21ST INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

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

Oh, Kwansuk; Kim, Daeyoung; Hong, Yoo S.
Seoul National University, Republic of Korea (South Korea)

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, Opertaions architecture

Contact:
Kwansuk Oh
Seoul National University
Industrial Engineering
Republic of Korea (South Korea)
oh0421@snu.ac.kr

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 2: Design Processes | Design Organisation and Management, Vancouver, Canada, 21.-25.08.2017.

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.

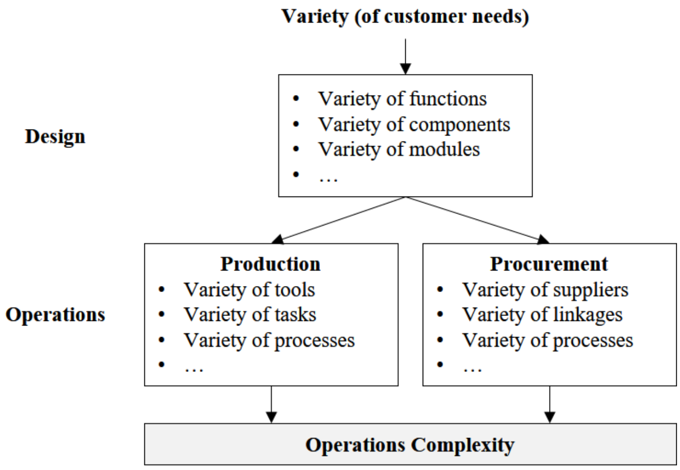

Figure 1. Mechanism of variety propagation

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.

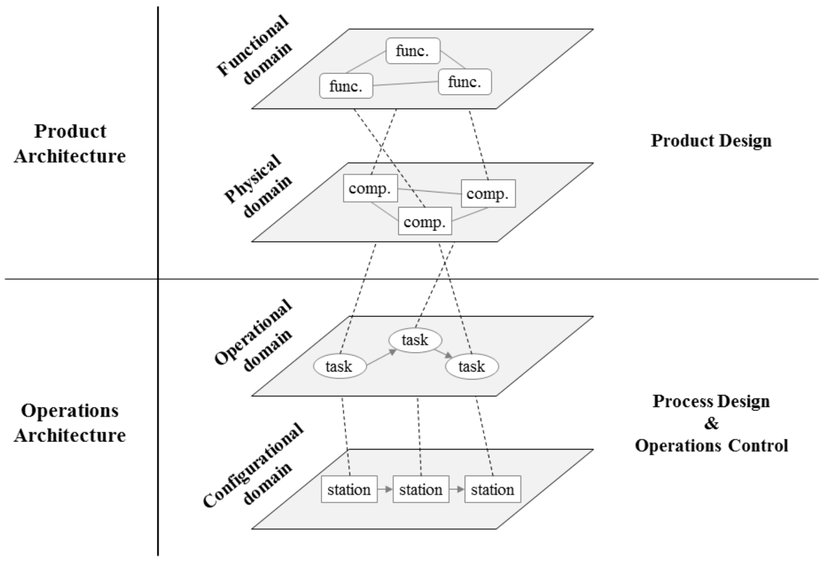

Figure 2. Product & operations architecture

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.

Table 1. Summary of complexity sources

Operations	Literatures	Complexity sources	PA		OA	
			Func.	Phys.	Oper.	Conf.
Manufacturing	MacDuffie et al. (1996), Schleich et al. (2007)	Model mix, Part variants		●	●	
	Martin and Ishii (1997)	Degree of commonality and differentiation, Setup		●	●	
	Fujimoto et al. (2003)	Functions, Key characteristics (No. of parts, sequence), Features, Task details (positioning, gripping, conveying)	●		●	●
	Deshmukh et al. (1998)	Part similarity, System size, Product design changes		●		●
	Frizelle and Woodcock (1995)	States of manufacturing process			●	●
	Hu et al. (2008), Zhu et al. (2008)	Part, fixture, tool and procedure choice activities			●	●
	ElMaraghy and Urbanic (2003, 2004), ElMaraghy et al. (2005), Kuzgunkaya and ElMaraghy (2006)	No. of features and tasks, No. of types of tasks, machines, buffers and material handling systems			●	●
	Papakostas et al. (2009), Efthymiou et al. (2014)	Time variability, Unpredictability, Configuration			●	●
	Mattsson et al. (2011, 2012, 2013, 2016), Fast-Berglund et al. (2013),	Product variants, Work content, Layout & tools, Support tools & work instructions, Variability			●	●
	Jenab and Liu (2010)	Dissimilarity of products in manufacturing process (process time, required skills)			●	●
	Zeah et al. (2009)	Process time, Task similarity, Worker cognition			●	
	Vrabic and Butala (2012)	Unpredictable patterns of manufacturing process			●	
	Sarkis (1997)	No. of robots and machine tools				●
	Samy and ElMaraghy (2010, 2012), Samy et al. (2015)	Part attributes in manufacturing processes, System functions (feeding, handling, joining, transportation)				●
	Zeltzer et al. (2013)	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, No. of assembly directions				●
Supply chain	Gerschberger et al. (2012)	No. of elements and interrelations, Degree of uncertainty, Influence of supplier on customer-requested product variety, Geographical components	●	●	●	●
	Hashemi et al. (2013)	Product structure, Modularity, Product innovativeness, Demand volatility, Product life cycle, Supply chain configuration, Supply chain coordination and collaboration	●	●	●	●
	Milgate (2001)	Uncertainty, Technological intricacy, Organizational systems		●	●	●
	Zhou (2002)	No. of products, processes and markets, Inventory locations and sizes, Organization, Failures		●	●	●
	Vachon and Klassen (2002)	No. of tasks, processes, parts and echelons, Level of interations, Extent of supply network, Process capability, Setup, Scheduling changes, Late delivery, Demand volatility		●	●	●
	Perona and Miragliotta (2004)	Level of standardization, No. of finished and intermediate products, No. of suppliers and customers, Average order size		●	●	●
	Blecker et al. (2005)	Product/technology intricacy, Organization, Uncertainty		●	●	●
	Hu et al. (2008), Wang et al. (2010), Hamta et al. (2015)	Variants, Mix ratios		●	●	●
	Bozarth et al. (2009)	No. of customers, products, parts and suppliers, Heterogeneity of customers, Shorter product life cycles Batch production ratio, Schedule instability, Unreliable lead times, Glorbalization		●	●	●
	Serdarasan (2013)	No. of products, processes, suppliers, customers and process interactions, Uncertainty, Changes, Organization, Decision making process, IT systems		●	●	●
	Turner and Wiliams (2005)	No. of of stocking loacations, No. of of dealers in each major market		●		●
	Wilding (1998), Aelker et al. (2013)	Amplification, Deterministic Chaos, Parallel Interactions			●	●
	Arteta and Giachetti (2004)	Changes and state transitions			●	●
	Kaluza et al. (2006)	No. of elements and relations, No. of similar types			●	●
	Wu et al. (2007, 2013)	States of the system, Deviation from the schedule			●	●

Operations	Literatures	Complexity sources	PA		OA	
			Func.	Phys.	Oper.	Conf.
Supply chain	Battini et al. (2007), Allesina et al. (2010)	Degree of linkages			●	●
	Manuj and Sahin (2011)	Supply chain structure, Activities, Transactions, Processes, Difficulty of decision making			●	●
	de Leeuw et al. (2013)	Uncertainty, Diversity, Size, Variability, Structure, Speed, Lack of information synchronization, Lack of cooperation			●	●
	Cheng et al. (2014)	Structure of supply chain networks, System size, Degree of order (linkage), Categories of elements			●	●
	Brandon-Jones et al. (2015)	No. of suppliers, Level of differentiation, Delivery reliability Lead time, Geographic dispersion of suppliers			●	●
	Sivadasan et al. (2002, 2010), Isik (2010)	Order forecast, Delivery order, Actual production schedule			●	
	Choi and Krause (2006)	No. of suppliers, Degree of differentiation, Level of inter-relationships among the suppliers				●
	Modrak and Semanco (2011, 2012), Modrak and Marton (2012, 2014), Kito and Ueda (2014), Yang and Yang (2010), Meepetchdee and shah (2007), Caridi et al. (2010), Bezuidenhout et al. (2012)	No. of suppliers and links, Level of tier				●

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.

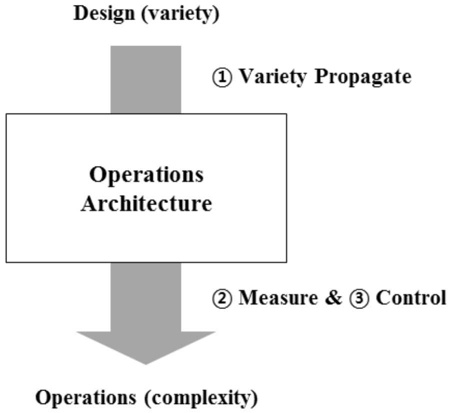

Figure 3. Complexity management frame

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.

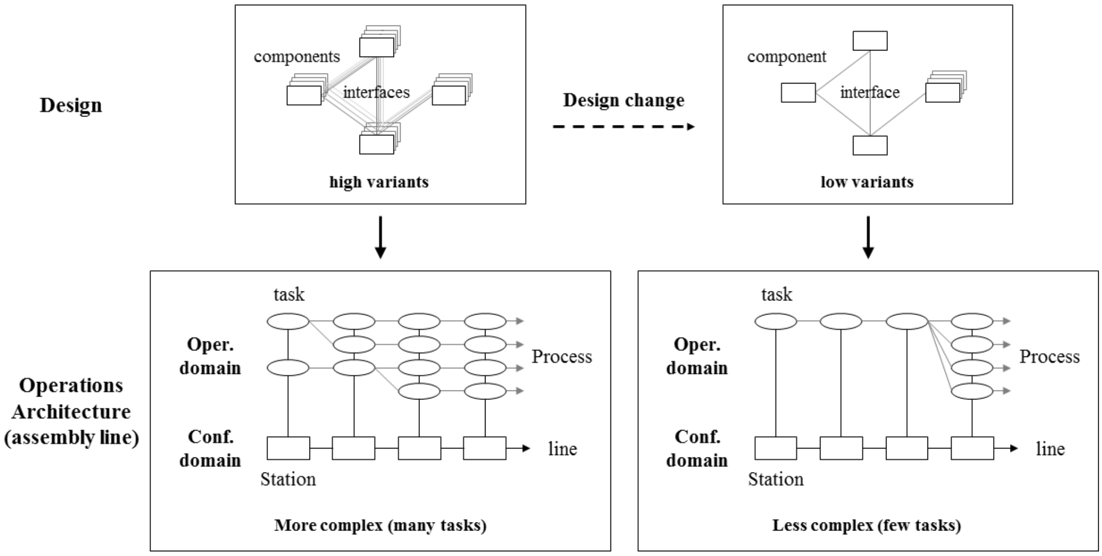

Figure 4. Propagation of design change to operations architecture

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

Bezuidenhout, C.N., Bodhanya, S., Sanjika, T., Sibomana, M. and Boote, G.L.N. (2012), “Network-analysis approaches to deal with causal complexity in a supply network”, *International Journal of Production Research*, Vol. 50 No. 7, pp. 1840-1849.

Caridi, M., Crippa, L., Perego, A., Sianesi, A. and Tumino, A. (2010), “Do virtuality and complexity affect supply chain visibility?”, *International Journal of Production Economics*, Vol. 127 No. 2, pp. 372-383.

ElMaraghy, W.H. and Urbanic, R.J. (2003), “Modelling of manufacturing systems complexity”, *CIRP Annals-Manufacturing Technology*, Vol. 52 No. 1, pp. 363-366.

ElMaraghy, W.H. and Urbanic, R.J. (2004), “Assessment of manufacturing operational complexity”, *CIRP Annals-Manufacturing Technology*, Vol. 53 No. 1, pp. 401-406.

ElMaraghy, H.A., Kuzgunkaya, O. and Urbanic, R.J. (2005), “Manufacturing systems configuration complexity”, *CIRP Annals-Manufacturing Technology*, Vol. 54 No. 1, pp. 445-450.
ElMaraghy, W.H., ElMaraghy, H.A., Tomiyama, T. and Monostori, L. (2012), “Complexity in engineering design and manufacturing”, *CIRP Annals-Manufacturing Technology*, Vol. 61 No. 2, pp. 793-814.
ElMaraghy, H.A., Schuh, G., ElMaraghy, W.H., Piller, F., Schönsleben, P., Tseng, M. and Bernard, A. (2013), “Product variety management”, *CIRP Annals-Manufacturing Technology*, Vol. 62 No. 2, pp. 629-652.
Erixon, G. (1998). *Modular function deployment: A method for product modularisation*, Royal Inst. of Technology.
Fast-Berglund, Å., Fässberg, T., Hellman, F., Davidsson, A. and Stahre, J. (2013), “Relations between complexity, quality and cognitive automation in mixed-model assembly”, *Journal of Manufacturing Systems*, Vol. 32 No. 3, pp. 449-455.
Frizelle, G. and Woodcock, E. (1995), “Measuring complexity as an aid to developing operational strategy”, *International Journal of Operations & Production Management*, Vol. 15 No. 5, pp. 26-39.
Fujimoto, H., Ahmed, A., Iida, Y. and Hanai, M. (2003), “Assembly process design for managing manufacturing complexities because of product varieties”, *International Journal of Flexible Manufacturing Systems*, Vol. 15 No. 4, pp. 283-307.
Gerschberger, M., Engelhardt-Nowitzki, C., Kummer, S. and Staberhofer, F. (2012), “A model to determine complexity in supply networks”, *Journal of Manufacturing Technology Management*, Vol. 23 No. 8, pp. 1015-1037.
Hashemi, A., Butcher, T. and Chhetri, P. (2013), “A modeling framework for the analysis of supply chain complexity using product design and demand characteristics”, Internati*onal Journal of Engineering, Science and Technology*, Vol. 5 No. 2, pp. 150-164.
Hu, S.J., Zhu, X.W., Wang, H. and Koren, Y. (2008), “Product variety and manufacturing complexity in assembly systems and supply chains”, *CIRP Annals-Manufacturing Technology*, Vol. 57 No. 1, pp. 45-48.
Hu, S.J., Ko, J., Weyand, L., ElMaraghy, H.A., Lien, T.K., Koren, Y., Bley, H., Chryssolouris, G., Nasr, N. and Shpitalni, M. (2011), “Assembly system design and operations for product variety”, *CIRP Annals-Manufacturing Technology*, Vol. 60 No. 2, pp. 715-733.
Isik, F. (2010), “An entropy-based approach for measuring complexity in supply chains”, *International Journal of Production Research*, Vol. 48 No. 12, pp. 3681-3696.
Kito, T. and Ueda, K. (2014), “The implications of automobile parts supply network structures: A complex network approach”, *CIRP Annals-Manufacturing Technology*, Vol. 63 No. 1, pp. 393-396.
Kumar, A. (2007). “From mass customization to mass personalization: A strategic transformation”, *International Journal of Flexible Manufacturing Systems*, Vol. 19 No. 4, pp. 533-547.
Kuzgunkaya, O. and ElMaraghy, H.A. (2006), “Assessing the structural complexity of manufacturing systems configurations”, *International Journal of Flexible Manufacturing Systems*, Vol. 18 No. 2, pp. 145-171.
MacDuffie, J.P., Sethuraman, K. and Fisher, M.L. (1996), "Product variety and manufacturing performance: Evidence from the international automotive assembly plant study", *Management Science*, Vol. 42 No. 3, pp. 225-239.
Marti, M. (2007). *Complexity management: Optimizing product architecture of industrial products*, Springer Science & Business Media.
Mattsson, S., Gullander, P. and Davidsson, A. (2011), “Method for measuring production complexity”, *28th International Manufacturing Conference*.
Mattsson, S., Gullander, P., Harlin, U., Bäckstrand, G., Fasth, Å. and Davidsson, A. (2012), “Testing Complexity Index–a Method for Measuring Perceived Production Complexity”, *Procedia CIRP*, Vol. 3, pp. 394-399.
Mattsson, S., Fasth, Å., Stahre, J., Karlsson, M., Dencker, K., Gullander, P. and Davidsson, A. (2013), “Validation of the complexity index method at three manufacturing companies”, *2013 IEEE International Symposium on Assembly and Manufacturing (ISAM)*, IEEE, pp. 55-57.
Mattsson, S., Tarrar, M. and Fast-Berglund, Å. (2016), “Perceived production complexity–understanding more than parts of a system”, *International Journal of Production Research*, Vol. 54 No. 20, pp. 6008-6016.
Meepetchdee, Y. and Shah, N. (2007), “Logistical network design with robustness and complexity considerations”, *International Journal of Physical Distribution & Logistics Management*, Vol. 37 No. 3, pp. 201-222.
Modrak, V. and Semanco, P. (2011), “Complexity assessment of supply chains structure: A comparative study”, *Research Journal of Applied Sciences*, Vol. 6 No. 7-12, pp. 410-415.
Modrak, V. and Semanco, P. (2012), “Structural complexity assessment: A design and management tool for supply chain optimization”, *Procedia CIRP*, Vol. 3, pp. 227-232.
Modrak, V. and Marton, D. (2012), “Modelling and complexity assessment of assembly supply chain systems”, *Procedia Engineering*, Vol. 48, pp. 428-435.
Modrak, V. and Marton, D. (2014), “Configuration complexity assessment of convergent supply chain systems”, *International Journal of General Systems*, Vol. 43 No. 5, pp. 508-520.

Oh, K., Kim, D. and Hong, Y.S. (2015). "Measurement of assembly system complexity based on the task differences induced from product variety", *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Boston, American Society of Mechanical Engineers, pp. V02BT03A040-V02BT03A040.
Pine, B.J. (1993), *Mass customization: The new frontier in business competition*, Harvard Business Press, Boston.
Shannon, C.E. (1948). "A mathematical theory of communication", *Bell System Technology Journal*, Vol. 27, pp. 379-423; 623-656.
Sivadasan, S., Efstathiou, J., Frizelle, G., Shirazi, R. and Calinescu, A. (2002), "An information-theoretic methodology for measuring the operational complexity of supplier-customer systems", *International Journal of Operations & Production Management*, Vol. 22 No. 1, pp. 80-102.
Suh, N.P. (2001), *Axiomatic design: Advances and applications*, The Oxford Series on Advanced Manufacturing.
Ulrich, K. (1995), "The role of product architecture in the manufacturing firm", *Research policy*, Vol. 24 No. 3, pp. 419-440.
Wang, H., Ko, J., Zhu, X. and Hu, S.J. (2010), "A complexity model for assembly supply chains and its application to configuration design", *Journal of Manufacturing Science and Engineering*, Vol. 132 No. 2, p. 021005.
Wu, Y., Frizelle, G. and Efstathiou, J. (2007), "A study on the cost of operational complexity in customer–supplier systems", *International Journal of Production Economics*, Vol. 106 No. 1, pp. 217-229.
Wu, Y.R., Huatuco, L.H., Frizelle, G. and Smart, J. (2013), "A method for analysing operational complexity in supply chains", *Journal of the Operational Research Society*, Vol. 64 No. 5, pp. 654-667.
Yang, B. and Yang, Y. (2010), "Postponement in supply chain risk management: A complexity perspective", *International Journal of Production Research*, Vol. 48 No. 7, pp. 1901-1912.
Zeltzer, L., Limère, V., Van Landeghem, H., Aghezzaf, E.H. and Stahre, J. (2013), "Measuring complexity in mixed-model assembly workstations", *International Journal of Production Research*, Vol. 51 No. 15, pp. 4630-4643.
Zhu, X., Hu, S.J., Koren, Y. and Marin, S.P. (2008), "Modeling of manufacturing complexity in mixed-model assembly lines", *Journal of Manufacturing Science and Engineering*, Vol. 130 No. 5, p. 051013.

ACKNOWLEDGMENTS

This work was supported by the BK21 Plus Program (Center for Sustainable and Innovative Industrial Systems, Dept. of Industrial Engineering, Seoul National University) funded by the Ministry of Education, Korea (No. 21A20130012638).