all processes which includes production (manufacturing and assembly systems) and procurement (supply chains).

The PA and OA are tightly linked in the perspective of variety propagation. The OA accommodates elements of the PA such as components, modules, interfaces, product structures and BOM (bill of material). The elements are variety-induced complexity sources in the design phase. The operational domain accepts the elements and determines operation processes such as tasks, processes, activities and schedules. Since the elements of the operational domain are invisible and intangible, the configurational domain constructs physical and structural elements to give body to the operational elements. In configurational domain, line configurations, stations, machines, tools, layout and supply chain structures are designed. For example, when a task which links component A and B is determined in the operational domain, the configurational domain decides which tool will be used, at which station will be worked and so on.

3 COMPLEXITY SOURCES SUMMARIZED BY THE OA

In this section, complexity sources dealt with in the previous studies are summarized based on the suggested architecture. This paper reviews literature focused on the variety-induced complexity since the fundamental idea of the paper is that the main driver of the operations complexity is product variety from the design phase. After Macduffie et al. (1996) validated that the variety of models and parts gives bad impact on the manufacturing performances, many studies were conducted to identify complexity sources in diverse areas of operations. Among them, this paper reviewed two kinds of complexity which are manufacturing complexity in production and supply chain complexity in procurement by the areas the sources are generated. Of course, there can be other areas such as after service.

One of the most active research area is manufacturing systems and assembly systems. The studies in this area mainly focused on operational and configurational elements in the manufacturing and assembly systems. Frizelle and Woodcock (1995) first introduced information entropy theory (Shannon, 1948) to develop complexity measures. They considered unstable states of manufacturing processes as the main complexity source. In some studies, specific elements in manufacturing systems, such as the number of
features and tasks and different types of machines, buffers and material handling systems, are regarded as complexity sources (ElMaraghy and Urbanic, 2003; 2004; ElMaraghy et al., 2005; Kuzgunkaya and ElMaraghy, 2006). On the other hand, Hu et al. (2008) and Zhu et al. (2008) concentrated on operators choice activities in assembly systems. In COMPLEX project progressed in Belgium and Sweden, product variants, work content, layout, tools, work instructions and variability are suggested as the main complexity sources after a workshop with manufacturers (Mattsson et al., 2011; 2012; 2013; 2016; Fast-Berglund et al., 2013). In the project, the number of packing types, work methods and assembly directions are also specifically considered (Zeltzer et al., 2013). Other complexity sources referred in other studies are summarized in Table 1.
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<td>MacDuffie et al. (1996), Schleich et al. (2007)</td>
<td>Model mix, Part variants</td>
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<td></td>
<td>Martin and Ishii (1997)</td>
<td>Degree of commonality and differentiation, Setup</td>
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<td></td>
<td>Fujimoto et al. (2003)</td>
<td>Functions, Key characteristics (No. of parts, sequence), Features, Task details (positioning, gripping, conveying)</td>
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<td></td>
<td>Deshmukh et al. (1998)</td>
<td>Part similarity, System size, Product design changes</td>
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<td></td>
<td>Hu et al. (2008), Zhu et al. (2008)</td>
<td>Part, fixture, tool and procedure choice activities</td>
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<td>Papakostas et al. (2009), Efthymiou et al. (2014)</td>
<td>Time variability, Unpredictability, Configuration</td>
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<td></td>
<td>Jemal and Liu (2010)</td>
<td>Dissimilarity of products in manufacturing process (process time, required skills)</td>
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<td></td>
<td>Zeal et al. (2009)</td>
<td>Process time, Task similarity, Worker cognition</td>
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<td></td>
<td>Vrabic and Butala (2012)</td>
<td>Unpredictable patterns of manufacturing process</td>
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<td></td>
<td>Sarkis (1997)</td>
<td>No. of robots and machine tools</td>
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<td></td>
<td>Zehtzer et al. (2013)</td>
<td>Picking technology, Bulk/sequence kit, No. of packaging types, No. of tools per workstations, No. of work methods, Distance to parts, No. of variants same model, No. of variants in workstations, No. of different parts in workstations</td>
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<td></td>
<td>Genschberger et al. (2012)</td>
<td>No. of elements and interrelations, Degree of uncertainty, Influence of supplier on customer-requested product variety, Geographical components</td>
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<td></td>
<td>Hashemi et al. (2013)</td>
<td>Product structure, Modularity, Product innovativeness, Supply chain configuration, Supply chain coordination and collaboration</td>
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<td></td>
<td>Milgate (2001)</td>
<td>Uncertainty, Technological intricate, Organizational systems</td>
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<td></td>
<td>Zhou (2002)</td>
<td>No. of products, processes and markets, Inventory locations and sizes, Organization, Failures</td>
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<td></td>
<td>Vachon and Klassen (2002)</td>
<td>No. of tasks, processes, parts and echelons, Level of interactions, Extent of supply network, Process capability, Setup, Scheduling changes, Late delivery, Demand volatility</td>
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<td></td>
<td>Perona and Miragliotta (2004)</td>
<td>Level of standardization, No. of finished and intermediate products, No. of suppliers and customers, Average order size</td>
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<td>Supply chain</td>
<td>Blecker et al. (2005)</td>
<td>Product/technology intricacy, Organization, Uncertainty</td>
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<td></td>
<td>Hu et al. (2008), Wang et al. (2010), Hamata et al. (2015)</td>
<td>Variants, Mix ratios</td>
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<td>Becarthy et al. (2009)</td>
<td>No. of customers, products, parts and suppliers, Heterogeneity of customers, Shorter product life cycles, Batch production ratio, Schedule instability, Unreliable lead times, Globalization</td>
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<td></td>
<td>Serdarsan (2013)</td>
<td>No. of products, processes, suppliers, customers and process interactions, Uncertainty, Changes, Organization, Decision making process, IT systems</td>
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<td></td>
<td>Turner and Williams (2005)</td>
<td>No. of of stocking locations, No. of of dealers in each major market</td>
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<td>Wilding (1998), Aekler et al. (2013)</td>
<td>Amplification, Deterministic Chaos, Parallel Interactions</td>
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<td>Arteta and Giachetti (2004)</td>
<td>Changes and state transitions</td>
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<td></td>
<td>Kaluza et al. (2006)</td>
<td>No. of elements and relations, No. of similar types</td>
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<td></td>
<td>Wu et al. (2007, 2013)</td>
<td>States of the system, Deviation from the schedule</td>
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Supply chain complexity is another important area since today’s supply chains are getting bigger with globalization. One part of the research in this area focused on operational elements. Sivadasan et al. (2002) defined the complexity as amount of information needed to explain the status of supply chains. Isik (2010) also showed forecast error of suppliers makes operations more complex. Wu et al. (2007, 2013) considered states of the system and deviation from the schedule as the complexity sources in operations. On the other hand, another part of the research concentrated on structures of supply chains. Yang and Yang (2010) defined supply chains as networks including system size and linkages between suppliers. They measured the number of suppliers in a supply network. In other research, links between suppliers were more concentrated than the number of suppliers (Meepetchdee and Shah, 2007; Caridi et al., 2010; Bezuidenhout et al., 2012). Modrak and Semanco (2011, 2012) tried to measure the complexity from the number of suppliers, links and the level of tier in supply chains. Kito and Ueda (2014) introduced the concept of nestedness to the supply chain complexity. They compared different structures of supply networks by the nestedness measure. Other complexity sources studied in other research are shown in Table 1.

As shown in above paragraphs, many studies were conducted to capture specific sources of the complexity in manufacturing and assembly systems and supply chains. Some research tried to show the operations complexity in the viewpoint of the design phase. ElMaraghy et al. (2013) arranged design strategies related with the variety such as commonization, standardization and platform design. They also suggested how the operations cope with the design strategies. ElMaraghy et al. (2012) constructed the structure of the complexity sources in general level and treated design issues related with the operations complexity. There were other tries to focus on the design phase by measuring product complexity itself. Erixon (1998) and Marti (2007) measured product complexity in the design phase and showed the impacts of this complexity on performances of the operations. Fujimoto et al. (2003) developed a methodology for management complexity in assembly process design considered functional variety from the design phase. Although there were efforts on considering both design and operations phases, establishment of the relationship between design and operations is rare.

In Table 1, complexity sources in manufacturing and assembly systems and supply chains are arranged as the previous studies referred. Then, the sources are classified by functional, physical, operational and configurational domain. ’●’ marks cover the areas the complexity sources generated and impacted. From the result of classification, the authors identified that the complexity sources are not only staying in a domain but propagating their impacts to other domains. Of course, some studies already considered this relationship (ElMaraghy et al., 2012; 2013; Fujimoto et al., 2003). However, those studies did not consider the relationship with a structured tool. In this paper, the OA organized the status of the complexity sources. Furthermore, the result emphasizes that the complexity management needs to be design-centered because the complexity sources are linked with each other and all sources are derived...
from the product variety in the design phase. Therefore, the OA will help to manage the operations complexity generally with a structured tool, even this paper do not specify the mechanism of the relationships.

4 COMPLEXITY MANAGEMENT FRAME BY THE OA

As discussed in the previous sections, the OA gives a new viewpoint to the manufacturing firms for managing complexity. The architectural viewpoint focuses on the relationship between the design and operations phases since the complexity in operations is mainly caused by product variety from the product design. This section describes applicability of the OA for complexity management. Figure 3 shows complexity management frame by OA: 1) Analyzing propagation of design elements to operations, 2) Measuring the complexity in operations and 3) Controlling the complexity by the measure. Next subsections explains the three management issues by each.

4.1 Analyzing propagation of design elements to operations

The OA defines the relationships between design elements and operations elements. Thus, the OA has an ability to show how the inputs from the PA are propagated to operational and configurational elements. Figure 4 shows that the impact of decisions on design change is described through the OA. In the figure, for example, when engineers implement commonization of components and standardization of interfaces between each component, the OA represents that the design strategies reduce the number of different kinds of tasks in assembly systems. Then, the manufacturers could catch the impact of the strategies by checking the OA and using complexity measures. The specific mechanism of the relationships is explained in the previous research (Oh et al., 2015). Thus, when the manufacturing firms would like to see changes in operations by design changes, the OA is a useful tool for showing decision impacts from the design phase.

4.2 Measuring the complexity in operations

In industry, complexity measures can be used as supportive indices to manage inefficiencies in operations. Examples of inefficiencies are longer lead time, less quality and higher cost. Thus, subjects of complexity measures should be highly related with the inefficiencies which the manufacturing firms are ultimately interested in. The OA represents subject candidates of the measures by which the firms estimate the operations complexity. For example, Oh et al. (2015) considered different tasks done in an assembly line as the object of a measure called task difference complexity (TDC). TDC measures heterogeneity of tasks in an assembly system using dissimilarity function. As Figure 4 shows, TDC can help to compare different strategies from the design phase by suggesting quantitative values.

4.3 Controlling the complexity by the measure

The manufacturing firms use key performance indices (KPIs) to evaluate operations cost, product quality and lead time of all operations areas. Although KPIs are insightful to identify the current status of operations, it is limited to control the operations in that KPIs show only the result of the state. On the
other hand, complexity measures derived from the OA shows the reasons that the current status of operations are complex and inefficient by identifying main cause of the complexity. As Figure 4 shows, the complexity measures can reflect design-centered management strategies by showing change in operations. Furthermore, the complexity measure can compare the inefficiencies of manufacturing systems, assembly lines and supply chains. Therefore, the measures from the OA offer better controllability of complexity than KPIs generally in both design and operations phases.

![Figure 4. Propagation of design change to operations architecture](image)

### 5 CONCLUSION

This paper first introduces the OA which is a new concept for structuring the relationships of complexity sources in the design and operations phases to show the mechanism of variety propagation. Then, complexity sources considered at the previous studies are classified by the four domains in the PA and OA. Finally, complexity management frame is shown through the OA and three management issues are introduced. The OA is meaningful for complexity management in that it gives a new viewpoint for both academia and industry. Complexity measures based on the OA enables to control inefficiencies in the operations phase by showing impacts of design changes from the design phase on the operations phase. Furthermore, the OA can capture the main complexity sources and evaluate different kinds of complexity mitigation strategies. The OA has more applicable areas for complexity management.

Specific description of the OA and case study are omitted in the paper, since this paper concentrates on the introduction of the OA concept and classification of complexity sources based on the OA. In the previous study, the authors developed the OA in assembly systems and a complexity measure calculating task differences (Oh et al., 2015). The authors are now studying to develop complexity measures in assembly systems and supply chains and to construct the OA of supply chains. For future studies, both marketplace and operations will be considered together because revenue from marketplace and complexity cost from operations cannot be separated to gain profits for the manufacturing firms. Then, management of overall product life cycle including design, production, procurement and after service will be achieved through the unified frame based on the OA.

### REFERENCES


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