공학석사 학위논문

Impact of technology infusion on system attributes, focusing on system complexity and modularity

시스템 복잡도와 모듈화에 기반한

기술 주입 효과 분석

2014 년 8 월

서울대학교 대학원

산업공학과

민광기

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이 논문을 공학석사 학위논문으로 제출함
2014 년 8 월

서울대학교 대학원
산업공학과
민광기

민광기의 공학석사 학위논문을 인준함
2014 년 8 월

위 원 장 ___홍 유 석___ (인)

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Abstract

Impact of technology infusion on system attributes, focusing on system complexity and modularity

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For many complex systems with long lifecycles, it is of great importance to keep their performance up-to-date, as system requirements change over time. This is often accomplished by infusing new technologies into host systems, as technology infusion can improve overall system performance. However, the infusion of technologies often results in disturbance of the host system in the form of system redesign, changing inherent attributes of the system. In this paper, a process-based framework to measure the impact of technology on system attributes, specifically complexity and modularity, is introduced. The proposed framework is demonstrated through two kinds of real systems and the evaluation process of several technology concepts, where new technology is infused into systems of various complexity and modularity.

Keywords : technology infusion, system complexity, system modularity

Student number : 2012-23308

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Chapter 1. Introduction

Complex systems often have long lifecycles. Throughout their lifetime, each system must meet various performance requirements, which may change with time and customer's preferences. For example, the B-52 Stratofortress strategic bomber was commissioned in the 1950s, and is expected to be in service until the 2040s. According to Boeing, it has had the longest service period in U.S. military history. Throughout its operation history, many upgrades have been made to the aircraft, where new technologies have been implemented in the aircraft to enhance its performance.

When new technologies are infused into a host system, the host system is typically redesigned to accommodate the infused technologies, sometimes at a major scale. This redesign of the host system to accommodate the infused technologies can change inherent system attributes, in particular the system complexity and modularity.

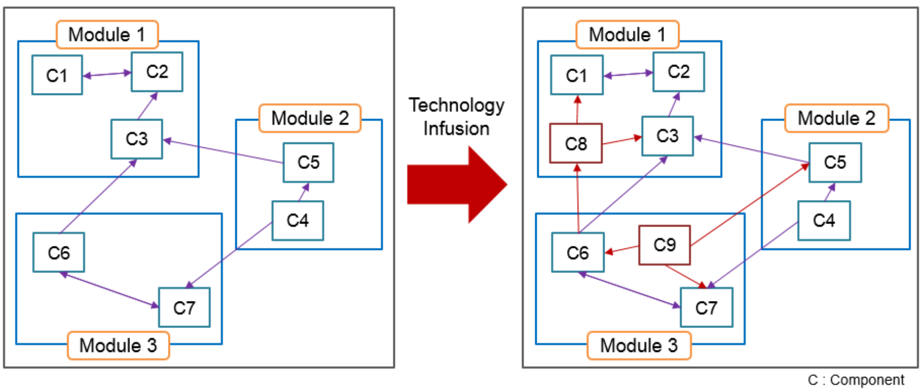


Figure 1. Example of technology infusion to the existing system

Figure 1 shows an example of technology infusion to the existing system. Before a new technology was infused, the existing system consisted of 3 modules. Each of modules had 2 or 3 components. After the technology infusion, components 8 and 9 were added. Also, new connections between the existing components and new ones were made for connecting the related components. As an example of technology infusion to the existing system, systems are influenced by the infusion of new technologies. This impact causes the entire system to reconfigure, and various changes happen such as system attributes and properties.

This leads to some interesting research questions. How can these system attributes be measured in a quantitative way? How does the infusion of new technologies affect system attributes? How can this information be used to improve the design and redesign process of a complex system?

In this paper, we propose a process to quantitatively assess attribute changes in a complex system, when the system is subject to new technology infusions. The new process involves abstraction of the complex system into a matrix model, and measuring specific system attributes with metrics created for that purpose. Measurements are made to the system before, and after, the technology infusion, for comparative analysis. In this paper, two specific system attributes, of complexity and modularity, are measured. Three kinds of systems are presented, to demonstrate the proposed process.

Chapter 2. Literature Review

2.1. Technology Infusion

In academia, many researchers have explored frameworks for technology infusion in complex systems. Smaling and de Weck (2007) proposed a strategic framework for evaluating the risks and opportunities, when various technologies were infused in the current system. Using a component-based Design Structure Matrix (DSM) and Fuzzy Pareto Frontier concept, they suggested a process for finding optimal solutions, considering various risks and opportunities. Many companies can make decisions on technology portfolios from a strategic framework, to increase their benefits. Suh *et al*. (2010) took a new viewpoint on the framework of Smaling and de Weck (2007), and expanded its potential utilization. In the expanded research, the Net Present Value (NPV) concept was substituted for the utility function. Kirby and Mavris (2001) focused on the technology selection, with efficient allocation of restricted resources. Through Technology Identification, Evaluation and Selection (TIES) processes, a specific technology is determined. After that, the estimation and forecasting of technology impact are also performed.

2.2. Change Propagation

The infusion of new technologies often causes the host system to be changed, and results in redesign and modification of the existing system. Clarkson *et al.* (2004) proposed the change propagation concept for predicting the impact of changes in complex systems. During redesign of the current system, a change of a specific part results in many changes to other parts. They focused on the change propagation paths, and calculated the risk of change propagation and impact on the system. Companies can prepare for uncertain situations they may encounter in the future, through predicting the impact of change propagation. Many researchers (Eckert *et al.*, 2006; Giffin *et al.*, 2009; Hassan and Holt, 2004) proposed various change propagation concepts for various factors (e.g. requirements, functions and components).

2.3. Design Structure Matrix (DSM)

A component-based DSM concept is widely utilized for system decomposition and modeling. DSM is a modeling tool for decomposing systems into various elements connected in their networks (Ulrich and Eppinger, 1995). DSM is composed of N elements (e.g. components, functions or teams) that are expressed as an N by N matrix. The structural arrangement of elements and their interactions provides a compact representation format. Due to its formal features, DSM has ease of mathematical calculation, and provides a system-level view that can be utilized in a global decision making process (Eppinger and Browning, 2012). The component-based DSM has four domains: spatial, energy flow, mass flow, and information flow (Browning, 2001). Interfaces between elements can be expressed as binary numbers one and zero. If an element has a relationship, it is set to one; if not, zero. In many studies (Browning, 2002; Chiriac *et al*., 2011; Guenov and Barker, 2005; Sharon *et al*., 2013), the DSM concept is widely used for analyzing and organizing a complex system.

2.4. System Complexity

Complexity is a common research topic in many fields, including anthropology, computer science, economics, neuroscience, and physics. Baldwin and Clark (2000) defined the term "complex" as 'two or more separated parts that are chained together'. Each part can be various objects (e.g., components, processes, or organizations). From the viewpoint of a product system, Lindermann *et al*. (2009) defined the same word as 'a system that is composed of different parts or projects, which is characterized by its own dependencies'. According to the degree of dependencies, systems are influenced by the infusion of new technologies. This impact causes the entire system to reconfigure, and various changes happen. Lindermann *et al*. (2009) explored structural complexity management, focusing on the linkages between objects in the product design process. In this paper, we choose the structural complexity concept as a system complexity.

Past work in these areas has focused on the system complexity concept for analyzing the overall effect of technology infusion on an existing system. Some authors have focused on the information entropy theory. Suh (1998) introduced the concept of Axiomatic theory. When designing a system, entropy is defined as a relation between the amount of required information, and functions that should be satisfied in the system. Braha and Maimon (1998) also proposed a complexity concept, which has a connection with the information entropy concept. In the product design process, they defined the amount of information and achievability function to fulfill this information. Crespo-Varela (2011) suggested an efficient process connecting components and functions of products. In addition to the information entropy theory, there are other works that have applied functions and structure-based concepts. Bashir and Thomson (1999) focused on the functionalities of product systems, and proposed function-trees. Ameri *et al*. (2008) studied the relationship between components and functions of products. Sinha and de Weck (2013) suggested a system complexity index that was based on graph energy theory.

Elmaraghy *et al*. (2012) proposed, when dealing with product complexity, a modular architecture that can deal with various constituents (e.g. complexity, cost, design quality management and variety). If the degree of system complexity can be efficiently managed, companies could save their product development time and costs. In system architecture, Ulrich and Eppinger (1995) defined modular architecture as ‘a specific system that has one-to-one mapping connections between functional elements and physical components, and between interfaces connecting components within the system’. McClelland *et al.* (1986) viewed the system from a structural perspective, and they defined a module as ‘certain components strongly connected within modules if they have a high correlation, while between connections have weak relationship between components in the system’. Focusing on the last concept for modularity, the degree of modularity is calculated for technology infusion in the current system.

2.5. System Modularity

Numerous studies have attempted to achieve a modular architecture, and analyze the degree of system modularity. According to Suh and Kott (2010), if system architecture is modular, then the system can be decomposed into sub-system parts, and each part can be independently managed. In a modular system, design changes can be applied more easily, than in integral systems. Moreover, Simpson (2004) applied the modular architecture concept to the product family, and designed platform-based systems. Also, many researchers proposed various system modularity indexes and optimization algorithms. Guo and Gershenson (2004) proposed a modularity index by dividing connections into within module connections, and between module connections. Similarly, other researchers suggested various indices, and conducted many studies (Allen and Carlson-Skalak, 1998; Newcomb *et al.*, 1998; Sharman and Yassine, 2004). Some authors suggested other approaches to system modularity. Hölttä-Otto and de Weck (2007) proposed the Singular Value Modularity Index (SMI) and the Non-Zero Fraction (NZF) that analyze the internal couplings that exist in the modules, and the scarcity of interrelationship between components. Also, there is literature on analyzing the relationship between the functions and structure of components in a system. Applying the Quality Function Deployment (QFD) concept (Hauser and Clausing, 1988), Ericsson and Erixon (1999) explored a modularity analysis algorithm, through the Modular Function Deployment (MFD) concept. Similar works for analyzing the modules of systems have been studied by many others (Dahmus *et al.*, 2001; Holmqvist and Persson, 2003; Stone *et al.*, 2000).

2.6. Management of System Complexity and Modularity

Several authors (Lindermann et al., 2009; Sharman and Yassine, 2004) proposed various strategies for managing system complexity. An effective way for managing system complexity is avoidance or reduction of it. Generally, the system complexity of each system can be reduced, if some elements or relations can be eliminated while maintaining the system functions. Furthermore, it is possible to reduce the system complexity in one domain by increasing it in another domain. Modular designs, platforms, or standardized interfaces also can be used for reducing system complexity.

Baldwin and Clark (2000) proposed 6 module operators and analyzed the sources of their economic values for improving system modularity. These are: 1) splitting: split any module, 2) substituting: substitute a newer module design for an older one, 3) excluding: exclude a module, 4) augmenting: augment the system by adding a module that didn't exist before, 5) inverting:

collect common components across existing modules and reconfigure them as a new module, and 6) porting: create a 'port' for specific modules and it synthetically works in systems.

2.7. Research Gap Analysis

According to the literature review, it is obvious that most researches have focused on the classification and metric development of system attributes. The past literature has not considered the system attributes of complexity and modularity together, and each system attribute concept has been analyzed independently, in various studies. Also, even less work has been done on analyzing system attributes in technology infusion.

This paper utilizes previously developed complexity and modularity metrics for measuring system attributes. Then, when the existing system is changed, the impact of new technology infusion into the existing system will be analyzed. For this study, three different systems (i.e. two kinds of real systems and one system design concept) are analyzed. The rest of this paper is arranged as follows. Section 3 introduces the methodology to analyze the system attributes, and impact of technology infusion on real systems. Section 4 presents the application of research framework on system design. Finally, Section 5 is the conclusion, which provides a brief summary, and suggests future research topics.

Chapter 3. Research Framework

The overall framework for this study consists of two phases: system modeling and analysis. Figure 2 shows the system attributes analysis process, when technologies are infused. First, specific systems will be selected for analysis of their attributes. After that, a set of technologies or features is defined in each system. Systems can be modeled as a component-based DSM, in which spatial, mass flow, energy flow, and information flow can be expressed. Based on the modeled DSMs, system attributes can be calculated, through various system metric indices. In this paper, system attributes will be measured, in particular, the system complexity and modularity. Finally, comparative analysis of each pair of technologies or features will be conducted. Through comparative analysis of each attribute, the impact of technology infusion on existing system can be analyzed.

Three kinds of technology infusion cases were selected for this study. First, through the in-depth teardown of a simple system, many changes can occur in a product family. To demonstrate the overall framework, a computer mouse product family is analyzed. Second, we focus on a more complex system (i.e. a printing system) will be analyzed. In the printing systems, the system complexity and modularity of the two systems, i.e. before and after technology infusion, are compared. Finally, the research framework will be applied in hydrogen-enhanced combustion engine concepts for selecting better system design alternatives. Through analysis of several technology concepts, many changes are considered for the improvement of the existing system. In this section, system attributes analysis of a simple system will be introduced. The application of research framework on system design will be introduced in section 4.

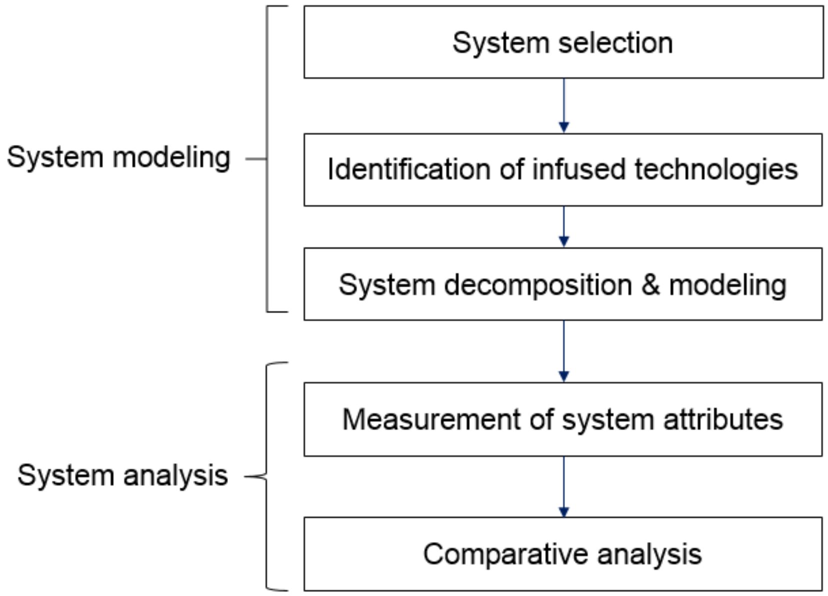


Figure 2. Framework for analyzing the impact of technology infusion on system attributes

3.1. System Modeling

In the system selection process, products or a product family should satisfy certain conditions. Products should have specific technologies or features that are able to be clearly identified from each other. Also, if many pairs can be made for comparative analysis in a product family, it is much better to compare between technologies or features. A computer mouse product family was selected, due to the relative simplicity of the products, and the ease of identifying technologies infused into high-end computer mouse products. Nine mouse variants from the Logitech mouse family were chosen for analysis.

A set of technologies or features is defined in the product family, which enables the product to offer desired functions. This set is what customers expect, when they purchase products. These can be replaced by technology concepts to compare each product, when it is difficult to define them. For the mouse family, four features can be listed, as follows: number of buttons, wired/wireless connectivity, connection type, and sensing type.

The first feature is the number of buttons on the mouse. In the early phase, many mouse variants have two buttons. Three button mouse variants are offered at the intermediate price range. Also, some variants have a wheel button as a third button. As customers expect many functions in high-end variants, the number of buttons is increased, some with as many as seven. The second feature is the existence of a wired connection. When wireless technology was far from universal, each mouse was connected by wire to the main computer. However, with the rise of wireless technology, companies now offer both wired and wireless version of the mouse. From common to high-end variants, different technologies are utilized for satisfying customers. The third feature is the mouse connection interface. The connection interface is divided into three types. PS/2 is the first type used for mouse connection. In majority of mouse products, the USB connection type is used. In high-end mouse products, the Bluetooth connection type is used. Finally, the sensing technology is divided into three types. The Ball type was the first, and was followed by the Light Emitting Diode (LED) type, and then the Laser type. The Laser type is a more developed version of the LED type. Figure 3 shows a list of the nine mouse variants used for the analysis, with defined technologies for their key features discussed in this section.

Specification	S-34
Number of Buttons	2
Existence of Wire	Wired
Connection Type	PS/2
Sensing Type	Ball

Specification	S-48a
Number of Buttons	3
Existence of Wire	Wired
Connection Type	PS/2
Sensing Type	Ball

Specification	Mombasa
Number of Buttons	5
Existence of Wire	Wired
Connection Type	PS/2
Sensing Type	LED

Specification	M90
Number of Buttons	3
Existence of Wire	Wired
Connection Type	USB
Sensing Type	LED

Specification	M100
Number of Buttons	5
Existence of Wire	Wired
Connection Type	USB
Sensing Type	LED

Specification	M185
Number of Buttons	3
Existence of Wire	Wireless
Connection Type	USB
Sensing Type	LED

Specification	M325
Number of Buttons	5
Existence of Wire	Wireless
Connection Type	USB
Sensing Type	LED

Specification	M555b
Number of Buttons	5
Existence of Wire	Wireless
Connection Type	Bluetooth
Sensing Type	Laser

Specification	M905
Number of Buttons	7
Existence of Wire	Wireless
Connection Type	USB
Sensing Type	LED

Figure 3. Specification of computer mouse variants

A spatial domain was adopted in the system decomposition process of mouse variants. In the modeling process of the DSMs of the computer mouse product family, the commonly used components were assigned higher component-numbers. Figure 4 shows a decomposition result of the computer mouse and its modeling process in DSM. Table 1 shows the number of components and spatial connections of mouse variants.

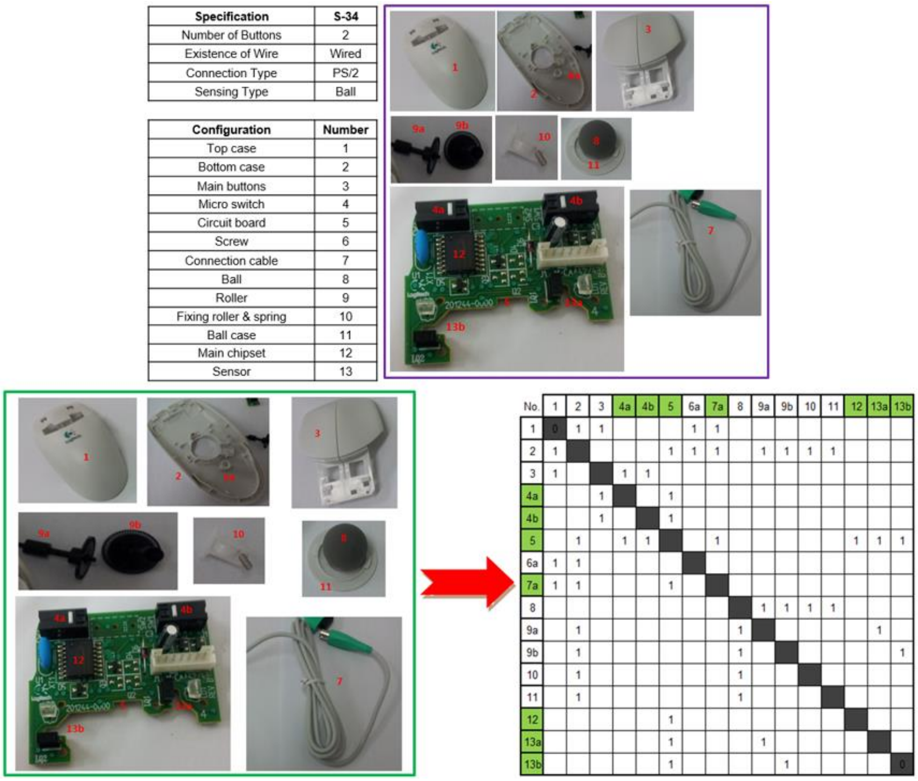


Figure 4. Example of decomposition and modeling process of computer mouse to DSM (Sample: S-34)

Table 1. Decomposition information of computer mouse variants

No.	Model	Number of Components	Number of Connections
1	S-34	16	50
2	S-48a	20	64
3	Mombasa	18	58
4	M90	15	46
5	M100	17	54
6	M185	19	62
7	M325	24	76
8	M555b	46	182
9	M905	75	298

3.2. System Analysis

There are many kinds of system attributes. In this paper, the system complexity and modularity were selected to analyze the system attributes.

In order to select the complexity index for analysis, we reviewed the literature for various complexity indices. As mentioned above, many researchers proposed various measures for quantitatively analyzing the system complexity (Braha and Maimon, 1998; Crespo-Varela, 2011; Suh, 1998). Some authors focused on the relationship between functions, and components of products. They suggested that complexity could be measured by the uncertainties of achieving each function. Also, they suggested that the complexity could be diminished, by minimizing the degree of dependencies, and making independent relations between components and functions. Moreover, other studies focused on the complexity in the manufacturing processes (Deshmukh *et al.*, 1998; Elmaraghy *et al*., 2005; Fujimoto *et al*., 2003). Various methods have been proposed to quantify the manufacturing complexity. Poli (2001) developed Design for Manufacturing (DFM) methods, to reduce manufacturing complexity. Hu *et al*. (2008) proposed a unified measure and models of complexity in assembly systems. They also described the complexity propagation from assembly systems to supply chains. Previous research has focused on various areas of the complex system, from product development to supply chain. Many authors apply entropy functions to quantify the complexity. Each function is defined as a probability of uncertainty. The analysis results depend on how researchers estimate the systems.

Based on our review on complexity indices, we focus on the product complexity itself. We selected the graph energy index that was created by Sinha and de Weck (2013). In the graph energy index, product attributes are only considered in the complexity estimation process. In the early stages of the product development process, it is useful for designers to focus on the components and their connections of the product. This index was applied to component-based DSMs made for our research. According to Sinha and de Weck (2013), when a system is decomposed, it can be divided into three categories. The first one is the properties of the components themselves. The second one is the interfaces between components, and the last one is the architecture of the products (Lindermann *et al.*, 2009). Sinha and de Weck (2013) developed a complexity metric, based on these three factors, and made it more usable, with DSM-based system models. Equations (1) through (7) show details of the complexity metrics in Sinha and de Weck (2013).

$$\text{Product Complexity} = C_1 + C_2 C_3 \tag{1}$$

System complexity is composed of C_1, C_2 and C_3, as in Eq. (1). C_1 represents the technological level of components, C_2 is the component interfaces, and C_3 is the system architecture of the product. C_1 is the sum of the Technological Readiness Level (TRL) values of the components (Mankins, 1995), and is calculated as in Eq. (2).

$$C_1 = \sum_{i=1}^{n} \alpha_i \text{ where } \alpha = 5\left(\frac{TRL_{\max} \text{-} TRL}{TRL_{\max} \text{-} TRL_{\min}}\right) \tag{2}$$

TRL values are determined on a scale of (0, 5), based on each component in Eq. (2). If a component plays the role of a case in the product, it is estimated with a low TRL value, such as 1. If it is a core part of the product, then it has a high TRL value, such as 5.

$$C_2 = \left[\sum_{i=1}^{n}\sum_{j=1}^{n} \beta_{ij} A_{ij}\right] \tag{3}$$

$$\beta_{ij} = f_{ij}\alpha_i\alpha_j \text{ where } \alpha_i, \alpha_j \neq 0 \tag{4}$$

$$A_{ij} = \begin{cases} 1 & \forall\left[(i,j) \middle| (i \neq j) \text{ and } (i,j) \in \Lambda\right] \\ 0, & \text{Otherwise} \end{cases} \tag{5}$$

C_2 is the components interfaces, and is calculated as in Eq. (3). The coefficient of beta is calculated as in Eq. (4). This depends on the interfaces between components (α_i and α_j) and interface type (f_{ij}). In component-based DSM, the spatial domain matrix has a symmetric structure, the coefficient of beta is estimated as 0.5, and other domains are estimated as 1. In Eq. (5), A_{ij} represents inter- connections between the i^{th} component and j^{th} component.

$$C_3 = \gamma E(A) \text{ where } \gamma = \frac{1}{n} \text{ acts as a normalization factor} \tag{6}$$

$$E(A) = \sum_{i=1}^{n} \sigma_i \text{ where } \sigma_i \text{ represents } i^{th} \text{ singular value} \tag{7}$$

C_3 represents the structure of the product, and it is estimated by the graph energy of DSM in Eq. (6). In Eq. (6), Λ means the set of connected nodes. The eigenvalue of each variant is calculated using Eq. (7).

We present an example of an artificial system for demonstrating this index, using a hypothetical information system as shown in figure 5.

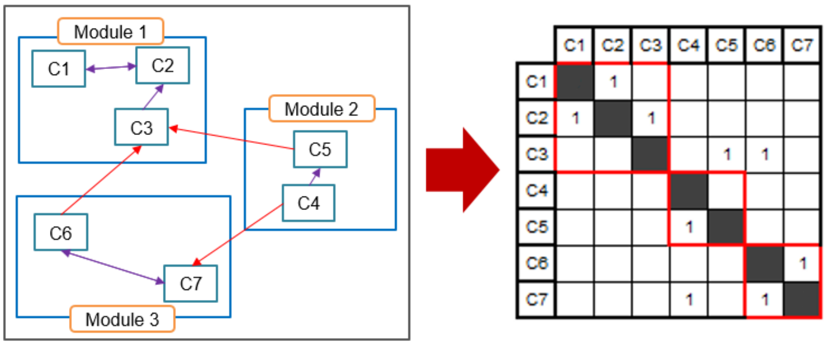


Figure 5. Example of an artificial system for system complexity: it consists of 7 components. Each component is connected by information flow.

Based on the matrix of this system, the graph energy was calculated as E(A) = 4. We assumed each of components had different component complexity vector be {(C1=1); (C2=2); (C3=1); (C4=4); (C5=3); (C6=2); (C7=3)}. Depending on the criteria for estimating each component, various component complexity vectors can be made. The sum of component complexities C_1 = 1+2+1+4+3+2+3 = 16. Let us use the following connection complexities: $\beta^{spatial}$ = 0.5, $\beta^{mass/energy/information\ flow}$ = 1. Note that spatial connections are bidirectional, while other flows are unidirectional. The sum of connection complexities C_2 = 9*1 = 9. The normalization factor γ equals 1 of n where n means the number of components of the system. Therefore, the structural complexity is (16+9*(4/7)) = 21.14.

In this index, product complexity increases, when the number of components, or their between connections, are increased. Table 2 shows the analysis result for product complexity of mouse variants.

Table 2. Analysis result for product complexity in computer mouse variants

No.	Model	C1[a]	C2[b]	C3[c]		Product Complexity
				E(A)	*γ*E(A)*	
1	S-34	34	25	21.3	1.3	67.3
2	S-48a	42	32	27.0	1.4	85.3
3	Mombasa	38	29	23.2	1.3	75.4
4	M90	33	23	20.4	1.4	64.3
5	M100	37	27	22.1	1.3	72.0
6	M185	45	31	25.9	1.4	87.2
7	M325	52	38	30.4	1.3	100.2
8	M555b	78	91	54.9	1.2	186.6
9	M905	124	149	92.1	1.2	306.9

[a.] C1 is the sum of TRL values.
[b.] C2 is the sum of connections between components. Their interfaces were also considered in this.
[c.] C3 is the sum of graph energy of each component. After being calculated, it was normalized by gamma. Gamma is the normalization factor, and is equal to 1/ n.

As previously mentioned, various studies have been conducted on system modularity (Allen and Carlson-Skalak, 1998; Guo and Gershenson, 2004; Newcomb *et al.*, 1998; Sharman and Yassine, 2004). We selected the modularity index, which was created by Guo and Gershenson (2004). This index is widely used in various studies related to the modularity concept. It measures the intra- and inter-connections in a system matrix. The value of the system modularity ranges from -1 to 1, through normalization on the size of the system. If there are more connections between modules than within modules, the system modularity is estimated as a negative value. On the other hand, if a system has more connections within modules than between modules, a positive value can be obtained.

$$M_{(G\&G)} = \frac{\sum_{k=1}^{M} \frac{\sum_{i=n_k}^{m_k} \sum_{j=n_k}^{m_k} R_{ij}}{(m_k - n_k + 1)^2} - \sum_{k=1}^{M} \frac{\sum_{i=n_k}^{m_k} (\sum_{j=1}^{n_k - 1} R_{ij} + \sum_{j=m_k+1}^{N} R_{ij})}{(m_k - n_k + 1)(N - m_k + n_k - 1)}}{M} \qquad (8)$$

where,

n_k is the index of the first component in the k^{th} module

m_k is the index of the last component in the k^{th} module

M is the total number of modules in the product

N is the total number of components in the product

R_{ij} is the value of the i^{th} row and j^{th} column element in the modularity matrix

In (8), the diagonal matrix of DSM is assumed to be one. Because the diagonal matrix of the DSM made for our study was set to zero, this equation was modified, as in Eq. (9).

$$M_{(G\&G)} = \frac{\sum_{k=1}^{M} \frac{(m_k - n_k + 1) + \sum_{i=n_k}^{m_k} \sum_{j=n_k}^{m_k} R_{ij}}{(m_k - n_k + 1)^2} - \sum_{k=1}^{M} \frac{\sum_{i=n_k}^{m_k} (\sum_{j=1}^{n_k - 1} R_{ij} + \sum_{j=m_k+1}^{N} R_{ij})}{(m_k - n_k + 1)(N - m_k + n_k - 1)}}{M} \qquad (9)$$

where,

n_k is the index of the first component in the k^{th} module

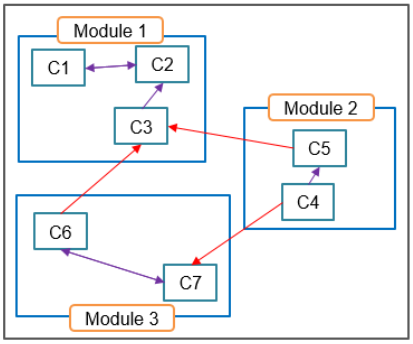
m_k is the index of the last component in the k^{th} module

M is the total number of modules in the product

N is the total number of components in the product

R_{ij} is the value of the i^{th} row and j^{th} column element in the modularity matrix

Similar with the structural complexity index, the artificial system, mentioned earlier in system complexity, also used for explaining this index. The artificial system was expressed as shown in figure 6.



	C1	C2	C3	C4	C5	C6	C7
C1		1					
C2	1		1				
C3					1	1	
C4							
C5				1			
C6							1
C7				1		1	

Figure 6. Example of an artificial system for system modularity: it consists of 7 components. (Gold areas are intra-module areas. Green areas are inter-module areas.)

Module 1 has 3 intra-connections and 2 inter-connections. Module 2 has 1 intra-connections and 2 inter-connections. Module 3 has 2 intra-connections and 2 inter-connections. Considering the maximum number of intra- or inter-connections of each module, the sum of modularity ratios can be calculated as [(3/6)-(2/24)] + [(1/2)-(2/20)] + [(2/2)-(2/20)] = 1.72. Therefore, the degree of modularity of this system is $M_{(G\&G)} = 1.72/3 = 0.57$.

Before calculating the degree of modularity, a clustering algorithm should be applied, for binding components into clusters. Among various clustering algorithms (Borjesson and Hölttä-Otto, 2012; Newman, 2004; Thebeau, 2001), the method created by Thebeau (2001) was selected. This method has ease of use, and is known to be bug-free. Moreover, it can be downloadable on the DSM website.

In this method, each component is moved from one cluster to another. The total interactions between clusters are minimized, and interactions within clusters are maximized. This algorithm uses a stochastic hill-climbing process, so the clustering results are always changing. To analyze the consistency of the clustering results, Thebeau (2001) measured the consistency of like clusters. The like elements between any two clusters were counted by taking the dot product of the two cluster matrices. This measure was done for every combination of clusters and runs. Also, interaction levels between components were varied for evaluating the impact of interaction. A strong interaction was defined as an important interaction for operating a system. While, a weak interaction was defined as an interaction not critical to operate a system. After the many runs and the variation process on the interaction levels, the analysis results showed that the components of clusters were not always highly similar. Also, clustering was strongly improved if the DSM interaction levels varied according to their importance in each system.

Considering the limitations of Thebeau's, this clustering algorithm is iterated in each metric over fifty times. The optimal solution is detected through this clustering algorithm for fifty iterations. Based on the optimal solution obtained by iterations, additional clustering processes will be conducted a further 10 times. If we get a better solution than the previous optimal solution during 10 iterations, the previous optimal solution is replaced by the new optimal solution. If not, the additional clustering processes will be over. In that case, the previous optimal solution will be selected as the final optimal solution. Also, in complex systems, the interaction levels were varied by making one weighted-domain matrix.

After the clustering process, the degree of modularity is calculated. Table 3 shows the results for product modularity for the mouse variants. Table 4 shows an example of modules in mouse variants, after clustering.

Table 3. Analysis result for product modularity in computer mouse variants

No.	Model	Number of Components	Number of Connections	Number of Modules	M (G&G)
1	S-34	16	50	5	0.616
2	S-48a	20	64	7	0.670
3	Mombasa	18	58	7	0.653
4	M90	15	46	4	0.545
5	M100	17	54	5	0.604
6	M185	19	62	5	0.598
7	M325	24	76	6	0.600
8	M555b	46	182	13	0.688
9	M905	75	298	22	0.690

Table 4. Example of modules in mouse variants after clustering (Model: S-34)

Module No.	Components	Module Description
Module (1)	1, 2, 5, 6a, 7a, 12	Basic part
Module (2)	8, 10, 11	Ball part
Module (3)	3, 4a, 4b	Button part
Module (4)	9a, 13a	Vertical movement sensor part
Module (5)	9b, 13b	Horizontal movement sensor part

It was observed that each component was bound as a set of modules, which perform specific roles in the computer mouse. This means that this clustering result can reflect the real modules that are proposed from the design teams.

After the estimation of system complexity and modularity, product variants are chosen in pairs, with each pair utilizing different technologies for their intended features. Comparative analysis is conducted on the product complexity and modularity, to check the validity of technology infusion. If the number of experiment samples is sufficient, this should be accompanied by statistical analysis.

In the computer mouse product family, there are nine variants. We compared the marginal change ratio of a specific pair with different technologies, assessing the effect of technology infusion.

3.3. Results for the Computer Mouse Product Family

Figures 7 and 8 capture the results for the computer mouse product family.

Figure 7 shows the result of comparative analysis for the product complexity of four features. In most cases, the comparative analysis results show that when a new technology was infused into the previous system, the values of product complexity were increased. When the number of buttons was changed from two to seven, the configuration (e.g. the number of components and arrangement of components) of each system was changed. This increased the value of the product complexity. The same trend was captured in the existence of wired connection. However, in Figures 7 (b) and (d), some results showed the opposite trend (e.g. the sensing type from ball to LED), in comparison with other pairs. As the sensing type was changed from ball to LED, the operation method of the sensor was changed to electrical. This change could not be expressed in the spatial domain of mouse variants. Product complexity inherent in the mechanical method was transferred to another domain, such as information flow or energy flow.

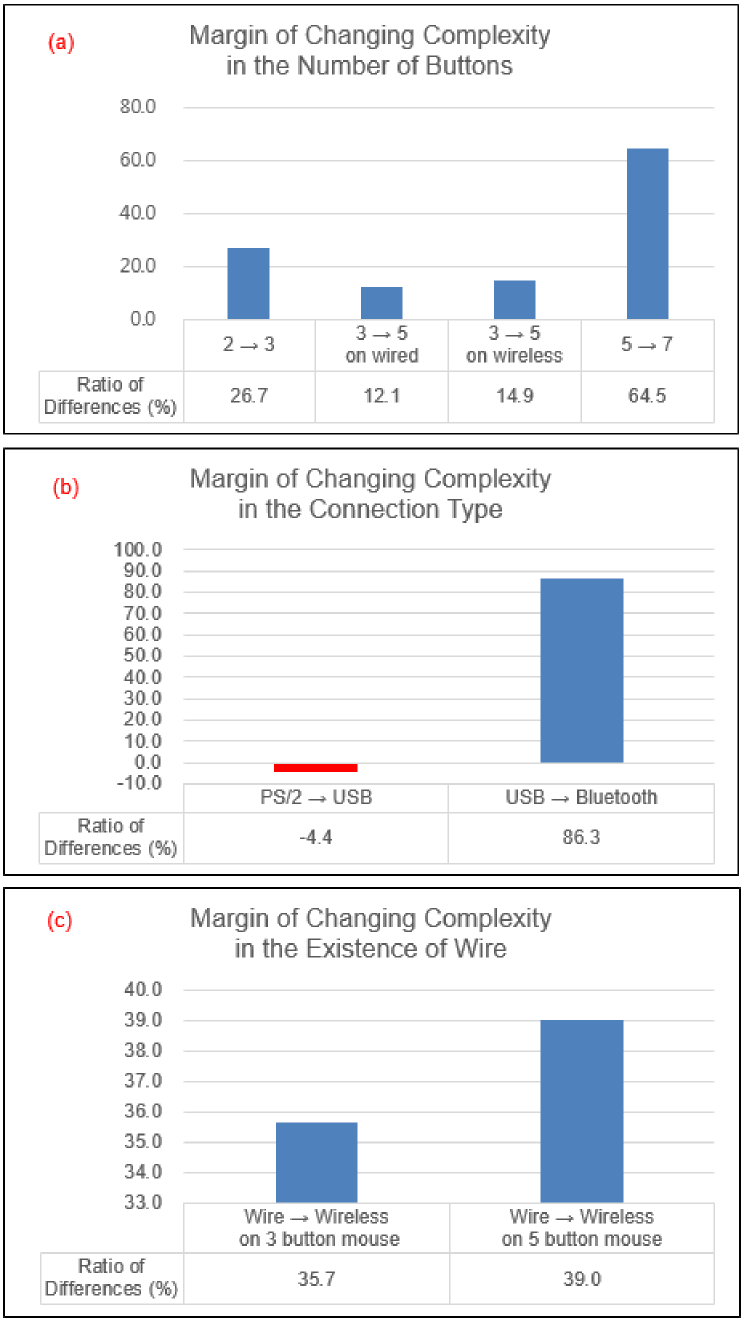


Figure 7a. Comparative analysis result for product complexity in mouse variants: number of buttons (a), connection type (b), and existence of wire (c)

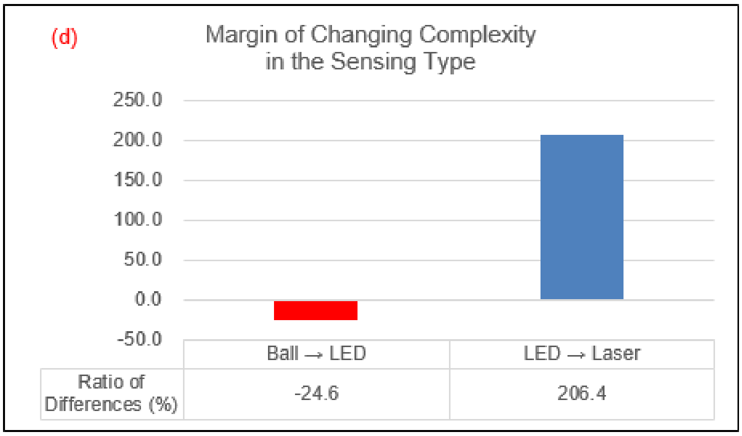
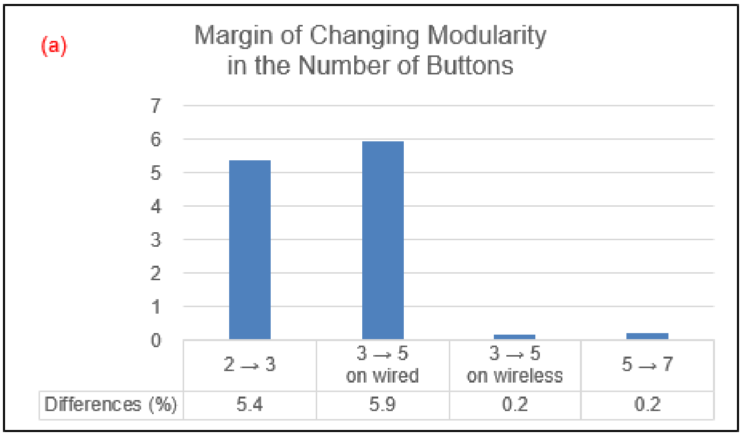
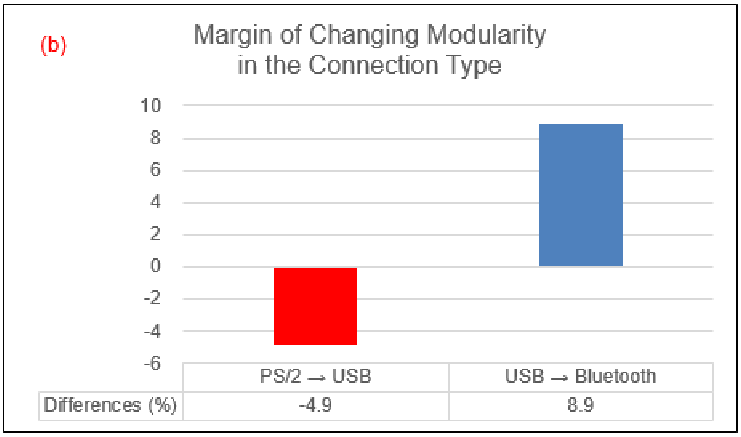


Figure 7b. Comparative analysis result for product complexity in mouse variants: sensing type (d)

Figure 8 presents the same analysis for product modularity. Most cases showed that when a new technology was infused, the degrees of modularity were increased. Interestingly, exceptional cases, detected in the product complexity analysis, also showed opposite trends in product modularity. In these cases, technology infusion decreased the degree of modularity. When the connection type was changed from PS/2 to USB, the system modularity was changed, to become more integral. It has been a long time since the PS/2 mouse was launched, though the USB-type mouse is the latest. This time gap causes large influences on several elements. For example, each of the components in the computer mouse product family can be upgraded. The design of mouse variants can also be optimized over time.





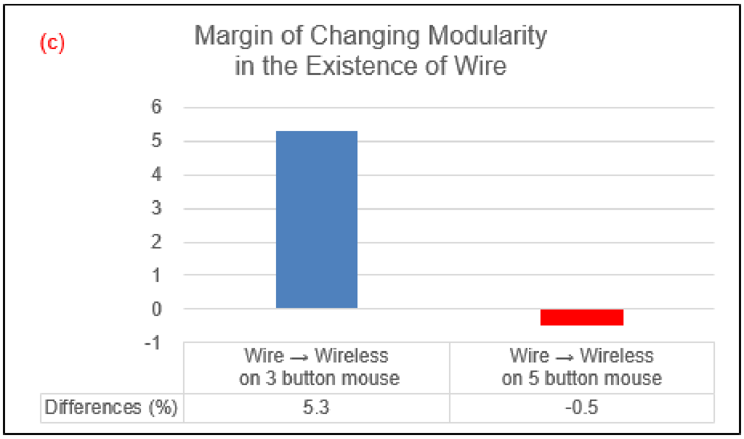


Figure 8a. Comparative analysis result for product modularity in mouse variants: number of buttons (a), connection type (b), and existence of wire (c)

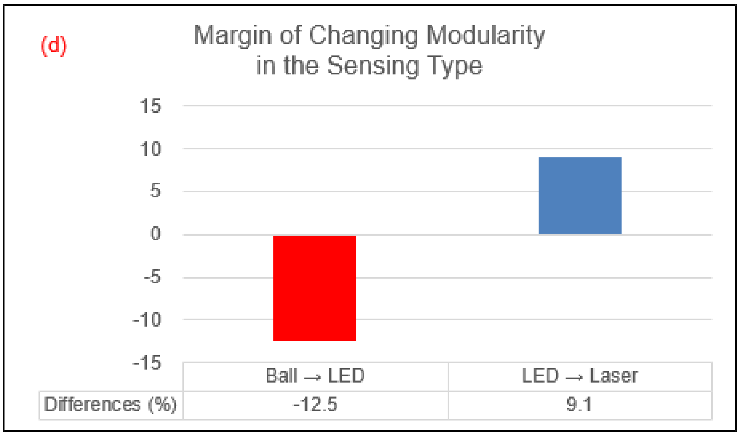


Figure 8b. Comparative analysis result for product modularity in mouse variants: sensing type (d)

Some cases showed opposite trend, in comparison with other pairs, on system complexity and modularity. When the connection type was changed from PS/2 to USB, this could be caused by several reasons. First, this study only focused on the physical domain of mouse variants. If other domains were included in this study in addition to the physical domain, the analysis result might have been different. Also, correlation between technical features can influence the analysis results. Moreover, the design changes of components or printed circuit boards can make this difference. As technologies are developed, specific components can be a cause of change propagation in the existing system. Lastly, the lack of mouse variants meant that some of the pairs (e.g. the design change from LED to laser) could not be fully matched. If we can make up for the weak points of this analysis, we can further improve the analysis results.

3.4. Technology Infusion on Complex Systems

In the previous section, the computer mouse variants were simple products. In real systems, most products have many components, and the connections between components are intricately tangled with each other. We now focus on complex systems, in particular, two versions of printing systems (iGen3). They were analyzed using the framework of this study.

In the component-based DSM modeling process of complex systems, four domains were included. Each system was decomposed into four different DSMs, representing spatial connection, mass flow, energy flow, and information flow. After that, they were integrated as a weighted domain-matrix. In the weighted domain-matrix, the ratio of each domain is equal to 0.25. For example, if a specific cell has two domain connections, then the weighted-domain cell has 0.5 value.

In the graph energy (i.e. product complexity) calculation process, we assumed that each component had the same TRL values, to focus on the changes of product structure, rather than the product components themselves. Also, we assumed that if components were changed on their shapes only, it had no effect on their interfaces or product structure.

Each system consists of normal components commonly used for all systems, and specific components used for differentiation. In addition to the modularity analysis, the reusability ratio of modules was considered. If the ratio of reused modules in a new system is high, the components used in the existing product can be recycled. This can reduce the development time and costs (Fortune and Valerdi, 2013).

3.5. Printing System

The data for the printing system was obtained from Eppinger and Browning (2012). Figure 9 shows DSM examples of the printing systems. This printing system, named iGen3, is made by Xerox, which is one of the most prominent printing system companies in the world. In comparison with the cases mentioned earlier, the number of components was the highest, and the interfaces were the most complex. Table 5 shows the information of the printing systems before, and after, technology infusion.

Based on the weighted domain matrix of the printing systems, the graph energy index was used in the calculation of the complexity metric. Most of the processes were the same as previous mouse variants, but the coefficients of beta were different for each domain. If the DSM domain was spatial, the coefficient of beta was 0.5. If not, it was set to 1. We compared two cases: the baseline printing system, and the upgraded version of the baseline, where a new technology was infused.

Table 5. Information of printing systems baseline and technology-infused

No.	Concepts	Number of Subsystems	Number of Connections (Overall)
1	Base System	84	612
2	Technology-Infused	88	635

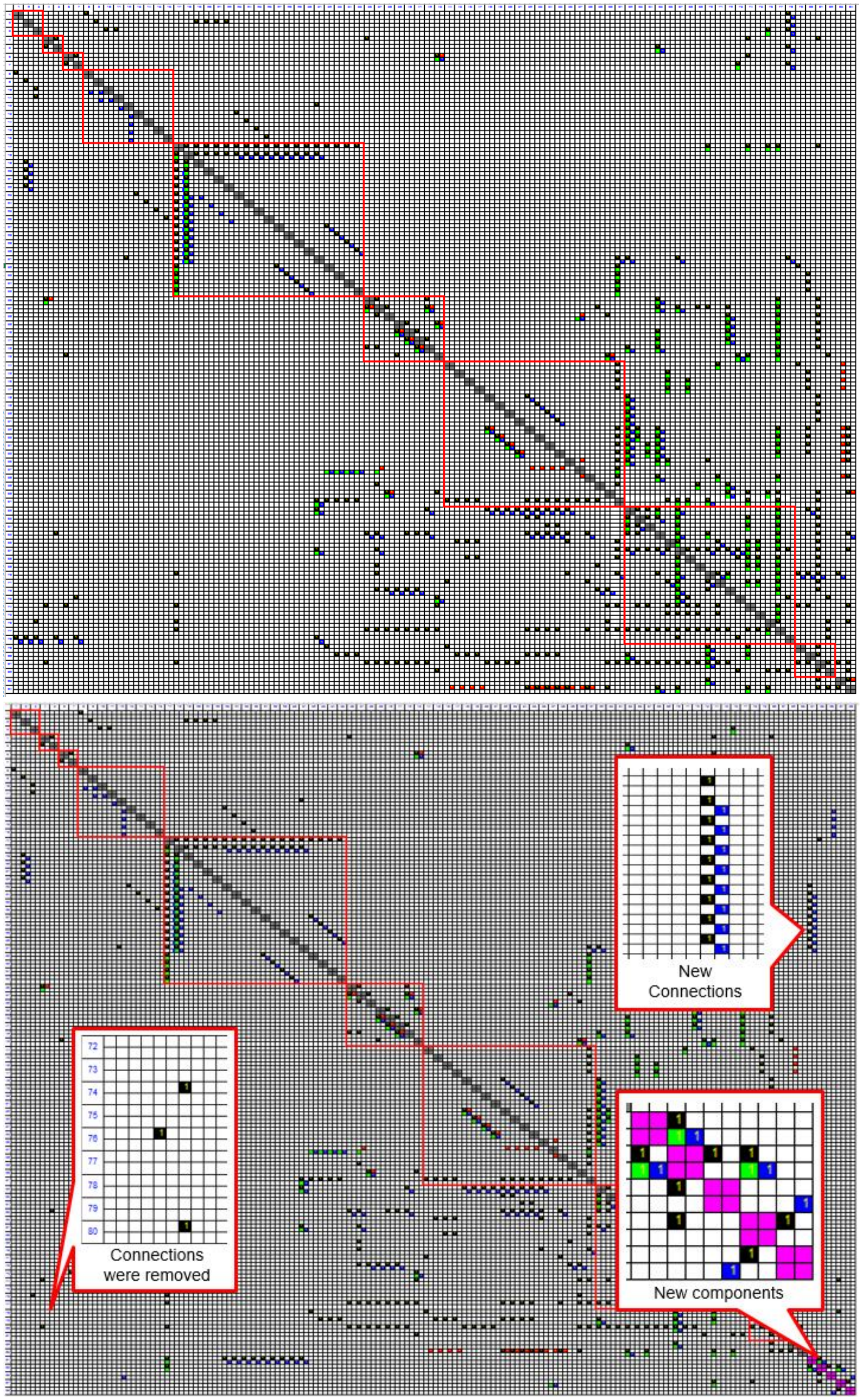


Figure 9. Component-based DSM examples of printing systems (iGen3): baseline DSM (upper) and upgrade version of iGen3 (lower)

3.6. Results for the Printing System Technology Infusion

The analysis result of product complexity and modularity can be found in Tables 6 and 7.

Table 6. Analysis result for product complexity in the printing system

No.	Model	C1[a]	C2[b]	C3[c]		Product Complexity
				E(A)	*γ*E(A)*	
1	Baseline	252	612	152.1	1.8	1360.4
2	Technology-infused	264	635	157.6	1.8	1401.0

[a.] C1 is the sum of TRL values.
[b.] C2 is the sum of connections between components. Their interfaces were also considered in this.
[c.] C3 is the sum of graph energy of each component. After being calculated, it was normalized by gamma. Gamma is the normalization factor, and is equal to 1/ n.

Table 7. Analysis result for product modularity in the printing system

No.	Model	Number of Modules	Number of Reused Modules	M (G&G)
1	Baseline	28	Criterion	0.599
2	Technology-infused	28	6 (21%)	0.575

When new technology was infused in the printing system, the value of the product complexity was increased by 3.1%. Because this system was bigger than the above cases, the ratio of the increased product complexity value was smaller.

The degree of product modularity decreased by 2.4%. This means that the property of the system architecture changed to become more integral. 6

modules were reused in the new system after technology infusion.

Table 8 presents a summary of the analysis results of the two different systems. In most cases, the value of product complexity increased, when new technology was infused. In product modularity, the analysis results depended on the system. The trend of each system varied. In the computer mouse product family, the degree of product modularity increased, when new technology was infused. However, in the printing systems, the opposite results were observed.

Table 8. Summary of the analysis results of real systems for the impact of technology infusion on system complexity and modularity

No.	System Information	The impact of technology infusion	
		Product complexity	Product modularity
1	Computer mouse product family	Increased	Increased (more modular)
2	Printing system	Increased	Decreased (more integral)

Chapter 4. Application of Research Framework for System Design

In the previous section, two different real systems (i.e. a computer mouse product family and printing systems) were analyzed for system complexity and modularity. From now on, we will focus on complex system design, in particular, the hydrogen-enhanced combustion engine (HECE). Similar processes to the printing system cases were applied to these HECE concepts.

4.1. Hydrogen-Enhanced Combustion Engine

Smaling and de Weck (2007) explored six different concepts of technology infusion into an existing hydrogen-enhanced combustion engine (HECE). Figure 10 shows component-based DSM examples of hydrogen-enhanced combustion engines. The HECE has several components, and each component includes complex inter-connections with various technologies. Infusing a new technology into the HECE creates engineering design changes, and results in different system attributes. In the product development stage, each concept focused on operational performance advancement. For the improvement of operational performance, four variables (i.e. basic engine, compression ratio, dilution method, and engine size) were varied in each concept. Six technology infusion concepts were considered. Table 9 shows the information of each technology infusion concept, where EGR means Exhaust

Gas Recirculation. Considering the changes of components and their connections, the baseline DSM was modified for each concept.

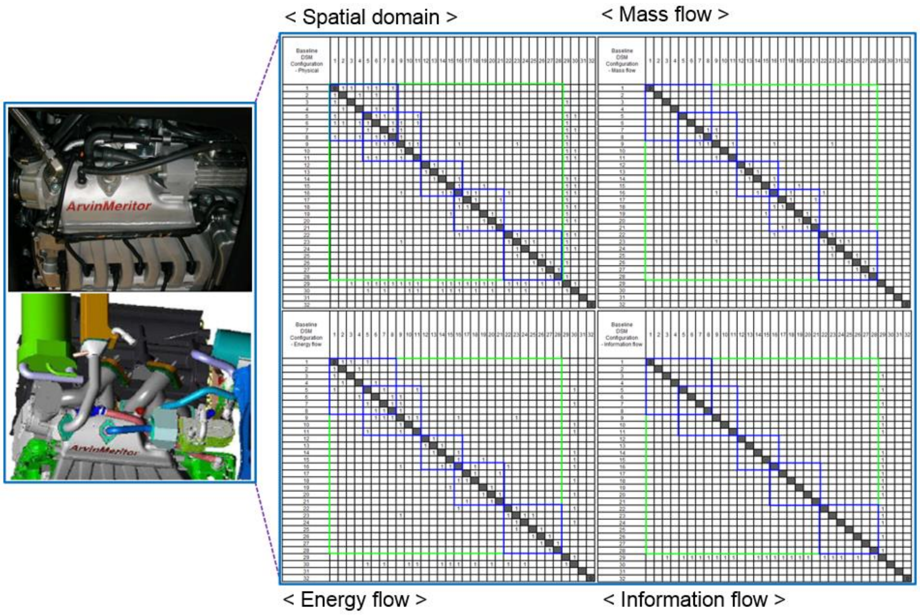


Figure 10. Component-based DSM examples of the hydrogen-enhanced combustion engine (Baseline DSM)①

Based on the weighted domain matrix of HECE concepts, the graph energy index was used in the calculation of the complexity metric. Most of the processes were the same as previous printing systems. Table 10 shows the analysis result for product complexity in the HECE.

① Each of the figures can be viewed in the online websites. The first one is available at www.greencarcongress.com. The other is available at Smaling and de Weck (2007).

Table 9. Information of technology concepts and base system in the hydrogen-enhanced combustion engine

No.	Concepts	Number of Components	Number of Connections (Overall)
1	Base System	30	144
2	Naturally Aspirated AIR diluted	30	152
3	Naturally Aspirated EGR diluted	31	160
4	Boosted AIR diluted	30	154
5	Boosted EGR diluted	31	162
6	Boosted AIR diluted Downsized	30	154
7	Boosted EGR diluted Downsized	31	162

Table 10. Analysis result for product complexity in the hydrogen-enhanced combustion engine

No.	Model	C1[a]	C2[b]	C3[c]		Product Complexity
				E(A)	*γ*E(A)*	
1	Baseline	90	144	29.3	1.0	230.7
2	Concept 1	90	152	29.9	1.0	241.2
3	Concept 2	93	160	31.4	1.0	255.2
4	Concept 3	90	154	30.4	1.0	245.9
5	Concept 4	93	162	31.1	1.0	255.6
6	Concept 5	90	154	30.4	1.0	245.9
7	Concept 6	93	162	31.1	1.0	255.6

[a.] C1 is the sum of TRL values.
[b.] C2 is the sum of connections between components. Their interfaces were also considered in this.
[c.] C3 is the sum of graph energy of each component. After being calculated, it was normalized by gamma. Gamma is the normalization factor, and is equal to 1/ n.

In the calculation of the modularity index, the same processes (i.e. clustering algorithm and modularity calculation) were applied in each metric. Table 11 shows the analysis result for product modularity in the HECE.

Table 11. Analysis result for product modularity in the hydrogen-enhanced combustion engine

No.	Model	Number of Modules	Number of Reused Modules	M (G&G)
1	Baseline	10	Criterion	0.692
2	Concept 1	10	2 (20%)	0.680
3	Concept 2	11	3 (30%)	0.683
4	Concept 3	9	3 (30%)	0.621
5	Concept 4	10	2 (20%)	0.676
6	Concept 5	9	5 (50%)	0.646
7	Concept 6	9	1 (10%)	0.632

4.2. Results for the Hydrogen-Enhanced Combustion Engine Technology Infusion

Figure 11 shows the analysis result of the hydrogen-enhanced combustion engine for their technology infusion concepts.

In product complexity, observation of the results shows that the system, after it has been subject to technology infusion (regardless of the concepts to implement it), becomes more complex, as the metric values indicate. In concept 1, 3 and 5, the values of complexity were less increased than other concepts.

In product modularity, most cases showed that the degrees of modularity were changed to become more integral. The values of modularity were less decreased in the concept 1, 2, and 4. However, from the viewpoint of reusability of modules, 2 or 3 modules were reused in most concepts, but 5 modules were reused in concept 5.

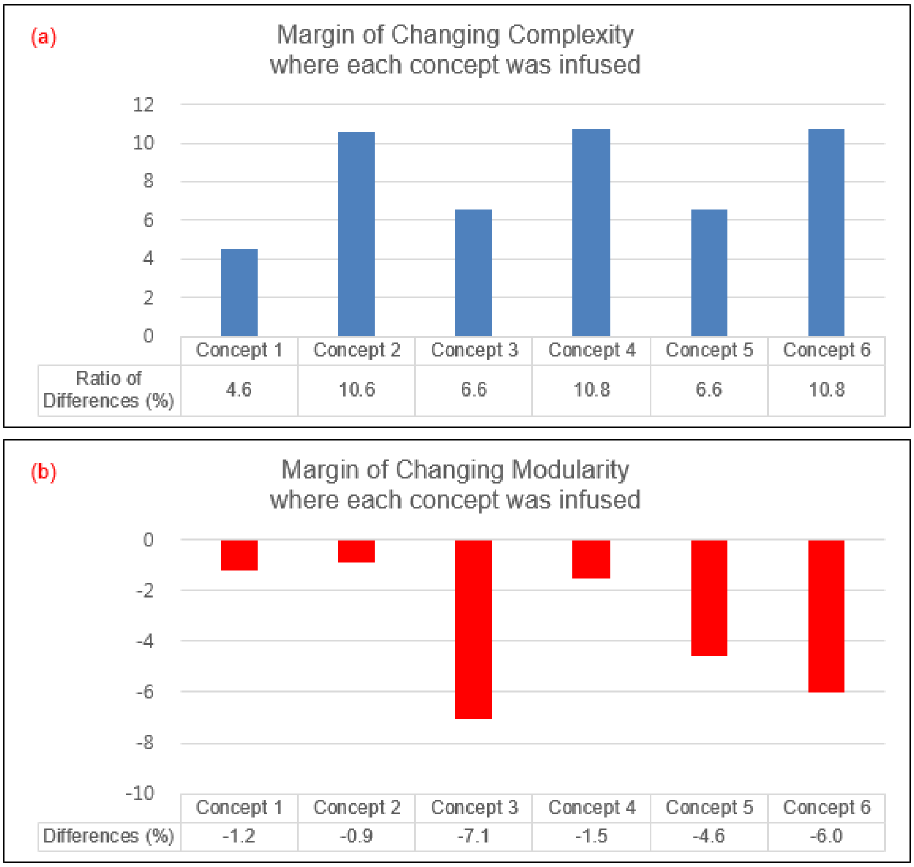


Figure 11. Comparative analysis result for (a) product complexity, and (b) modularity, in the hydrogen-enhanced combustion engine

According to Smaling and de Weck (2007), the concept 5 is the technology infusion architecture of choice among the 6 alternatives. This analysis result was confirmed by inclusion of cost, technology invasiveness and several scenarios under future uncertainty. Comparing with the analysis results of complexity and module reusability, it is partially matched with the analysis of Smaling and de Weck (2007). Based on the system attributes, several alternatives could be identified.

4.3. Design Guideline for Technology Infusion

In simple systems, the number of components and connections of products is not as many as complex systems, it is easier to handle the system complexity and modularity for system engineers. On the other hand, in complex systems, most products consist of many components, and the connections between components intricately tangled with each other. For this reason, the design process of new products takes more costs and time.

Based on the analysis results of three different systems, we suggested some guidelines for improving the design or redesign process of products. Technology infusion on the existing system changes system attributes especially system complexity and modularity. In most cases, the system complexity usually increases, but the system modularity shows different patterns in each system. When system engineers redesign the existing system, they should consider the change of system complexity and modularity.

Chapter 5. Conclusion and Future Work

In this study, a framework for assessing the impact of technology infusion on complex systems was proposed, to validate several research questions. For analyzing system attributes in a quantitative way, a structural complexity index based on the graph energy was selected. In system modularity, the modularity index proposed by Guo and Gershenson (2004) was selected. In complex systems, when new technology is infused into an existing system, the value of system complexity increases. The degree of system modularity increased in the computer mouse product family. This means that technology infusion in the computer mouse makes the system architecture more modular. On the other hand, the degree of modularity decreased, and became more integral, in complex system cases. The results of the modularity analysis represent that the property of the system architecture is dependent on each case.

The analysis results of system complexity and modularity can be utilized in the design process of a new system. When a new technology is infused into a current system, the system complexity usually increases, so it is recommended to choose a concept that increases the system complexity less. The system modularity shows different patterns in each system, so it should be studied case-by-case. Also, from the viewpoint of module reusability, the number of reused modules should be maximized, to reduce redesign costs and time. The impact of technology infusion on system attributes can be minimized by utilizing some design strategies. Therefore, it is recommended to design better systems through various design strategies, after the analysis of system complexity and modularity.

More effort is required to better understand what happens when a new technology is infused into an existing system. Do existing metrics of system properties properly capture changes in these complex systems? How can these analyses be used for manufacturing processes and supply chains? All these issues are interesting subjects that can contribute to both academia and industry in the future.

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초 록

긴 제품주기를 갖는 복잡한 시스템들은 시간이 지남에 따라 최신 제품에 비해 성능이 떨어지게 된다. 이러한 문제점을 해결하기 위해, 시스템들이 출시된 이후에 지속적인 업데이트를 통해 성능을 향상시켜줘야 한다. 이 과정에서 지속적인 성능 개선을 위한 다양한 시스템 요구 사항이 발생하며, 이러한 요인들은 기존 시스템에 새로운 기술을 주입하는 것을 통해 성능 개선을 이루어냄으로써 해결될 수 있다.

새로운 기술의 주입은 기존 시스템의 재설계, 특성 변화 등을 발생시키며, 이러한 영향을 고려하여 새로운 시스템에 대한 설계가 필요하다. 본 논문에서는 새로운 기술이 기존 시스템에 주입될 때, 시스템 특성에 어떠한 변화를 주는지 알아보고자 한다. 특히, 시스템 복잡도와 모듈화 개념에 초점을 두고, 각 특성에 대해 새로운 기술의 주입이 어떤 영향을 주는지 알아보고자 한다.

시스템 복잡도와 모듈화에 관련된 다양한 문헌을 조사하여 시스템 특성 평가에 알맞은 지표를 선정하였고, 이를 바탕으로 각 시스템 특성이 어떻게 변화하는지 분석하였다.

본 논문의 연구를 위해 다양한 시스템들 중 두 가지 실제 시스템이 분석되었다. 비교적 단순한 제품군인 컴퓨터 마우스와 복잡한 제품인 대형 프린터의 분석 결과를 바탕으로 하여, 자동차 내연 엔진 사례를 통해 시스템 특성을 반영한 의사결정 방법론을 제안하였다.

주요어 : 기술주입, 시스템 복잡도, 시스템 모듈화
학　번 : 2012-23308