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Complexity and Control: Comparative Study of Automobiles and Electronic Products

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Complexity and Control:
Comparative Study of Automobiles and Electronic Products

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Abstract

The aim of this paper is to analyze similarities and differences of the architectures and designing processes for the mechanical, electronic, and software system by studying fundamentals of design logic. This paper has analyzed sources of complexity in the design and development processes of complex products of mechanics, electronics, and software and has searched for more effective processes. In particular, this paper has asserted that a difference in design philosophy results in difficulty in integrating structural and functional designs because functional design is emphasized in designing electronic and software systems which are control systems, while structural design is emphasized in designing mechanical systems which are controlled systems. We found electronic control systems are used rather than a controlled system in case of automobiles. On the other hand, electronic products are vice versa.

Keywords

Complexity, Control relationship, Mechanical System, Electronic System, Software System

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Many firms in today's business environment utilize diverse information systems to sustain their competitive advantages. However, too often the return of investment on information technologies is not as obvious as expected. This is particularly true with many small and medium enterprises. This paper presents a research model and examines how mobile display manufacturers implement their information systems for the enhancement of supply chain performance. For the purpose of this research we involve two firms and consider critical success factors of their information integration practices. One successful firm which has organizational capability in IT use links its existing database to new information systems and aligns its information system for the larger requirements of supply chains. Another firm possesses different organizational capabilities and accordingly shows the poor outcomes. Based on extensive interviews with the IT executives, supply chain professionals and IT vendors within the supply chain network of these two firms, we present our findings. Lessons and implications are discussed.

Keywords (five words) Organizational Capability, Database Integration Capability, Supply Chain Management, Information System, Mobile display manufacturers

1. INTRODUCTION

As consumers' demands have become increasingly uncertain, diversified, and sophisticated, current products tend to be more complex. Further, the development periods for these products need to be reduced. Thus, it has become difficult for today's corporations to design and develop such complex products in a short period. An increase in product functions requested by customers, quantity of structural elements such as parts corresponding to these functions, and number of correlations between the functional and structural elements lead to an increase in the number of procedures required for development. In addition, synchronization and duplication of these functions are requested, and consequently, both corresponding products and processes have become more complex.

In particular, complexity is apparent in products consisting of a number of mechanical parts (mechanics) that need to be controlled by a number of electronic circuits (electronics), and software is deeply related to such a control system. Hereafter, such products will be called "complex products of mechanics, electronics, and software." Conventionally, "complex products of mechanics, electronics, and software" are called "mechatronics products." Initially, in many mechatronics products, a single mechanics was controlled by a single circuit. However, in recent years, mechanical parts of mechatronics products have become multiple and integrated (i.e., complex), and the role of software has also increased. For example, a car is a complex product consisting of about 30,000 mechanical parts, and in recent years, most of these parts are electronically controlled. Thus, in some cases, many circuit boards are required and their embedded software reaches over 10,000,000 steps. Some products having similar complexity have appeared recently in semiconductor manufacturing equipments, mobile phones, digital home electrical appliances, and multi-function office equipments. In these types of products, not only the number of functions and structures of the products and their mutual interaction but also the different types of designing logic for mechanics, electronics, and software are becoming complex and inter-related with each other, which seems to accelerate the complexity of products and product development process.

Research to find a complete solution to this problem has started recently. However, it is clear that any corporation that makes a mistake with respect to this problem can face difficulties in the future. Thus, this paper intends to analyze the source of complexity of designing and development processes for complex products of mechanics, electronics, and software, and then search for more effective processes. The causes for complexity and the directions followed in the design of artifacts, which have become more complex, will be examined to know how the design process, digital information technology (IT), organizational capability, and architecture progress simultaneously. This is done by comparing IT supporting development for electronic, mechanical, and software system design, and analyzing the master–subordinate relationship between controls on functional and structural design, and studying the development processes for automobile and home electrical appliances. For this purpose, focusing upon IT supporting design and development, which is considered to be essential in reducing product development lead-time in today's corporations, we set a hypothesis that development of such complex products in a short period is difficult because of the differences in design logic of the mechanical, electronic, and embedded software systems. In addition, master–subordinate relationships between the controls on the functional and structural design among mechanics, electronics, and software will be analyzed. Further, automobile and electronic products will be analyzed by comparing the master–subordinate relationship among mechanics, electronics, and software.

2. FRAMEWORK FOR ANALYSIS

2.1 Mutual Adaptation of Architecture, Design process, IT, and Organizational Capability

This paper describes an exploratory research for the complex development of complex products of mechanics, electronics, and software. A rough framework for analysis exists based on previous researches. According to this framework, there exists a type of dynamic, mutually adaptive relationship (fit) among the design concept (architecture) of a product, design (development) process of the product, IT tools that support development, and organizational capability (Fujimoto, 2003; Fujimoto, 2004; Fujimoto, 2006).

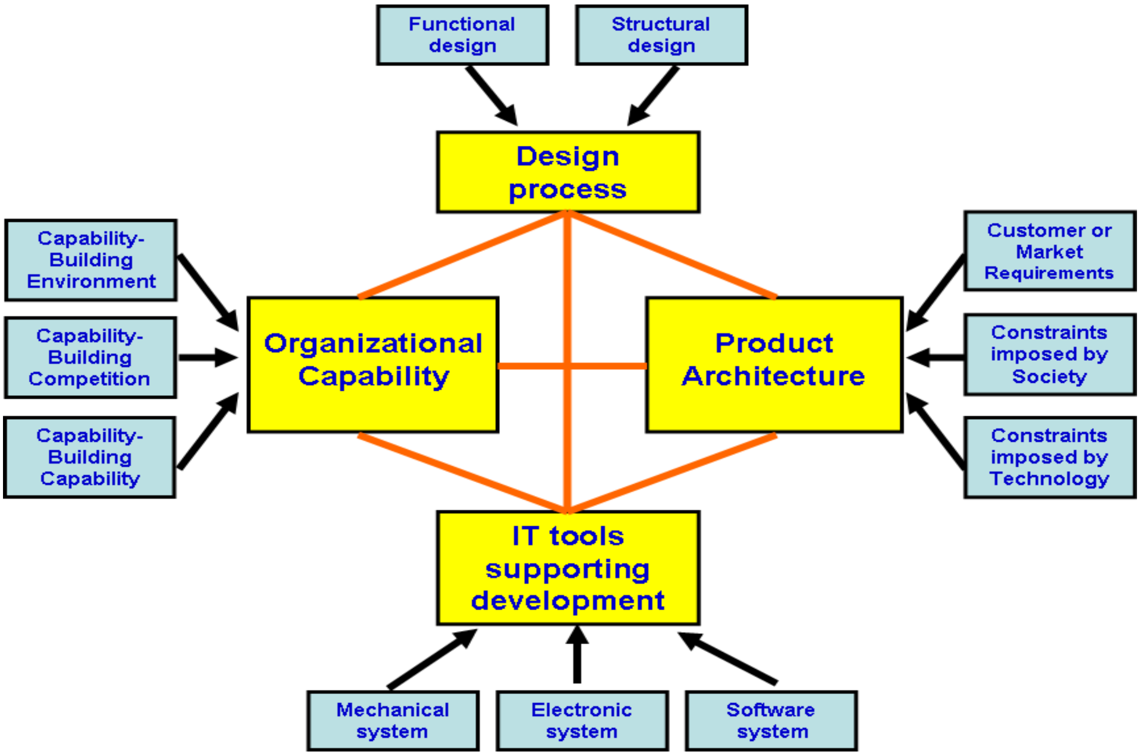

Figure 1. Mutual Adaptation Framework among Architecture, Design process, IT, and Organizational Capability

2.1.1 Manufacturing, Design Information, and Product

"Manufacturing (Monozukuri)" as mentioned in this paper is a broad concept that expresses the behavior of entire corporations and industries to achieve customer satisfaction through design, development, production, purchase, and sale of artifacts. This concept is a general-purpose technology for controlling the "flow of product design information" toward customers and includes not only production (transfer of design information to materials) but also product development (creation of design information).

"Product" refers to an artifact produced by corporations to satisfy customers. "Artifact" as mentioned here refers to all "designed" objects irrespective of their tangibility. Thus, product (artifact) in this paper is a broad concept that includes not only commodities but also services. In any case, product refers to an object in which "design information," expected to provide additional value to customers, is transferred to some type of "a medium".

From this viewpoint, "manufacturing" in a broad sense is an entire corporate activity that produces the "flow of design information" from the creation of design information to the transfer to a medium and then to the transmission of a completed "product (=artifact)" to customers. In other words, the essence of "manufacturing" is not "creating an object" but creating design information for an object (medium) (Fujimoto, 2003). By changing the viewpoint from products to information, manufacturing is no longer an enclosed process restricted to manufacturing sites at plants, but an open process in which development, purchase, production, and sales departments cooperate, involving suppliers, retailers, and customers as well as headquarter departments and top managements. Creating design information is the responsibility of the development department, transferring the created design information to a medium (object) is the responsibility of the production department, securing a medium on which the information is to be transferred is the responsibility of the purchasing department, and transmitting the transferred design information to customers is the responsibility of the sales department. Then, customers receive such design information from corporations and consume the design information (Fujimoto, 2006). Thus, it can be inferred that the most essential characteristic of manufacturing is not an "object or a medium" but "design."

2.1.2 Design Process

As mentioned before, the core concept of "manufacturing," which is a corporate activity, is "design". "Design activity" can be defined as envisaging a relationship between the function of an artifact and its structure prior to production of the actual object. In other words, a design process is represented as a process for establishing a structural parameter group in correspondence to a functional parameter group requested by customers or users of a particular artifact (Suh, 1990).

When a product or an artifact is designed, the product function that reflects customers' needs is divided into multiple groups of functional element and this division is indicated as a multi-stage hierarchical structure. This is known as functional design. Similarly, structure (such as shape, dimension, and material) of a product is sequentially divided into multiple groups of structural elements (e.g., collective parts and a single-element part). This division is described as a multi-stage hierarchical structure (e.g., a table of parts is BOM). The design of a part at each hierarchical level can be classified as: special for the product, common within a company, or a standard in the industry.

A mutual dependence occurs among structural elements. An “interface” is a portion for connecting these structural elements (parts and modules). The process of designing and classifying an interface is similar to that of a part.

2.1.3 Architecture (design concept)

A basic philosophy about disconnecting and connecting elements in the design information of a product or an artifact is called architecture (Ulrich, 1995; Aoshima and Takeishi, 2001; Fujimoto, 2001). Product architecture can be classified in various ways and the most important classifications are “modular type” and “integral type” or “open type” and “closed type” (Ulrich, 1995; Fine, 1998; Baldwin and Clark, 2000; Fujimoto, 2001). Although not described in detail here, for a “modular-type” product or artifact, the relationship between a product functional element (required function) and a product structural element (component module) is close to a one-to-one relationship, and because the interface for structural parts is common, the function of the entire product can be assured by combining already designed parts. In contrast, for an “integral-type” product or artifact, the relationship between the product functional element and product structural element is determined to correspond to multiple interrelated needs, and a corresponding interface is unique to a specific product. Consequently, the performance of the product is not assured until all the parts are designed optimally for each product. Among the modular type, the architecture of in which the entire function of an artifact is achieved by combining common parts within a company is called a “closed modular type.” The architecture in which the entire function of an artifact is achieved by combining parts designed from different companies through an industry standard interface is called an “open modular type.”

However, actual products cannot be characterized by simple classification. Even the same products may have different architectural characteristics depending on the location and layer (Fujimoto, 2003). Thus, it should be considered that architecture of actual products is distributed continuously on a spectrum ranging from integral to modular. Oshika and Fujimoto (2006) evaluated some architectural characteristics subjectively using Likert scaling and they estimated this spectrum using an integral degree index based on multivariate analysis. In addition, Shintaku (2003), Shintaku, et al. (2004) and Nobeoka, et al. (2006) estimated this type of spectrum based on accumulated case studies.

As a result, for example, according to Oshika and Fujimoto (2006), automobiles and their components are distributed in a layer having highest integral degree and electronic products are distributed in a layer having lowest integral degree (or a region having highest modular degree). On the basis of case analysis, Fujimoto (2001), Shintaku (2003), and Nobeoka, et al. (2006), selected a Japanese automobile as a typical product of the closed integral-type architecture and a desktop PC as a typical example of the open modular type. Their research addresses that a number of digital home electrical appliances have architectural characteristics close to that of the modular type.

In general, in the integral-type product, structural design is performed within strict constraint conditions, such as required performance and tradeoff between its structure and function. For example, assuming that there is a market need, small mechanical products that have severe restrictions on weight, strength, and volume and analog-type products in which structural and functional design need to be expressed by a continuous quantity tend to be close to the integral type (Nishimura, 2004).

Thus, integral-type assembled products tend to have a high ratio of custom design parts unique to that product and a high ratio of parts that are based on designs within the company and contain a number of analog basis and mechanical parts. In contrast to integral-type products, modular-type products are assumed to have a high ratio of standard general-purpose parts in the industry, common parts within the company, and digital basis and electrical/electronic parts. For example, the ratio of electrical and electronic parts accounts for 50% or more of the product cost of PCs and digital home electrical appliances, 30% of the cost for deluxe cars, and 10% of the cost for cheap automobiles. Similarly, general-purpose parts account for 50% or more of the product cost for PC, 30% of the cost for home electrical white goods, and 10% or less of the cost for deluxe cars. These are approximate criteria for determining architecture.

2.1.4 IT Tools that Support Development and Design

IT has been increasing its presence as a tool for creating “excellent design information flow” at development and production sites in recent years. Particularly, tools such as

Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), and Computer-Aided Engineering (CAE) assist in product development.

Generally, in the design process, a solution (design plan) to a problem is determined. Major factors in the design process are the search for an alternative design plan and simulation of problem-solving ability of each design plan. IT used primarily to support the search for a design plan is called CAD, and IT used to support the problem-solving simulation for the design plan is called CAE. In particular, IT to support mold design is called CAM, which may be considered as CAD for mold design (Ueno, 2005).

As described above, IT tools that support development assist not only in designing but also in simulating product performance and manufacturability by using design information of the accumulated electronic media. As a result, prior to verification of functions and manufacturability of a product by using an actual prototype, a virtual problem-solving cycle (design, prototype, and experimental cycle) can be conducted. This is called “front loading” which indicates that problem solution is carried out “in advance” and is considered to be one of the decisive means for establishing superiority in the race to develop products (Thomke and Fujimoto, 2000).

2.1.5 Organizational Capability for Manufacturing

In general, organizational capability is an organizational routine (repetitive action pattern) unique to a corporation or an organization and provides continued superiority in competitiveness and profitability over other corporations. It is developed continuously in a company, resulting in progress, and is difficult for other companies to copy.

If this concept is applied to the aforementioned broad concept of “manufacturing,” then “organizational capability for manufacturing” denotes an organizational capability for producing “excellent design information flow.” That is, organizational capability denotes a system that executes a process for creation, transfer, and transmission of design information corresponding to customers’ needs (with flexibility) with consistently high accuracy (and high quality), high efficiency (at a low cost), and more rapidly (with a shorter lead-time) than other competitive companies. Therefore, this capability helps in simultaneous achievement and improvement of QCDF. Organizational capabilities of development, purchasing, production, and sales departments are integrated and are closely interrelated (Fujimoto, 2001).

Toyota’s so-called production style is a typical example of such “organizational capability for manufacturing” (Fujimoto, 1997; Fujimoto, 2003; Fujimoto, 2004), namely, it is important to minimize “time when no creation or transfer of design information is performed, creating smooth flow” of design information toward customers.

Organizational capability for the design and development of products indicates capability to create continuously good flows of design information better than other rivals in the aforementioned “design process for problem solving,” and in short, is an “organizational problem finding/problem solving capability” (Clark and Fujimoto, 1991).

2.1.6 IT for Product Development and Organizational Capability

It is important to consider the relationship between IT and organizational capability with respect to product development. In the past decade, experimental studies have obtained the following conclusion by applying the aforementioned framework to IT for supporting product design and development. That is, introduction of cutting-edge IT tools that support development, such as three-dimensional solid model CAD in the 90s, is not a necessary and but a sufficient condition to establish superiority in industrial competition. In other words, IT provides no superiority in competition unless it accompanies “organizational capability for manufacturing,” for example, problem finding/problem solving capability through teamwork (Fujimoto, 1997; Fujimoto et al., 2002; Thomke and Fujimoto, 2000). For example, there may be a big difference in “competitiveness of the back side” among companies, irrespective of the same CAD package being used. This is because electronic media and groups of people form a single design information system, such that both are closely interconnected at manufacturing fields (Genba).

2.2 Mutual Adaptation of Process, Architecture, IT, and Organizational Capability

2.2.1 Dynamic Mutual Adaptation

Product characteristics, development processes, and IT organizational capabilities for manufacturing tend to progress simultaneously in a mutually adaptive direction over a long period, even if they are not mutually adaptive in a short period. This mutual adaptation provides competitiveness, i.e., competitiveness on the front side (vitality of product) and competitiveness in the back side (vitality of manufacturing fields). For example, in Japanese companies, after World War II, there was a tendency in which “integrated organizational capability for manufacturing” based on teamwork of multi-skilled workers existed eccentrically because of historical reasons. The fitting design concept is “integral-type architecture” that requires complex mutual adjustments among design elements, and IT that supports teamwork under a cooperative environment is suitable. An easily fitting development process includes simultaneous engineering, which requires teamwork among departments or within a department, front loading, and co-location (Fujimoto and Tokyo University’s Manufacturing Management Research Center, 2007). These factors are mutually adaptive.

2.2.2 Integral-type Architecture and Integral-type Design Process

Design process and organizational configuration are related deeply with product architecture (Pine Ⅱ, 1993; Ulrich, 1995; Ulrich and Eppinger, 1995; Kogut and Bowman, 1995; Sanchez and Mahoney, 1996; Chesbrough and Kusunoki, 2001; Suh, 2001; Baldwin and Clark, 2002; Fujimoto, 2003).

In the case of integral-type architecture product development, a number of structural parts are newly designed to keep up with a functional element group requested by customers. A functional mutual dependence (achieving a function by cooperation of multiple parts), dysfunctional mutual dependence (interference by factors such as electromagnetic wave) and structural mutual dependence (such as mutual interference by part allocation) exist among these parts. Further, many mutual interferences are generated during the design process and are found to be ex post facto. Therefore, it is important to carefully verify beforehand the structural design of individual parts and the mutual dependence between parts. That is, for the design process of integral-type products, the structural design of individual parts and mutual adjustment between part designs tend to be emphasized. The mechanical design mentioned below tends to reflect characteristics of the integral-type design process.

However, in case of complex integral products, there is a fear that performing such new design of parts from scratch may require allocation of more man-hours for design. Then, some measures are adopted to reduce required man-hours.

For example, “compilation design” for part structure is available. In case of mechanical parts, the new design can often be corrected by adding a new demand level or constraint condition to an existing design. The compilation design is an indispensable tool for integral-type development although some malfunctions that suppress a new idea are shown.

Another method is “narrowing down functional requisites.” In this case, customers present only a functional requisite necessary for differentiation of products. Structure designers complement an unspecified “hidden functional requisite” while satisfying the functional requisites and then present the structural design to a customer. When it is approved by the customer, all the functional requisites are determined as ex post facto. That is, by virtually delaying the time required for determination of all the functional requisites, complexity is absorbed partially.

In the case of the integral-type architecture in which the entire product function depends on optimal design of groups of parts, “the adoption” of newly designed parts for each product, i.e., optimization process, is important. Therefore, in the search for an alternative design plan for the integral-type product, “adoption” of a new design plan rather than a search for any existing design plan is a characteristic of the design process.

Thus, as the organizational capability, “the integration force” and “the adjustment force” that perform mutual adjustment among part designs in real time are important. Then, development of CAD software, such as the mechanical system CAD, which emphasizes “optimization of new part design” is important.

2.2.3 Modular-type Architecture and distributed-type Design Process

Design of individual parts can progress independently even if a new part needs to be designed for improvement in the function because modular-type architecture has low functional and structural mutual dependence on individual structural elements (parts) required to configure a product. Consequently, large adjustment load for design parameters between parts is not applied. If a conventionally requested function is satisfactory, designed parts may be selected from internal or external existing parts lists (library) so that no new design for the part is produced.

In the design process for a new group of modular-type products, it is important to carefully envisage a highly expandable interface (design rule) that is difficult to deteriorate. Thus, there is a tendency that more man-hours in designing are allocated to establishing a preliminary framework than in integral-type products.

In the “modular-type architecture” product in which completed functional-type parts correspond to requested function of the product in a one-to-one relation, parts required for the product are selectively purchased from a catalog of already designed parts and combined together. That is, it is preferred to search for existing designed parts for alternative design plans. In other words, selection of designed parts or processes is important. In terms of organizational capability, planning ability to divide a target product to completed functional groups of parts or a “preliminary discerning ability” in selecting existing parts that have excellent properties is important. Then, development of CAD that emphasizes “selection of optimum existing designed parts” is important. For an electronic system, CAD that emphasizes arrangement of electronic parts database (library) has a strong feature of this type.

Assuming that the development process or suitable IT is different depending on the architectural characteristic of each product, it is necessary to consider a fitting property for each product. The architecture of each product is affected by the characteristics of market needs of the product (e.g., whether limited performance is required, whether a balance between functions is emphasized, and whether reduction of weight and size is important) or technical characteristics of the products.

2.2.4 Information Transfer Style: Batch Transfer or Sequential Transfer

Irrespective of the architecture, a transfer style for transferring design information to a medium (raw material) is an important product characteristic. For example, it is expected that a difference occurs in development or production between a “batch transfer style” of transferring design information in which a number of functions are performed in a batch (upper-stream step of semiconductor production, integral mold press) and a “sequential transfer style” of transferring design information in which discrete components divided by functional and structural elements are connected (printed circuit mounting process, automobile assembly process).

2.3 Key Research Question of This Paper: Comparative Analysis of Mechanical, Electronic, and Software Aspects

As described above, from the viewpoint of technical characteristics, architecture seems to be affected considerably depending on whether a target product is a “mechanical product” designed primarily in terms of mechanics, an “electronic product” designed primarily electronically, or a “software product” in which a function is achieved primarily by software read in by a computer. If other conditions are constant, the electronic design using printed circuits as its basis is expected to become a modular-type product through “a product design process which selects existing designed parts” and is based on the sequential transfer style using discrete parts. On the other hand, the mechanical design is expected to become an integral-type product through “a product design process introducing newly designed parts.” Although assembly of the mechanical parts is executed primarily by the sequential transfer style, the design of semiconductors is executed primarily by the batch transfer style of design information irrespective of the architecture.

From this viewpoint, in the case of a mechanical, electronic, and software complex product, all the aforementioned characteristics exist in a single product. Therefore, an integral component and a modular component as well as the sequential transfer style and batch transfer style are combined in one product. Needless to say, there is a high possibility that these different parts might be governed by different design logic, design concept, and development process characteristics; therefore, integrating and synchronizing development processes based on different logic is an important task for a corporation.

In conclusion, it can be said that in an environment in which mechanical products such as automobiles, digital equipment, and precision are becoming increasingly complex, effectively synchronizing development processes for mechanical, electronic, and software aspects along with IT and organizational capabilities has largely affected productivity, lead time, and design quality of new product development. However, there are few business administration studies that have approached this problem systematically. For example, with respect to IT, there are some studies conducted by authors in business field, such as by Araki (2005) on the mechanical system, Ueno (2005) on the electronic system, and Fujitsu and Japan’s Manufacturing Society (2007) on synchronizing mechanics, electronics, and software. However, academic analyses based on design logic and product development logic have recently started.

Table 1. Previous research classification

Design Process	Suh, 1990	Academic research
Architecture (design concept)	Ulrich, 1995; Aoshima and Takeishi, 2001; Fujimoto, 2001; Fine, 1998; Baldwin and Clark, 2000; Shintaku 2003, Shintaku, et al., 2004; Nobeoka, et al. 2006; Oshika and Fujimoto 2006; Nishimura, 2004;	Academic research
IT Tools that Support Development and Design	Thomke and Fujimoto, 2000; Ueno, 1995	Academic and Business research
Organizational Capability for Manufacturing	Fujimoto, 1997; Fujimoto, 2003; Fujimoto, 2004; Clark and Fujimoto, 1991	Academic research
Design process and organizational configuration	Pine II, 1993; Ulrich, 1995; Ulrich and Eppinger, 1995; Kogut and Bowman, 1995; Sanchez and Mohoney, 1996; Chesbrough and Kusunoki, 2001; Suh, 2001; Baldwin and Clark, 2002; Fujimoto, 2003	Academic research
Mutual Adaptation of Architecture, Design process, IT, and Organizational Capability	Fujimoto, 2003; Fujimoto, 2004; Fujimoto, 2006	Academic research
Comparative Analysis of Mechanical, Electronic, and Software Aspects	Araki, 2005; Ueno, 2005; Fujitsu and Japan's Manufacturing Society, 2007.	Business research

This paper will examine similarities and differences of the architectures and designing processes for the mechanical, electronic, and software system by studying fundamentals of design logic as a starting point of research on such complex products of mechanics, electronics, and software. In addition, it will use and analyze actual cases of automobiles and electronic products.

3. DESIGN CONCEPT AND DESIGN PROCESS OF MECHANICAL, ELECTRONIC, AND SOFTWARE ASPECTS

Here, characteristics of mechanical, electronic and software design are compared and analyzed.

3.1 Mechanical Design

As mentioned above, a mechanical product is the design of a group of parts required for achieving a specified function under physical constraints such as weight, volume, and strength.

Because the physical constraint tends to be different for each product, design of new parts in terms of their structures has been enhanced recently. In addition, design of appearance is often an important functional element. In particular, when a customer requests for some function and design performance is high, mechanical products are likely to have integral-type architecture.

Therefore, describing functions of a product logically alone cannot result in structural design of each part. That is, a logically assumed sequence from the completion of functional design to the transfer to structural design is hardly carried out completely.

For example, in case of automobiles, functional design is carried out by narrowing down key points to present a simple functional requisite, which is followed by detailed structural design. Then, a prototype is produced based on the detailed design, and functional verification is carried out to complement the functional design as ex post facto. At the initial basic design stage, an approximate structural design (layout) and a design sketch as well as design of the functional requisite are presented on an upper stream of development process so that the functional and structural design are likely to be combined. Further, in the case of mechanical design, parts having weight and volume are connected mechanically to maintain strength, avoid interference between parts, and exchange kinetic energy between the parts. Consequently, constraint conditions of structural design become very complicated. This tendency becomes particularly evident when high performance or reduction in size and weight is requested.

In addition, because the mechanical product often has dynamic cause-and-effect relationship between structure and function, it is easy to verify the function once the shape (structure) is completed. By presenting a structural design to a function designer or customers, hidden functional requisites may be proposed in the reverse order. That is, presentation of some of the requested functions may be delayed until the structural design is performed.

In summary, although the design is executed sequentially in the order of functional to structural design according to axiomatic design theory, the mechanical design has a feature where the functional and structural designs are overlapped and combined for executing the structural design in advance and then postponing the functional design. In particular, mechanical products, such as automobiles, which are functionally and structurally complex, have a remarkable tendency of this type.

In short, one characteristic of the mechanical design is placing an “emphasis on the structural design.” This is the reason why drawings are considered important in mechanical design and the structural design is penetrated into the functional design.

3.2 Electronic Design

In short, electronic design is the design of a control system. The functional design of a control system can be expressed with logic circuits. General-purpose logical devices such as AND, OR, and NOT are connected according to Boolean algebra to build an independent function or logic (Ogata, 1970, edited by Sawai). A relatively flat structural hierarchy (parts list) is likely to be produced because required functions are built directly from general-purpose logic devices or logic blocks (alphabet or words if expressed with language). Further, needless to say, at least a lower hierarchical level is likely to be of open/modular-type architecture because the required functions are configured with general-purpose logic devices. Physical design of general-purpose electronic parts or semiconductor needs to be arranged to correspond to logic devices and logic blocks. However, once a logic design (functional design) is completed, expansion to the physical design may be mostly achieved by repetition, enabling easy automation.

Therefore, in the case of electronic design, an emphasis is placed on the logical expression of a function requested by means of a circuit design. That is, functional design (circuit design) is emphasized more than structural design (layout design). Further, another characteristic seems to be that the sequential relationship “from functional design to structural design” is more evident in electronic design than in mechanical design. Thus, during the initial period of development, pressure to prepare functional design information completely may be stronger than that for the mechanical design.

3.3 Software Design

Software design in the complex products of mechanics, electronics, and software is usually the control software for controlling the mechanics, or is an artifact called “embedded software.” The control system of such an artifact is divided into electronic design and software design. A designer has the freedom to determine the division of the software into an electronic and a software range.

The software performs the same role as the electronics in the control system. However, in case of electronic design, “the sequential transfer style” (assembly type) is applied by selecting and inserting general-purpose parts into a PCB. In the case of semiconductors, the batch transfer style (processing type) is adopted by building transistors and circuits in a batch. This is a remarkable difference between the electronic and software design.

Control information possessed by software is expressed on a semiconductor. Thus, functional requisites must be provided completely as logic design information beforehand. This information is expressed using a compiler language, which is similar to natural language. That is, software is translated in the sequence of expression of functional symbol (language) to expression of logic design to physical design. Software design cannot delay the presentation of the functional requisites like the mechanical design. In this sense, software design is similar to electronic design in terms of being equipped with the functional design; however, it is quite different in terms of translation from the logic design to the physical design.

If the real-time request of an apparatus to be controlled is strict, interruptions are entered into a target software in a complex manner and the architecture of the software is likely to become an integral type. Further, there is a tendency, in which an application software described using an assembler rides over a CPU (semiconductor hardware), to produce a nonhierarchical structure. From this viewpoint as well, the software architecture is integral type.

If the functional request is not strict, the hierarchical structure takes the form of CPU→OS→application or the form of CPU→OS→middleware→application, and the software can be easily made modular. That is, the software architecture may be modular or integral depending on functional request. However, a product having a strict real-time request is more likely to be integral type.

3.4 Relationship between Functional and Structural Design

As mentioned above, the relationship between functional and structural design differ depending on the product architecture. In particular, in mechanical development, even if the definition of a requested function is incomplete, requested functions that do not involve structural design to a large extent can be defined in detail. However, such implementation is difficult in electronic design and even more difficult in software design. There may be a fundamental difference in the determination of mechanical, electronic, and software specifications. Here, relationships between the function and structure of mechanical, electronic, and software specifications are briefly explained in Table 1.

3.4.1 Mechanical Design

The functional design can be expressed using a numerical target value group by narrowing down key factors (specification) and using a natural language (such as unity of rider and horse). The structural design is expressed through drawings and CAD design information. The mechanical design indicates an actuator system of the side to be controlled, and a cause-and-effect relationship of structure→function is evident in regard to a relationship between the function and structure. A design process is primarily composed of the structural design and is implemented based on drawings. The functional design is supplemented ex post facto. Thus, the function may not be described completely as a target value.

3.4.2 Electronic Design

The functional design includes flow and circuit diagrams, which need to be described in detail. The structural design is a layout diagram of the physical design. Thus, the electronic design is on a control side and its control target is clear. Such a cause-and-effect relationship of function→structure is evident in regard to a relationship between the function and structure. A design process is mainly composed of the functional design, and the structural design is completed by selecting parts.

3.4.3 Software Design

Conventionally, the functional design of software primarily includes design information (typically, circuit diagrams) such as Program Analysis Diagram (PAD) and flow charts. The Unified Modeling Language (UML), which is a new expression method for standardizing model expression methods in object-oriented software designing, presents use case diagrams (diagrams that model a relationship between a user and a requested function), class diagrams (diagrams that model relationships among objects) and state transition diagrams (flow diagrams that model changes of state of a user).

Table 2. Comparison of Mechanical, Electronic, and Software Aspects

	Mechanical design	Electronic design	Software design
Functional design	Expressed with a numerical target value group (specifications) or natural language (such as unity of rider and horse)	Described completely using flow or circuit diagrams	Functional design is conventionally described using PAD or flow charts. UML presents use case diagrams, domain structural diagrams (hierarchy), and class diagrams (hierarchy)
Structural design	Drawings, CAD design information	Layout diagram of physical design	Structural design is expressed using source code.
Main body of control	Actuator system to be controlled	Control side and control target are naturally evident.	Control side and control target are naturally evident.
Main bodies of functional and structural designs	Determined primarily by structural design. Primarily based on drawings	Determined primarily by functional design	Determined primarily by functional design
Cause-and-effect relationship between function and structure	The cause-and-effect relationship of structure→function is evident. The functional design is complemented as ex post facto. The function may not be described completely as a target value.	The cause-and-effect relationship of function→structure is evident.	Translation from the functional design to the structural design is partially automated. For software engineering, requisite definition is a key factor. The structural design is automated.
IT tool for design support	M-CAD	E-CAD	Software development support tool

The structural design is considered as a source code. In any case, the software design is the design of a “control side” in the same manner as that of the electronic design, and thus, it needs to express in detail the relationship between input and output in a controlled target, i.e., functions. In the relationship between the functional and structural design, the functional design is the master while the structural design is the subordinate. Once details of the functional design are established, translation of the functional design to the structural design (source code) is partially automated. Therefore, in software engineering, it is important to define a functional requisite that carries out the functional design in detail. In addition, from this viewpoint, it can be inferred that software engineering is in contrast with mechanical design that requires the structural design to be determined in detail.

The above table summarizes the relationship between mechanical, electronic, and software designs, functional design, and structural design. Fig. 2 shows the design process of a product with respect to its mechanical, electronic, and software aspects according to the stream of function→structure→production by using a flow chart.

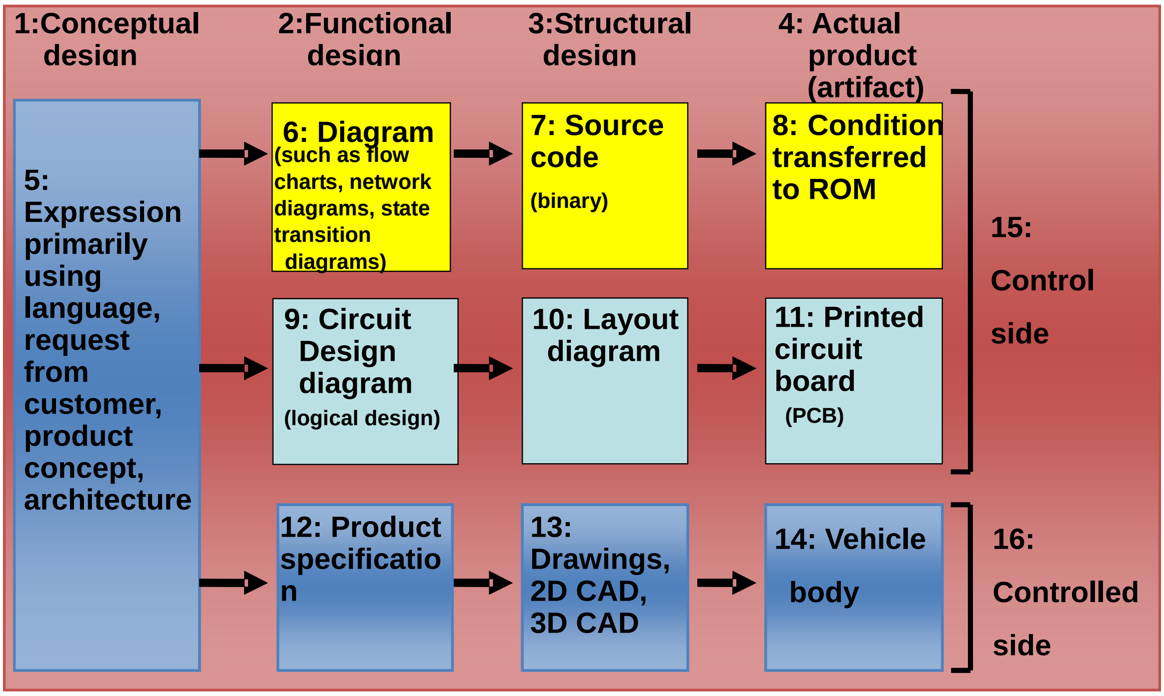

FIGURE 2. Relationship between Design Process of Product and Mechanical, Electronic, and Software Aspects

4. CASE ANALYSIS

Next, the relationship between the mechanical, electronic, and software aspects and the product architecture is discussed. Here, automobile and electronics products, which are assumed to have different architectures, will be compared. To compare Automobile with Eletronics, in-depth case studies were conducted with senior executives including CEOs and product development managers and IT managers through our research network during several years. We have interviewed and discussed about complexity problem. Data collection also involved interviews, informal documents and open archival records (newspaper reports and corporate presentations). Collected data are classified according to our research framework and we compared our research framework with case details.

4.1 Trend of Using IT for Product Development in the Automobile and Electronics Industry

First, the trend of using IT for product development (primarily CAD, CAM, CAE) for the automobile and electronics industry in Japan will be described (Park, et al., 2007). Regarding the automobile industry in Japan, its product development and production capacity depend largely on suppliers, and active participation of the suppliers in the development process produces high competitive performance (Clark and Fujimoto, 1991). Automobiles do not allow easy mutual adjustment between designs of individual parts because of severe restrictions on the layout. For example, one of the biggest problems in development of automobiles is interference between parts, which comprises about 70% of design modification problems in product development (Gu and Fujimoto 2000). To solve this problem in the automobile industry, 3-D CAD systems are installed on the development site as well as in IT, thereby realizing front loading of QCD and concurrent engineering (Thomke and Fujimoto, 2000). As a result, automobile manufacturers of Japan have succeeded in reducing the lead time of the development of new cars from 30 to 20 months (Ueno, 2005). On the other hand, an automobile is a complex product consisting of over 20,000 parts and requiring high product integration. Thus, coordination between assembly manufacturers and suppliers is extremely important (Clark and Fujimoto, 1991). In particular, the ratio of electric and electronic parts has increased because of digitalization in recent years, resulting in increased necessity of the 3-D CAD for effective product development. Thus, the degree of integrality of 3-D CAD between assembly manufacturers and suppliers is very high. With regard to the CAD specifications of the three major manufacturers, Toyota has introduced CATIA-V5 separating from TOGO-CAD, which was developed internally, and its engine department uses Pro-ENGINEER. Although NISSAN adopted I-DEAS of SDRC in 1995, it has been using UGS’s NX since 2005. In contrast to other automobile manufacturers, HONDA has used CATIA since the beginning without developing its own system internally. However, these assembly manufacturers have not only introduced their own system but have also forced suppliers to integrate the suppliers' systems with their system. For example, in recent years, most design and drawing modification information of automobile manufacturers have been exchanged with suppliers in the form of 3-D CAD data. Hence, unless suppliers have 3-D CAD compatible with the automobile manufacturers, they often cannot participate in any development competition. Thus, such manufacturers of parts have no option but to introduce a 3-D CAD system compatible with the automobile manufacturers to maintain business relationships with them (Gu, 2003). Thus, introduction of the 3-D CAD system from parts manufacturers tends to be an introduction for satisfying the basic factors of a transaction, i.e., the tendency of passive introduction is high. Consequently, some people assert that the functions of the 3-D CAD system have not been utilized strategically enough.

On the other hand, product life cycles (PLCs) in electronics industry are extremely short. Consequently, a reduction of the delivery time is strictly demanded. For example, PLCs of mobile phones and digital cameras of Casio Computer as of May 2006 are 4 and 6 months respectively (Toriya, 2006). Further, in the electronics industry, technological innovations of parts and installation technology are remarkable and individual projects have small size. Thus, initially, the electronics industry's attitude was negative towards approaching such process-oriented manufacturing. The use of CAD system for electronics products has not progressed much because this industry deals with typical modular products and PLC is extremely short. However, to maintain innovation in product development, which has increasingly advanced, the focus has shifted from an aspect of controlling actual products to that of controlling information, and the introduction of 3-D CAD has improved (Ueno, 2005). Electronic products are mostly constructed of general-purpose parts, and electronic manufacturers and parts suppliers tend to not use the same CAD system for the product designing process. The electronics parts industry has no hierarchical pyramid between assembly manufacturers and suppliers unlike that in the automobile industry. In the case of mobile phone products, some Japanese mobile phone manufacturers occasionally coordinate their system to meet the requirements of the CAD system of parts manufacturers so that Chinese parts manufacturers can supply parts that incorporate the change from conventional 2-G closed integral type to 3-G open modular type. Semiconductor products and electronic parts except for custom-made products can be obtained and printed circuit board design and manufacturing can be outsourced to many suppliers. This indicates that no specific supplier or gigantic production equipment will be required to develop electronic products. For this reason, the entry barrier is so low that many companies are engaged in the development of electronic products unlike that in the automobile industry. Because of such industrial characteristics, in the electronics industry, where no hierarchical pyramidal relationship exists as that in the automobile industry, the manner in which a company manufactures its products to differentiate itself from other companies by sharing information and process effectively with suppliers and partners is an important issue (Ueno, 2005). As mentioned above, the characteristics of architectures for automobiles and electronics products are different, and, consequently, the methods of using CAD are considered different. Fujimoto (2006) described a relationship between the product architecture and CAD stating that in contrast to decentralized product development of modular-type architecture of home electrical appliances and electronics products, the integral-type architecture of automobile industry needs CAD and CAE that allow centralized product development.

Table 3. Comparison between Automobile and Home Appliance Industry

Sector	Automobile industry	Home appliance industry
Relative domestic competitiveness	High	Low
Generation of added value	High	Low
Quantity of parts	Over 20,000 parts	Around 1,000 parts
Ratio between exclusive and common parts	Mainly, exclusive parts (special parts)	Mainly, general-purpose parts (common parts)
Development period	Long (24 months)	Short (12 months)
Manufacturing period	About 2 years	Less than a year
Quantity of production (per model)	Relatively large	Relatively small
Product Life Cycle (PLC)	Long	Short

4.2 Comparison of Mechanical, Electronic, and Software Controls in Automobile and Electronic Products

4.2.1 Automobile

In the case of an automobile, which is a typical integral product, although its structural design follows the entire functional design in the first step of product design, the functional and structural design not only picture a sequence of processes because an automobile is a product in which visual design is emphasized, but also sometimes determine their product function in a reverse order at a stage in which the structural design has started. The mechanical parts of automobiles are conventionally emphasized more than their electronic parts. The electronic parts and software embedded in those electronic parts follow the mechanical parts. However, as application of electronics has progressed rapidly in recent years, the quantity of electronic parts, such as ECU, has increased so rapidly that the importance of the electronic parts and the influences of the embedded software have greatly increased. For example, the number of source codes of the car navigation system, which is emphasized most in automobile electronics parts, has increased up to 5 million lines. This number is higher than the source codes of a unit electronic product. Because the automobile industry has no option but to adopt diversified electronics parts as well as the car navigation system, the importance of software is expected to increase. In particular, rather than adapting to conventional internal combustion engines, adapting to the control software in hybrid vehicle (HV), electric vehicle (EV), and smart vehicle (SV) might be a key factor for superiority in the competition of corporations.

It can be inferred that Toyota’s recent recall problem is deeply related to complexity of the products. With regard to this problem, Mr. Akio Toyoda, President of Toyota Motor Corporation, and the directors of Toyota participated in a public hearing of the US Congress, apologized to customers, and promised thorough countermeasures concerning the quality problem. However, a fundamental cause of this recall problem can be assumed to be closely related to the automobile production process that has become increasingly complex. While the automobile production process has become complex in the global market, the automobile manufacturers’ production systems are not able to follow quality controls. Japanese automobile manufacturers cannot compete in the global market by depending only on Japanese suppliers and may use diversified global suppliers. Although all problems concerning controls of conventional gasoline vehicles can be cleared by testing mechanical designs, the degree of complexity in HVs cannot be grasped sufficiently. Therefore, possible problems originating from foreign country suppliers remain unverified. Till now, in the global automobile business, Toyota is a front runner in the technology for producing complex products. In addition, Toyota has succeeded in responding to global market needs by continuing to develop deluxe vehicles and vehicles requiring complex design for environmental protection. In advanced countries, social restrictions on vehicles may become stricter in future. In particular, software for control has become intensely complex. Thus, automobile manufacturers who have entered markets of advanced countries are currently loaded with increasing demands for design, production, and quality control. Although Toyota has maintained its front-runner position in such a “product complexity” race because of excellent correspondence ability at its actual site, it faces greater risk than its rival companies because of its dependence on complex products. Toyota’s strengths were changed to its weaknesses. In Toyota’s case, there is no sign indicating that its design and capabilities at its actual manufacturing fields have deteriorated. However, as mentioned above, the load of design-related work may increase in future. It is inferred that the reason for the excessive load relating to design, production, and quality control in these years is the shortage of manpower, particularly in the field of quality control. This problem is not particular to Toyota alone, but is a problem which the entire automobile industry of the 21st century has faced.

The same problem occurred in B Company which was interviewed by these authors at a test stage prior to sale. This problem did not occur for suppliers who developed parts by cooperating with companies with which they had a long-term trusted relationship during the period in which automobile manufacturers such as Toyota expanded in the global market. However, this problem occurred when suppliers in foreign countries were employed to conduct business in those countries because of globalization. Most of these problems may be related to control software. A manager of B Company mentioned that “Only managers with experience in mechanical design lead a development organization. Although he instructs workers about development by considering mechanical, electronic, and software aspects during a product-development period, they don’t know control software at all.”

4.2.2 Electronic Products

In contrast to automobiles, in the case of electronic products, electronic parts lead the entire product design and the importance of electronic parts is higher than mechanical parts such as design parts. In particular, as small products with diversified functions have increased in recent years, the importance of electronic parts has become greater than the mechanical parts.

Consequently, the importance of embedded software for controlling the electronic parts has greatly increased. The source code contains 10 million lines for a mobile phone called FOMA of NTT Docomo, 6 million lines for a DVD player, and 4 million lines for a Flat panel TV. These are specific examples concerning the importance of software. When considering design cost, software occupies 60% for the DVD recorder and 80% for the mobile phone (Fujitsu Japan's Manufacturing Society, 2007). As a result, in the case of electronic products, the effectiveness of the software design will automatically determine its competitive superiority.

However, in the case of electronic products, as attraction to product differentiation because of matured market has intensified recently, reductions in size and consumption energy, and design performance as well as importance of electronic parts become important and mechanical design is emphasized. The reason for the reduction in size and consumption voltage for energy saving is that the parts must be arranged at high density in a small space, thereby creating noise and heat generation problems and increasing the difficulty of mechanical design. From a strategy of emphasizing high-quality feel and visual quality in design, the external material has changed from plastic to magnesium alloy or from aluminum to titan alloy, and there is demand for innovation of conventional mechanical design rule (Fujitsu and Japan's Manufacturing Society, 2007). Such a trend is noticeable in products in which reduction of size is a key differentiating factor.

Table 4. Product Type and Importance of Mechanical, Electronic, and Software Aspects

Product	Importance of mechanical, electronic, and software aspects
Automobile (integral product)	Mechanics > Electronics > Software
Electronic products (modular product)	Mechanics < Electronics < Software

5. IMPLICATION: WORKING HYPOTHESES

This paper has analyzed sources of complexity in the design and development processes of complex products of mechanics, electronics, and software and has searched for more effective processes. By focusing attention on IT (digital information technology) for design and development assistance, which seems indispensable in reducing product development lead time in contemporary corporations, this paper has confirmed that design logic differs among mechanical, electronic, and software systems.

Then, by placing emphasis on the comparison of IT tools that support development for an electronic and mechanical system and the comparison of the development process for automobiles and electronic products, this paper has searched for directions of the artifact design, which has become complex, to find out how the design process, architecture, IT, and organizational capability will progress simultaneously. In case of automobile, in recent years, electronic control systems are used rather than a controlled system, thereby generating interaction and tension among the mechanical, electronic, and software designs and accelerating a tendency of complexity in product development.

In particular, this paper has insisted that a difference in design philosophy result in difficulty in integrating structural and functional designs because functional design is emphasized in designing electronic and software systems which are control systems, while structural design is emphasized in designing mechanical systems which are controlled systems. Furthermore, this paper has asserted that when the product design is considered as a symbolic system which represents an artifact, differences in selected symbol systems and translation timings exist between the mechanical and electronic system. In addition, it showed that when these designs are carried out concurrently, a difference in the timing of information exchange occurs.

However, this paper provides a beginning for research in the design of artifacts that have become increasingly complex. Therefore, this paper is exploratory and tries to establish hypotheses. Although this research is still preliminary and has many issues that need further research, we present the following provisional conclusions and countermeasures with respect to complexity of the artifacts in the automobile and electronics product sectors that can be used by corporations.

5.1 Comparison of Products in terms of Complexity and Sophistication of Functions

- If the function required by customers or social constraint condition (such as environment and safety countermeasure) is sophisticated and complex, products that are artifacts tend to be functionally complex. Automobiles belong to such a product category.
- Some products cope with such functional complexity and sophistication through large scale modularization of products. For example, PC belongs to such a

product category.

- However, as the requested function and constraint condition become stricter, modularization becomes difficult and products definitely become integral and complex. To allow such artifacts to function properly, the development of electronic control system is indispensable. Automobiles belong to such a product category.
- To meet demands for more complex and sophisticated functions, as in some types of home electronic products, control and controlled system of artifacts have been converted from mechanical system to electronic and software systems. Further, their entire structure is digitized to reduce the complexity of development (for example, elimination of rotary parts). Thus, the demands for such functions can be met. For example, an IC recorder and digital MFP (Multi-Function Printer/Product/Peripheral) belong to this category.

5.2 Comparison of Products in terms of Mechanical, Electronic, and Software Aspects

- In some products, primarily for a controlled system, a number of mechanical parts are left as conventional for technical and physical reasons. As a result, simultaneous progress of mechanical parts and electronic/software parts are accelerated. Automobiles belong to such a category.
- As a result, automobiles tend to simultaneously have sophistication in the design of the mechanics which is a controlled system and in the design of electronic and software aspects which are control systems. However, the sophistications in the designs of mechanical, electronic, and software aspects do not always occur in a mutually cooperative manner.
- Because of functional and historical reasons, these three design systems are likely to have different design philosophies regarding the functional or structural design-centered, selection of a symbol system, and the method of translation between symbols. These factors tend to advance separately.
- In the case of automobiles, a power relationship of mechanics > electronics > software is still observed from a historical reason in which automobiles are artifacts considered as controlled systems. However, another power relationship of mechanics < electronics < software is observed in electronic products.

- To accelerate integration of the mechanical, electronic, and software designs for artifacts which have become increasingly complex against the aforementioned tendency towards separation, efforts for integration in the upper stream of development are extremely important. Such efforts include describing the artifact more accurately using natural language based on sources of design activity and searching for a new IT which enhances teamwork design involving mechanical, electronic, and software designers in the upper stream of development.

5.3 Construction of Coordination Ability in New Dimensional World

We expect that consumer needs will become more sophisticated and a tendency towards stricter environment, energy, and safety constraint conditions will continue in future. Thus, the corresponding complexity of the artifact should be considered as a long-term trend. To meet this trend, it is necessary to conduct various countermeasures, such as front loading by using development assistant IT (3-D CAD, CAM, CAE) and quality control engineering, upgrading electronic control system (particularly software), modularity of product architecture and standardization of parts, and construction of organizational capability for team development. Even though there are few business administration studies that have approached complexity problem systematically, academic analyses based on design logic and product development logic have recently started. In particular, we did case study comparing cases of automobiles and electronic products. In this meaning, our study is unique and provides clues for industrial benchmarking study in the future based on design information.

We have just started research for a synthetic solution to this problem. However, it can be expected at least currently that companies which that mistakes in addressing this problem may face many difficulties. This paper is a thesis that offers clues on the long-term issues concerning the design process of artifacts or manufacturing of products.

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