論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Dynamics of Product Design for Creating Market Value
著者(和文)	徳永達哉
Author(English)	Tatsuya Tokunaga
出典(和文)	学位:博士（技術経営）, 学位授与機関:東京工業大学, 報告番号:甲第12607号, 授与年月日:2023年9月22日, 学位の種別:課程博士, 審査員:齊藤 滋規,辻本 将晴,中丸 麻由子,因幡 和晃,杉原 太郎,藤村 修三
Citation(English)	Degree:Doctor (Management of Technology), Conferring organization: Tokyo Institute of Technology, Report number:甲第12607号, Conferred date:2023/9/22, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

Dynamics of Product Design for Creating Market Value

Tatsuya Tokunaga[1,2]

[tatsuya.tokunaga@gmail.com]

[1]Department of Innovation Science, School of Environment and Society,

Tokyo Institute of Technology, Japan

[2]Mitsui Chemicals, Inc.

Abstract

In this doctorial thesis, we propose a theory to determine a direction of product designing for increasing the market value. One of the most important research goals in business management is to clarify causal relationship between product design and market success. Although there have been countless academic studies on this issue, to study product design, technology and the market consistently still remains an academic challenge. We propose a theoretically consistent formulation to determine design directions in product design in order to realize the highest market value, namely innovation. The key is to define the dynamic impacts of design flexibility and technology advance on product design. As a basic idea, we generally define conceptual structure of design process as actual design, function design and modularity design. We first identify dynamics of product design through modularity matrix, which is defined as a set of permissible ranges for both functional requirements and constraints, and it is an extended theory of design structure matrix (DSM) and axiomatic design (AD) through hierarchy of constraints. Next, we introduce a product value represented by the "entropy of design" for product design to be realized by satisfying both functional requirements and constraints with an impact of technology advance as a new parameter to regularize the modularity matrix by using an analogy of statistical mechanics in physics and information theory. We show that two limits of the entropy of design are logically equivalent to the modularizations on real option theory in DSM and information axiom in AD. Furthermore, we connect the entropy of design to the market using "seeds translation matrix" to map functional requirements in product design to customer needs in the market; thus, the entropy of design can be identified as a kind of utility function in economics in the market. Theoretically, it can be shown that a modular system is more flexible for technology advance to cover a variety of product designs that satisfy the expected market value over other modularity systems. The

theory highlights the importance of managing modularity and technology advance separately while at the same time understanding the market coverage of product designs, which will be a prediction for future innovations by simulation, in order to avoid a risk of sudden business failures in the future, inspired by the disruptive innovation.

要旨（Abstract in Japanese）

本研究では、市場価値を最大化する、つまり、イノベーションを実現するための製品設計の方向性を示す理論を構築する。まず、基礎的な一般論として、デザインプロセスのコンセプト構造を定義する。設計構造行列(Design Structure Matrix)と公理的設計(Axiomatic Design)の拡張として、設計・部材・市場などの基底空間から、機能要求と制約条件への写像を用いて、機能要求と制約条件の両方を満たして実現される製品設計の許容範囲を行列要素として持つ、モジュラー行列を新しく定義する。統計力学や情報理論のアナロジーから、製品設計のモジュラー行列に対する製品価値として、デザインエントロピー(entropy of design)を導入する。ランカスター消費技術行列を拡張して用いて、製品価値（デザインエントロピー）を市場価値である効用関数へ写像することによって、テクノロジーの寄与も考慮された形で、理論的に、市場価値を最大化する製品設計の方向性を決定することができ、研究開発の方向性や破壊的イノベーションのメカニズムが示される。

Table of contents

1. Introduction
2. Literature Reviews
   - Design Structure Matrix (DSM)
   - Axiomatic Design (AD)
   - Hierarchy of Constraints
3. Concept Structure of Design
4. New Definition of Modularity Matrix in Product Design
5. Product Value as Entropy of Design for Modularity Matrix
6. Entropy of Design as Shannon Entropy in Product Design
7. Applications of Entropy of Design to Product Design
8. Entropy of Design and Utility Function as Market Value
9. Conclusions and Future Work

Acknowledgements

References

Appendix A. Derivative of Modularity Matrix

Appendix B. Mathematical Description of Modularity Matrix

Appendix C. Short Review of Statistical Mechanics

Main Symbols (Notations)

DSM Design Structure Matrix

AD Axiomatic Design

FR Functional Requirements

DP Design Parameters

PC Physical Components

CN Customer Needs or Customer Attributes

$i,j,k,...$ labels of base vector space coordinates such as design parameters

n number of modules or base vector space coordinates

X_i design parameter (DP) coordinates

dX_i small transformations of DP

Y_i physical component (PC) coordinates

f_i functional requirement (FR)

df_i small transformations of FR

C_i constraints

Kf diagonal matrix $Kf_{km} = diag(\alpha_1, \alpha_2, ..., \alpha_n)$

α_i permissible ranges of functional requirement (f_i)

Ai, Bi maximum or minimum of α_i

[○,●] permissible ranges between ○ and ●

Kc diagonal matrix $Kc_{ij} = diag(\gamma_1, \gamma_2, ..., \gamma_n)$

γ_i permissible ranges of constraints (C_i)

Pi, Qi maximum or minimum of γ_i

T new parameter to modify modularity matrix, related to technology advance

G modularity matrix

Gf modularity matrix for functional requirements

Gc modularity matrix for constraints

Gd modularity matrix for functional requirements on DP

Gp modularity matrix for functional requirements on PC

$\cap$ intersection for sets

$\supset$ inclusion for sets

S entropy of design

$n_i(f_k)$ customer needs (CN) as a function of FR

$\{\cdot\}$ a set

Z_i coordinates of firms and sectors such as company names and brands

$\Phi 1_{ij}$ a mapping of DP→PC

$\Phi 2_{ij}$ a mapping of PC→FS

$\theta(\cdot)$ step function

P_A , P_B : probability distribution

1 Introduction

In this doctorial thesis, we propose a theory to determine a direction of product designing for increasing the market value. Historically, many researchers in economics, marketing, and product design have sought to clarify the relationship between product design/development and customer needs/attributes in order to realize maximum product value in the market. Arthur (2009) emphasized the importance of technology as "*More than anything else, technology creates our world,*" and Ulrich (2011) described in his essay that *"product design is conceiving and giving form to goods and services that address needs.*" Terwiesch and Ulrich (2009) defined innovation as "*a new match between a need and a solution."* Thus, the roles of product design and technology are very important to realize innovation in the market.

Although in many research articles on business field, the structure of the products which are identified in the market has been discussed as design, it is only a result after designing and manufacturing the products. Here, we define "design" as a behavior to consider, and it is a result to formalize realization methods for functional requirements of the planned products. As the most important point, we define product design as trying to realize an unknown system by its structural dynamics. Namely, "designing" is an action to be done before realizing the product, not to be identified after existing in the market. In Christensen (1997)'s book, *"Markets that do not exist cannot be analyzed: Suppliers and customers must discover them together. Not only are the market applications for disruptive technologies unknown at the time of their development, they are unknowable. The strategies and plans that managers formulate for confronting disruptive technological change, therefore, should be plan for learning and discovery rather than plans for execution."* Thus, we can not know the market exactly before realizing the product. Product design is a set for information to realize the product that a designer has created even in his/her brain, and the product design must include uncertainty to realize the product and to satisfy customer needs in the market. In this doctorial thesis, we will deeply study the designing before realizing the product.

In product design, the functional requirements, such as product architecture, are critical to the development process as products because products are always designed to satisfy functional requirements (Ulrich, 1995; Eppinger and Ulrich, 1995). The modularity of product architecture has been explored as a useful method to classify designs, products, and industries by introducing modularity matrices on base vector spaces, such as design parameters, organizations, functional requirements, physical components, and products (e.g., Eppinger and Browning, 2012). The modularity matrix has been mainly defined in two ways. The first definition includes the concept of “Design Structure Matrix” (DSM), which was devised by Steward (1981), developed by Eppinger (1991), and formulated by Baldwin and Clark (2000) in order to analyze and manage complex systems, and applied to many case studies (e.g., Browning, 2001; Eppinger and Browning, 2012; Browning, 2016). DSM is a mapping between the same base vector space to visualize the structures of design systems. Interactions within a DSM signify the transfer of material, energy, and information, which are defined in abstract terms and remain beyond the reach of facile mathematical definitions. We find many applications of DSM, for examples product, organization and process architectures in the reviews (Browning, 2001, Eppinger and Browning, 2012). Recent studies have analyzed the relationships among DSMs across different base vector spaces, which are referred to as domain mapping matrices (DMMs) and multiple domain matrices (MDM) (Jacobides and Winter 2005; Danilovic and Browning 2007; Baldwin, 2008, Lindemann et al., 2009; Luo et al., 2009).

The second definition was formulated by Ulrich (1995) to highlight a shift in emphasis from mapping functional requirements to physical components, theoretically systematized by Suh

(2001) as a general framework to analyze the interplay between different vector spaces, called "Axiomatic Design theory" (AD), and applied to many case studies such as Krishnan and Ulrich (2001). Interaction in AD is defined by a mathematical approach to the mapping of the physical components and functional requirements in order to optimize product design. We find many applications of AD, for examples product, software, supply chain, manufacturing systems in the reviews (Krishnan et.al., 2001, Kulak et.al., 2010).

Although these two theories (DSM and AD) have been developed independently towards almost the same goal, a crucial problem is that the relationship of DSM and AD, as well as the differences of their models, largely remains unclear, despite that Dong and Whitney (2001) and Tang et al. (2009) have addressed the topic. One objective of this doctorial thesis is to clarify equivalence of the modularity matrices of DSM and AD and the applicable ranges of these theories. Since DSM is defined to improve only the existing product design and not clear to relate with the functional requirements in product designing, and AD does not express interactions in design space, both DSM and AD are methods to describe a static product design for a fixed set of functional requirements and do not contribute to the dynamic designing process before realizing a product. In this doctorial thesis, we will define the modularity matrix for product design beyond DSM and AD to explicitly show the dynamic designing process in section 4, which can express flexibility of the product design for changes of functional requirements.

Another objective tackled in this doctorial thesis is how constraints can change modularity. Previous studies on the modularity theory often neglect the topic of constraints for products. In DSM, constraints must implicitly be imposed to realize products; in AD, constraints cannot be systematically included within the theory. In fact, three types of constraints—physical, equipment, and operational constraints—are essential for the technological realization of products (Fujimura, 2000). We will construct a modularity matrix for constraints as well as functional requirements, which is useful for the study of how constraints contribute to modularity, and clarify the hierarchy of product design.

Next, we must clarify a meaning of "value" in product design and in the market. Baldwin and Clark (2000) proposed *"designers see and seek value in new designs"* as one axiom and emphasized the importance to clarify the meaning of "value" in product design; "*Finally, a designer must be able to weigh potential changes in structure and function, adjust for uncertainty (the fact that the structural changes may not have the desired effect), and decide whether a new design is worth trying or not. In other words, the designer must have mental concepts of value and of value changes. The designer's concept of value may be primitive (it works or it doesn't) or refined (market prices, option values), but some concept of value must be in the designer's head, to provide a guide for action (the new design is worth trying or isn't).*

The labor of design is thus a complex mental effort that relies on both imagination and intent. The designer must first associate changes in the structure of the artifact (the design parameters) with changes in its functions (what it will do). Then the predicted changes in function must be projected onto a change in "value". The change in value must in turn be compared to the effort of implementing the changes in the design (including the cost of producing and marketing the new artifact). If the result is positive, the designer will have a reason to go ahead and try the new design."

In the same textbook, Baldwin and Clark (2000) presented an important challenge as a research question to be addressed in the future work: *"By providing meaningful aggregate unit of valuation (the company), contract structure design rules economize on the use of market valuation technologies."*

In this doctorial thesis, we will introduce a product value represented by Fermi-Dirac entropy for the modularity matrix (here, "entropy of design") to realize the highest value of a product, based on Tokunaga and Fujimura (2016). It will be shown that the entropy of design means the number of product designs that satisfy functional requirements and constraints in analogy with statistical mechanics in physics. Also, the entropy of design is logically equivalent to the real option theory of DSM proposed by Baldwin and Clark (2000), and the information axiom of AD systemized by Suh (2001). Also, we will define a change of product design to be impacted by technology advances (Ulrich and Ellison, 1999), such as a new process technology.

Also, Baldwin and Clark (2000) defined the "value of design" as follows; "*The precise definitions of gain and loss that arise when a new design is introduced into a society. Consider the following thought experiment, well known in welfare economics: When an artifact with a new design is introduced, consumers will be polled on their willingness to pay for it. The sum of the amounts revealed at the time less production costs we define to be the 'value' of the new design.*" Thus, the value of design that Baldwin and Clark (2000) defined is a gain introduced by the product that the customers would like to pay for in the market. The "value of design" can be represented by mapping into the market through the product, and the product can cover a somewhat specific area, not one point, in the market space, which is indicated by the market value.

In economics, the utility functions of goods, or probabilities, have been studied in order to realize maximum value in the market by mapping market information and value/preference in the market (Fishburn, 1960; Barberà et al., 2004). Lancaster (1966) tried to connect goods in the market and the characteristics of goods by introducing Lancaster's consumption technology matrix as a method to map the relationship between goods and characteristics, and defined the utility function as a function of the characteristics.

In marketing, several marketing research methods have been used to identify the information necessary product design information from market information (Green et al., 1981; Hauser et al., 2006). In particular, conjoint analysis is one well-known market research method to find trade-offs of experimental product designs for consumers in the market (Green et al., 1978, 1981, 1990). Quality Function Development (QFD) is another established method used to translate customer needs (equally, Voice of Customer) to design attributes (Akao, 1972; Urban and Hauser, 1980; Hauser and Clausing, 1988). Hauser et al. (2006) proposed a research challenge for marketing science: *"importantly, the dynamics of customer demand for alternative product features and the heterogeneity of customer preferences as they relate to customer segments may have the potential to provide a fundamental theory to understand the interaction of technology and customer response.*"

One main purpose of clarifying product design for creating market value is to manage product design with technology advances that can support continuous success of business and innovation. Technology advance may make unexpectedly discontinuous product development (also business development) beyond existing successful firms, called "disruptive innovation" (Christensen, 1997). The Bell labs and Xerox's Palo Alto Research Center (PARC) lost continuous contributions to business success beyond the trend of the times because they could not manage research (long-term) & development (short-term) simultaneously in product development, even though they had many talented researchers to create great results along the existing technology (Buderi, 2000).

Thus, there remains the important challenge of relating product design, such as functional requirement and constraints with the permissible ranges, the modularity and technology advance, and customer needs/attributes in order to consistently maximize market value such as the utility function. Figure 1.1 outlines this doctorial thesis's step-wise procedure for theoretically solving this problem.

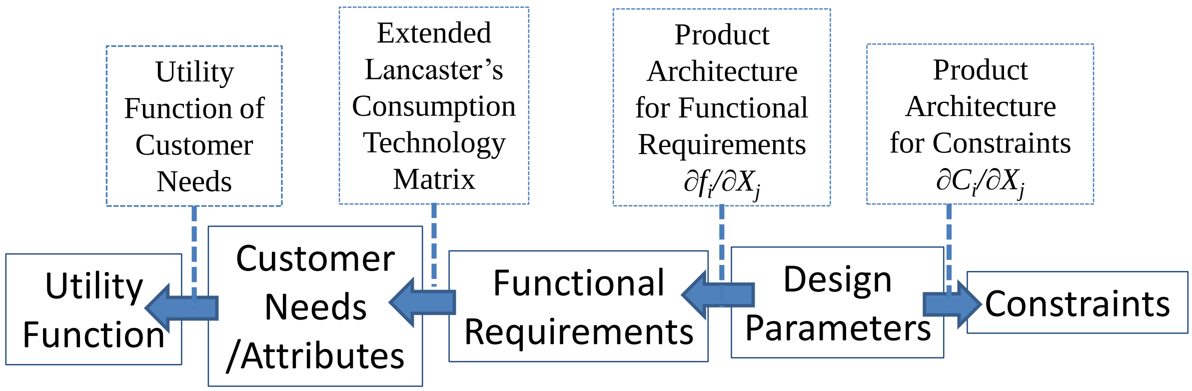

Figure 1.1: Step-wise mappings between utility function and product design

Blumrich (1970) proposed three phases in the design process. The first phase "*begins with an idea and ends with concepts; it brings into existence something which had not existed before and is therefore taking place in the border area between imagination and reality*." The second phase was described as "*between conceiving a structure and its final documentation*", "*the phase in which the structure is developed and given form*" and "*highly dynamic, permits an almost playful weighing of possibilities and alternatives, and, to an ever-increasing extent, demands clarification of all influences affecting the structure*". The third phase "*requires complete adjustment of the emerging structure to available technologies, and the methods of fabrication*". A theoretically consistent formulation using the step-wise process in Figure 1.1 will concretely express the second phase of the design process by Blumrich (1970) in section 7.

In Section 2, we review Design Structure Matrix (DSM), Axiomatic Design (AD) and hierarchy of constraints. As a methodology for theoretical study, in Section 3 we define the "concept structure of design" as basic idea. In Section 4, we introduce the relationship among functional requirements, design parameters, and constraints through the modularity matrix as an extended theory of DSM and AD, based on Tokunaga and Fujimura (2016). In Section 5, we propose useful connotations of a product value represented by the entropy of design for modularity matrix as Fermi-Dirac entropy with the impact of technology advances, and also, in Section 6, we interpret the entropy of design as one kind of Shannon entropy from the perspective of information theory. We study some applications for the entropy of design in product design in Section 7. In Section 8 we introduce "seeds translation matrix" to relate functional requirements in product design and customer needs/attributes in the market, and we show that the entropy of design can be identified as a utility function in the market. Then, we propose a new and consistent relationship between utility function of customer needs/attributes in the market and product design through entropy of design, which, in the product design process, determines the directions of product design that realizes the highest value in the market in a phase of technology even in any modularity case. Section 9 includes conclusions and future work.

This doctorial thesis consists of the research results in the full paper (Tokunaga and Fujimura, 2016), proceedings of DSM conferences (Tokunaga and Fujimura, 2013 and 2015), proceedings of International Conference on Creativity and Innovation (Tokunaga and Fujimura, 2018), proceedings or transactions of conferences in Japan; Japan Society of Mechanical Engineers (Tokunaga and Fujimura, 2013), the Academic Association for Organizational Science (Tokunaga and Fujimura, 2014 and 2017) and Japan Creativity Society (Tokunaga and Fujimura, 2017).

2 Literature reviews

In this section, we briefly review Design Structure Matrix (DSM), Axiomatic Design (AD) and hierarchy of constraints.

The first item for review is DSM. Historically, Steward (1981) developed the fundamental theory of DSM, and Eppinger (1991) applied DSM to concrete cases of product design as task-based DSM. By use of DSM, which provides the mappings of the same vector space as the design parameters (DP) in Figure 2.1 as an example of DSM, we can visualize the structures of systems for product design. In Figure 2.1, four sequence design tasks are labeled by alphabets, and a mark in a matrix means that executing a task requires information to be transferred from another task. In the left matrix of Figure 2.1, we find that the marks in the matrix are complicated, not in sequence, which needs many exchanges among tasks. In the right matrix of Figure 2.1, we see that the order of tasks labeled by alphabets such as B and D changes the structure of matrix to be a sequence of design tasks as the lower triangle of the matrix. Thus, DSM can be used for optimizing the design tasks in sequence. Generally, matrix elements of DSM express the transfers of material, energy, and information among base vector space coordinates. As a note, in DSM, functional requirements as well as constraints are implicitly satisfied to realize products.

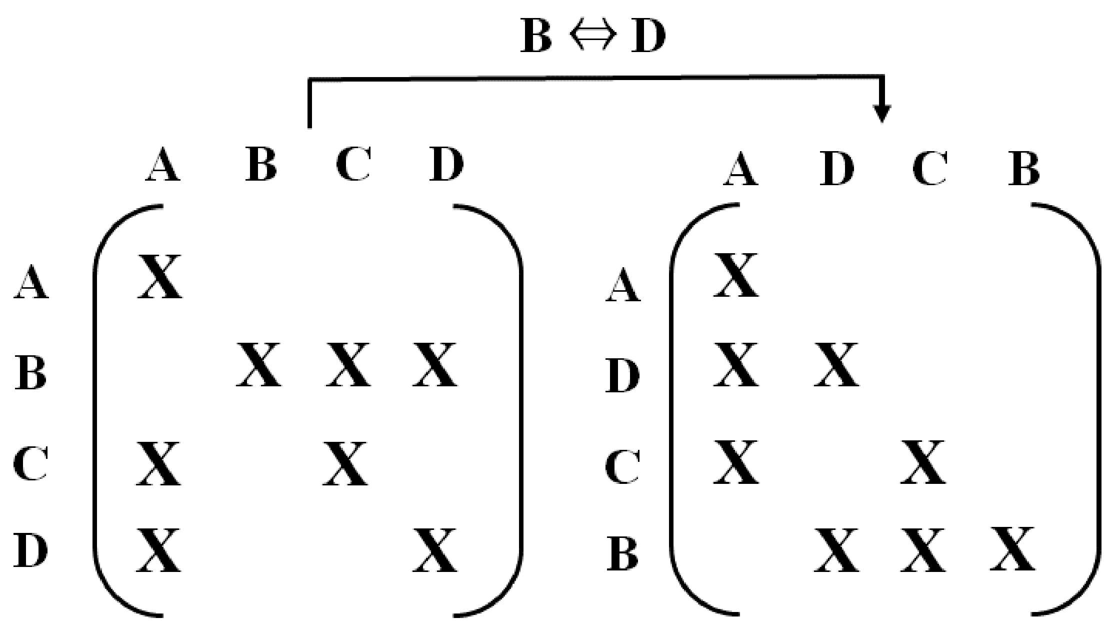

Figure 2.1: One example of DSM when exchanging the order of tasks

Baldwin and Clark (2000) proposed a base theory for DSM to apply, for example, complex tasks in semiconductor designing process. Baldwin and Clark defined a design rule that the task structure should be modularized to approach towards the best design by analyzing DSM. When the task structure is changing to modular, six complete modular operators such as splitting, substituting, augmenting, excluding, inverting and porting can change the task structure optimally. Since DSM is defined only to improve an existing product design and it is not clear to relate with functional requirements which are necessary for product designing, DSM describes only a static product design, and can not represent the designing before realizing a product.

As a definition of modularity, if the matrix elements of DSM are diagonal or block diagonal, then related products can be called as “modular.” If the upper triangular matrix elements of DSM are zero, then the products are “hierarchical.” If the upper triangular matrix elements of DSM are not zero, then the products are “integral.” Baldwin et al. (2014) defined modularity strictly by range, which is expressed by the use of a transitive closure of DSM to successive power. In this doctorial thesis, we adopt the definition of modularity by Baldwin et al. (2014).

As applications to various products, several types of DSM have been proposed, including tasks, design parameters (DP), physical components (PC), firms and sectors (FS), which represent a business ecosystem (Baldwin, 2008), and so on (Browning, 2001, Eppinger and Browning, 2012). In this doctorial thesis, design parameters, physical components and firms-sectors mainly will be considered as base vector spaces of modularity matrices.

For modularization, Baldwin and Clark (2000) proposed that one factor to determine the modularity of products is to increase the number of options for product designs by applying the real option theory. A distribution function *f(x)* of performance for a base vector space coordinate *x* is

$$f(x) = \frac{e^{-\frac{x^2}{\sigma^2}}}{\sqrt{2\pi}\sigma},$$

where σ is the standard deviation. A value of a product with one module V_1 is

$$V_1 = \int_0^\infty dx \cdot xf(x) = \frac{\sigma}{\sqrt{2\pi}} \quad .$$

When the standard deviation becomes larger, the value of the product increases linearly. For more general cases, we can refer Baldwin and Clark (2000).

As recent work on DSM, we review Multi-Domain DSM (Danilovic and Browning, 2007) and vertically permeable boundary (Jacobides and Winter, 2005). First, Multi-Domain DSM (Danilovic and Browning, 2007) is a set of DSM and Domain Mapping Matrix (DMM) to analyze relationships among DSMs on different base vector spaces. DMM is defined by mappings from one base vector space to another base vector space, for example DP→PC. Second, vertically permeable boundary happens as a firm boundary when a firm buys goods from upstream or sells goods to downstream (Jacobides and Winter, 2005). Baldwin et.al. (Baldwin 2008; Luo et.al. 2009) proposed that modularity of DSM on firms and sectors, shortly FS, may be predicted from modularity on DP or PC. The research for Japanese automobile and electronics sectors explained that more modular DSM on PC lowers transaction costs, and then vertically permeable boundary in FS (Firm-Sectors) appear, and furthermore DSM on FS can be more integral (Baldwin 2008). Through these recent researches such as Multi-Domain DSM and vertically permeable boundary, it has been interesting to study relationships among different base vector spaces.

The second item for review is Axiomatic Design, shortly AD. Suh (2001) defined product design as a mapping between what we want to achieve (for example functional requirements, shortly FR) and how we want to achieve it (for example design parameters, shortly DP). This mapping is represented by a design equation such that FR = [A] DP, where [A] is called a design matrix to determine the product design. AD is a basic theory of logical and rational design thinking process for designers to satisfy functional requirements explicitly.

Ulrich (1995) and Suh (2001) defined modularity from matrix elements of the mapping between FR and PC (or DP), which represents interactions in design process. When the matrix elements are diagonal, the product uncouples to adjust PCs (or DPs) satisfying FR independently. When the upper triangular matrix elements are zero (or not zero), the product decouples (or coupled), and we must consider designing the products by adjusting PC (or DP) interactively.

As the example for a trailer in Figure 2.2, Ulrich (1995) defined modularity as interactions of physical components and Functional Requirements (Functional Elements) in product design. We find that the modular case is easier than the integral case to design the product. For the example of a trailer, “protect cargo from weather” as one of functional elements can be determined only by “box” in the modular case. In the integral case, the “protect cargo from weather” must be adjusted by three components such as “upper half”, “lower half” and “spring slot covers”. Further details and the applications to various products are provided by Krishnan et.al. (2001) and Kulak et.al. (2010).

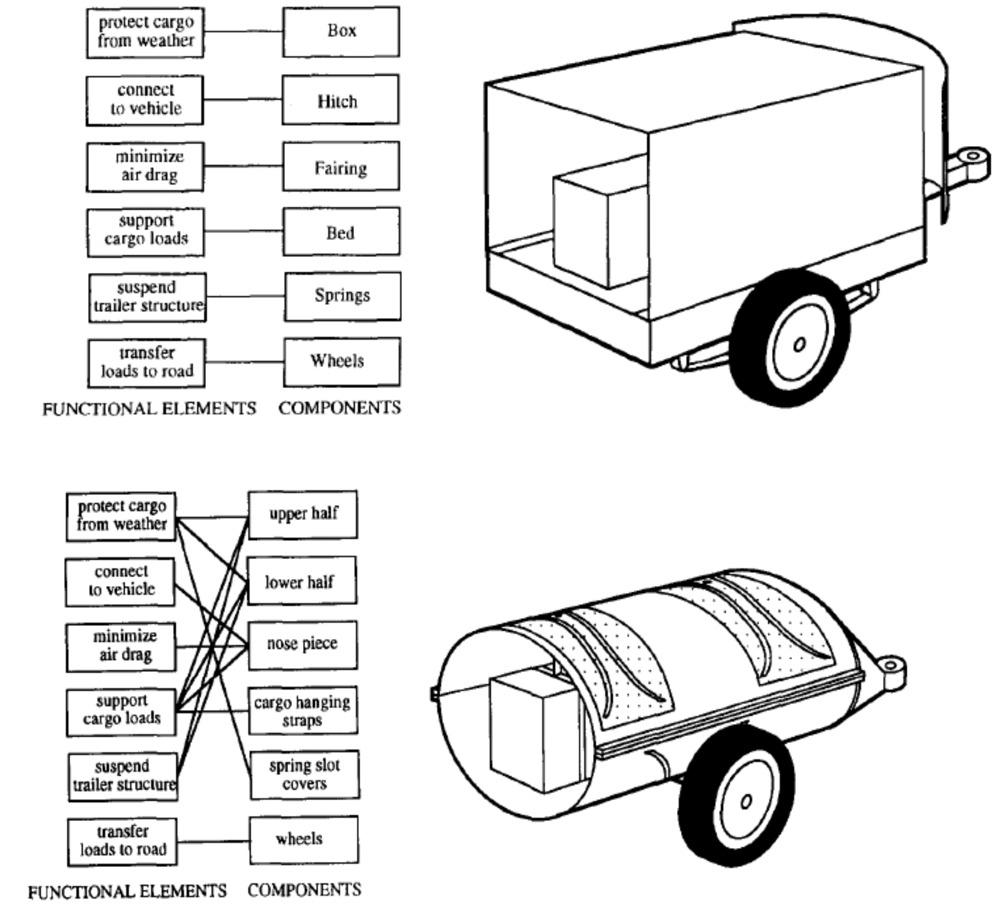

Figure 2.2: Examples of modularity for trailers (Ulrich 1995)

Suh (2001) proposed two axioms in AD for product design. The first is the independence axiom to maintain the independency of FR, which must naturally be satisfied for designing consistently. The independent axiom can secure FR to be completely determined only by mappings from PC. Generally, this independence axiom is often considered to be equivalent to maintain the modularity matrix of the mapping of FR→PC to be uncoupled. In this doctorial thesis, we assume that FR should be determined only by mapping from PC (or DP). The second is the information axiom to minimize the information content of product design in realizing an optimal product design. Generally, the systems can be defined by permissible ranges to satisfy FR, for example, robustness of product design. Regarding the information axiom, the information content I is defined as a logarithm of probabilities $\tilde{P}_i$ for $i=1,2,\ldots,n$, to realize the system such that

$$I = -\sum_{i=1}^{n} \log_2 \tilde{P}_i \, ,$$

where n is the number of modules in one system. For further details, we can refer the work of Suh (2001).

Notably, although AD evolved from the optimization theory to determine design parameters satisfying functional requirements, in AD, constraints to realize products have not been systematically introduced into the theory. Thus, AD can also describe only a static product design, not dynamics of product designing, to satisfy functional requirements and constraints.

Third, we review three types of constraints such as physical constraints, equipment constraints, and operational constraints (Fujimura, 2000). Constraints signify the conditions that must be satisfied in order to realize products, which are determined by steps for designing such as concept, prototype and business/sales. In Figure 2.3, we introduce a performance correlation diagram (Fujimura, 2000), which shows a hierarchy of constraints, wherein physical, equipment, operational constraints exhibit an ordered, nested relationship. Essentially, it is natural for us to consider functional requirements as well as constraints as sets, represented by parameters with permissible ranges.

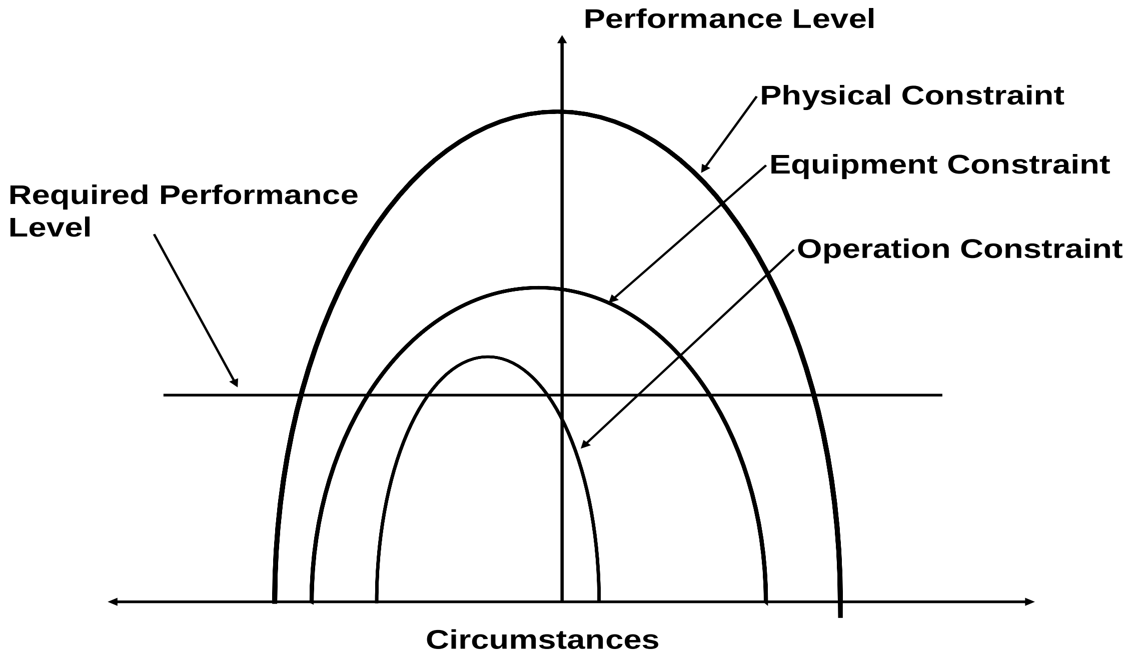

Figure 2.3: Performance correlation diagram (Fujimura, 2000)

Physical constraints are conditions based on the fundamental law of science, and this includes physical and chemical phenomena. Equipment constraints are conditions dependent on the precision of the technological equipment made to realize products; this includes machines and materials. Operational constraints are conditions determined by establishing the parameters of working environments, such as ambient temperature and atmospheric pressure, and business conditions, such as business decisions and regulations. This also includes a consideration of related circumstances ideal in order to realize products, including the use of time.

3 Concept Structure of Design

To develop a theoretical model that describes dynamics to determine product design mapped to the market, in this section we define "actual design" and "function design" as the concept structure of design. Here, we define "design space" with coordinates of design parameters considered by designers, and "market space" with coordinates of customer needs/attributes considered by consumers in purchasing a product. Designers are the ones who design the product functionally and artistically, and decide the design parameters of the product.

In many previous studies, designing has ever been regarded as decision making to obtain the one point in the intersection of functional requirements and constraints. Suh described this point in his book (2001) as follows: "*In reality, the probability of success (that the product realized according to the design satisfies all function requirements) is governed by the intersection of the design range defined by designer to satisfy the function requirements and the ability of the system to produce the part within the specified range.*" Here, we call "actual design" representing one point in the set intersection of functional requirements and constraints on design space. Namely, actual design is a vector. Newly, we define "function design" as securing the intersection of functional requirements and constraints in as wide a design space as possible. Thus, the function design is one set in the design space, and includes actual designs as elements—that is, function design is a set of actual design vectors. As drawn in Figure 3.1, the actual design such as D1 is only a point in function design in the design space. In this doctorial thesis, designing is also defined as decision making to obtain one set, not one point, as the intersection of functional requirements and constraints. As a note, an empty set as intersection of functional requirements and constraints means no degree of freedom for product design, which is not applicable for product design.

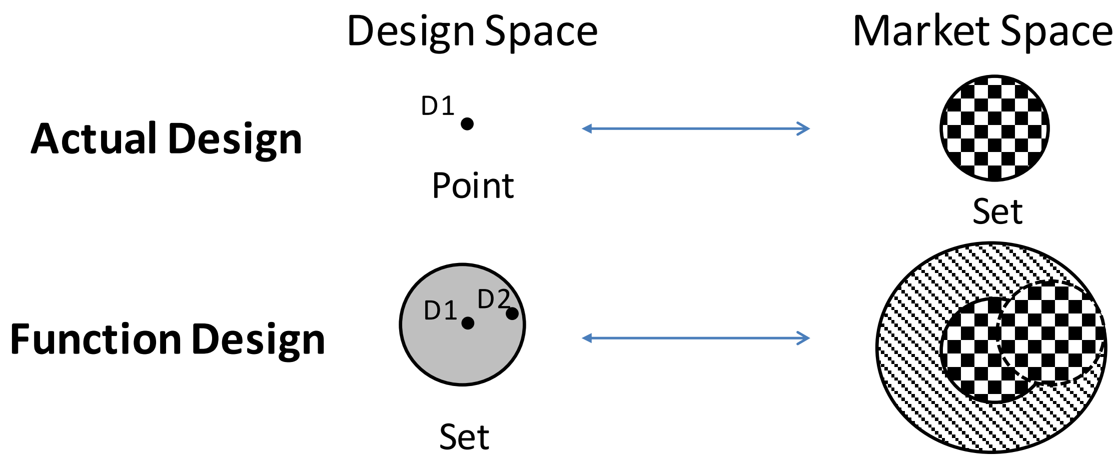

Figure 3.1: Concept structure of design for actual design and function design

The product realized according to one actual design has a specific coverage within the market. Even if two actual designs in the intersection of functional requirements and constraints, such as D1 and D2, are equivalent in securing the functional requirements and constraints in the design space, D1 and D2 might have different and individual coverages in the market, as shown in Figure 3.1. This is the reason why customers select one from a lot of products with the same functional requirements according to their own taste in the market. The difference between D1 and D2 in the market is attributable to the difference in some practical features that would affect customers' preference. Thus, we can find the most valuable actual design in the function design even if we do not change the function design such as the fundamental design concept. Substituting a subsystem to another subsystem can change the intersection of the functional requirements and the constraints. Then, the coverage area of the function design in the market can be broaden by substituting the subsystems to realize a big hit product.

We strictly define "modularity design" as building a structure among functional requirements on one system layer and those on one lower layer system. Modularity design can include function designs with a variety of modularity (for example, modular architecture and integral architecture) on the system layer. Modularity design includes trade-offs among function designs based on modularity on the system layer. Modularity design will be clearly defined in the modularity matrix in the next section. As a note, the concept structure of design, including actual design and function design, can be applied to any layer of the system, although the details of concept structure of design can be different in every layer. Then, “architecture” in product design is defined as a set of “modularity designs” on all the system layers. In this doctorial thesis, we will create a theoretical model to describe the dynamics of function designs with relevant modularity design mapping the design space to the market space.

Baldwin and Clark (2000) focused on the architecture of the product and evaluated an effect of modularity with “option value.” The market is basically fraught with uncertainty because consumers’ preferences are complex and unknown. The gain that the product will make in the market depends on the features that fascinate customers, and it is difficult for designers to anticipate the features. From these discussions based on the theories of Baldwin and Clark (2000) and Suh (2001), good design is the design that can cover a wide market area. That is, the design with wider market coverage has a higher possibility to include high value attributes (more preference) in the market. Thus, a designer should design to obtain larger market coverage by optimizing the product’s function design with relevant modularity design.

4 New Definition of Modularity Matrix in Product Design

In this section, we identify the dynamics of product design by defining a modularity matrix in a deeply meaningful manner. First, we formulate a mathematical expression to describe the designing process. DSM and AD are very useful and well-known methods to describe the design. DSM expresses whether there is any interaction between two components while AD expresses the relationship between functional requirements and physical components. Both DSM and AD are methods used to describe only the static state of design. Thus, when we study the designing process using DSM and AD, designing behavior can be recognized only as the difference between the static states before and after the designing process. However, as Gero (1990) mentioned, the designer must consider all of the changes for specifications of the components and for the functional requirements that inevitably arise in the designing process. That is, the designer needs to understand how one change to design parameters that affects one of the functional requirements can influence the other functional requirements and also the design parameters inversely. Here, we will identify the dynamics of design by using a mathematical expression for the designing process.

In the past, many conceptual studies for product design were developed within the context of creative thinking, system requirement engineering, product design and so on. An example of creative thinking is the "Geneplore Model" -- proposed by Finke et al. (1992) – which is a cycling process between the generation phase and the exploration phase for new product ideas under product constraints. An example of system requirement engineering is "requirement specification" -- Loucopoulos and Karakostas (1995) -- which constitutes an interrelated set of three requirements such as enterprise requirements, functional requirements, and non-functional requirements, some of which may be related to the product constraints. Thus, it would be essential to consider functional requirement as well as constraints in both of creative and incremental processes of new product development.

We study a change of product design from a fixed actual product design, such as DSM for existing products, to define the dynamics of product design. When we denote a vector of design parameters as $\{X_i\}$, called the "design space," and a vector of functional requirements as $\{f_i(X)\}$, which are functions of design parameters, we treat only small transformations $\{dX_i\}$ and $\{df_i(X)\}$ as linear approximations (Yassine and Falkenburg, 1999) around the initial values of the design parameters and functional requirements. We assume that the number of design parameters and functional requirements are the same as n in one system, the modules of which are labeled by $i = 1,2,\ldots n$. Here, the modules to build a system are defined by the design space and the consistent functional requirements. In general, the optimization theory for product design requires a set of solutions to be found to satisfy the following equations (Michelena and Papalambros, 1995; Fujimura, 2000):

$$df_i(X) = \alpha_i \quad ,$$

where α_i denotes parameters for permissible ranges of $\{df_i\}$ between A_i and B_i, which are denoted as $[A_i,B_i]$. In the case with only one module, every point of the design parameter as $\{X_1\}$ to satisfy the equation is the actual design, and the set of solutions to satisfy the equation is function design. Then, we have two directions of the design process to find the solution inside the fixed permissible ranges of $[A_i,B_i]$ or to find the solution in the changed permissible ranges as function design.

A new definition of the modularity matrix Gf_{ij} for functional requirements is proposed as a mapping as follows:

$$Gf_{ij} = \sum_{k,m=1}^{n} \left(\frac{\partial f_k}{\partial X_i} \right)^{-1} \cdot Kf_{km} \cdot \left(\frac{\partial f_m}{\partial X_j} \right),$$

where the matrix elements of the modularity matrix mean to change the product design among small transformations $\{dX_i\}$ on design parameters through the permissible ranges on functional requirements. In the case with many modules, the modularity matrix expresses the set of solutions as actual design to satisfy the equation as modularity design as well as function design to adjust actual design among the interactions of many modules. Thus, the modularity matrix includes all of actual design, functional design and modularity design.

Modularity matrix Gc_{ij} for constraints is defined as a mapping: $\{dX_i\} \rightarrow \{dX_i\}$ in a similar way to the modularity matrix for functional requirements as follows.

$$Gc_{ij} = \sum_{k,m=1}^{n} \left(\frac{\partial C_k}{\partial X_i} \right)^{-1} \cdot Kc_{km} \cdot \left(\frac{\partial C_m}{\partial X_j} \right),$$

where Kc_{ij} is a diagonal matrix, whose matrix elements are parameters γ_i for permissible ranges of $\{dC_i\}$ such that $Kc_{ij} = diag\ (\gamma_1, \gamma_2, \ldots, \gamma_n)$.

Modularity matrix G_{ij} for both functional requirements and constraints is defined as

$$\{G_{ij}\} = \sum_{k=1}^{n} \{Gf_{ik}\} \cap \{Gc_{kj}\},$$

where $\{G_{ij}\}$, $\{Gf_{ik}\}$ and $\{Gc_{kj}\}$ express sets for the permissible ranges. All matrix elements of $\{G_{ij}\}$ are defined by the intersections of two sets of matrix elements, $\{Gf_{ik}\}$ and $\{Gc_{kj}\}$. One main reason for this definition of modularity matrix is that a product should be designed to satisfy functional requirements after checking that it satisfies constraints. As a short note, we can find the mathematical description of modularity matrix in Appendix B.

Moreover, we can define modularity matrices on PC and FS (Firm-Sectors) for functional requirements and constraints in a way similar to that on DP. The coordinates $\{Y_i\}$ of PC represent the descriptions of products, and the coordinates $\{Z_i\}$ of FS (Firm-Sectors) represent company names and brands. Relationships among functional requirements and constraints for modularity matrices on DP, PC, and FS (Firm-Sectors) are displayed in Figure 4.1, where functional requirements are the same, if we can clarify customer needs in the market related to functional requirements even in the early stage of product development, but constraints are different on three base vector spaces. Regarding the meanings of constraints $C1_i(X_j)$ in DP, $C2_i(Y_j)$ in PC, and $C3_i(Z_j)$ in FS (Fujimura, 2000), we can consider that $C1_i(X_j)$ represents the physical constraints for design in the concept stage of product development, $C2_i(Y_j)$ represents the equipment constraints for components in the prototype stage, and $C3_i(Z_j)$ represents operational constraints for products in the business and in the market in Figure 4.1. For example, one of operational constraints is the cost of products. Generally, constraints become stronger in order when approaching the market such that there is $\{C1_i(X_j)\} \supset \{C2_i(Y_j)\} \supset \{C3_i(Z_j)\}$ as set inclusion.

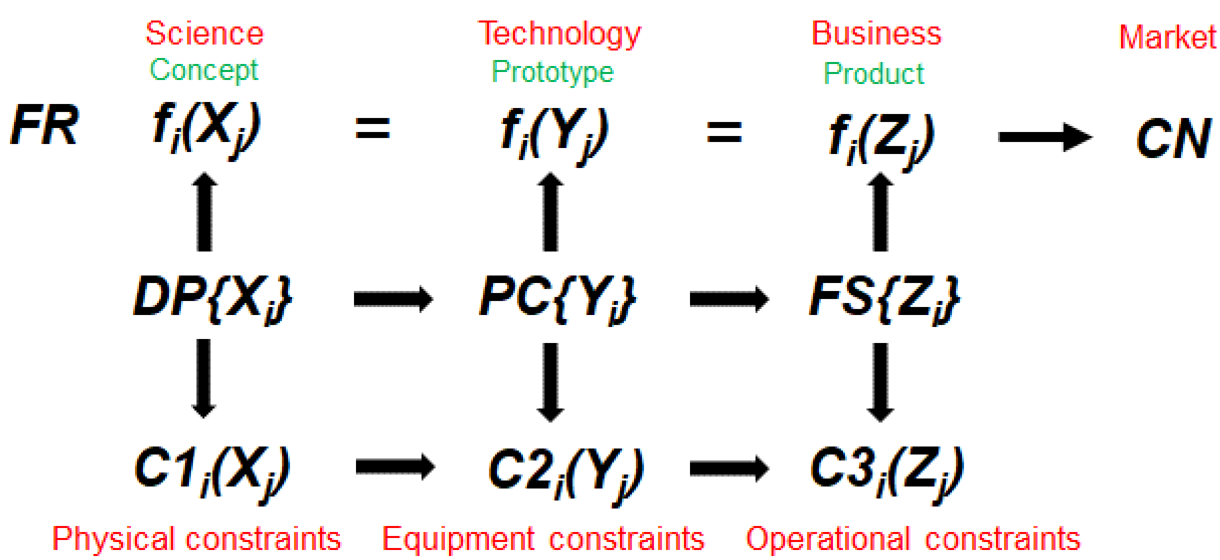

Figure 4.1: Relationship among functional requirements and constraints on DP, PC and FS

Finally, here we prove an equivalence of DSM and AD through modularity matrix. We denote two mappings as $\Phi 1_{ij}$: DP→PC and $\Phi 2_{ij}$: PC→FS, which are two examples of DMMs to connect modularity matrices on different base vector spaces (Danilovic and Browning, 2007; Lindemann et al., 2009). For regular matrix $\Phi 1_{ij}$ such that $dY_i = \sum_{j=1}^{n} \Phi 1_{ij} \cdot dX_j$, modularity matrices for functional requirements on DP and PC, denoted by Gd_{ij} and Gp_{ij}, are related as $Gp_{ij} = \sum_{k,m=1}^{n} \Phi 1_{ik} \cdot Gd_{km} \cdot (\Phi 1)^{-1}_{mj}$. The mapping of AD is defined as a mapping ψ_{ij} : FR→PC (Ulrich, 1995: Suh, 2001) such that $Y_i = \sum_{j=1}^{n} \psi_{ij} \cdot f_j(X)$. Since $\psi_{ij}^{-1} = \left(\partial f_i / \partial Y_j\right)$, DSM on PC for functional requirements is

$$Gf_{ij} = \sum_{k,m=1}^{n} \left(\partial f_k / \partial Y_i\right)^{-1} \cdot Kf_{km} \cdot \left(\partial f_m / \partial Y_j\right) = \sum_{k,m=1}^{n} \psi_{ik} \cdot Kf_{km} \cdot \psi_{mj}^{-1} .$$

Since Kf_{ij} have only diagonal elements, in terms of modularity, we can find that DSM Gf_{ij} on PC for functional requirements is equivalent to the mapping ψ_{ij} of AD. Here, we should note that constraints are ignored, and that DSM for both functional requirements and constraints on PC may generally be different from the mapping ψ_{ij} of AD.

5 Product Value as Entropy of Design for Modularity Matrix

In this section, we define "entropy of design" as one indicator of product value in product design. Exactly speaking, "entropy of design" means a product value in product design, not a product value in the market, which will be connected to utility function and preference in the market through a mapping from functional requirements to customer needs in Section 8. In product design, it is essential to consider functional requirements as well as constraints (Fujimura, 2000), such as the hierarchical constraints: physical, equipment and operational constraints, which also shows an impact on the process and the supply chain as well as the product by an analogy with three dimensional concurrent engineering (Fine, 1998; Fixson, 2005).

From the definition of modularity matrix for functional requirements and constraints, when the initial values are far from the permissible ranges, a modularity matrix on the initial values does not satisfy both functional requirements and constraints. Then, we must engage in trial and error to find initial values satisfying the permissible ranges of both functional requirements and constraints. We improve the definition of a modularity matrix to enable finding the permissible ranges of functional requirements and constraints in order to realize the system although we cannot recognize the solutions in advance or even if the initial values remain far from the permissible ranges. Concretely, we write Gf_{ij} and Gc_{ij} by using step functions in order to make the permissible ranges explicit. When the parameters α_i in Kf_{ij} are between A_i and B_i, denoted as $[A_i,B_i]$, by use of step functions $\theta(\cdot)$, Kf_{ij} is more explicitly written as

$$Kf_{ij} = diag(\alpha_i \cdot (\theta(\alpha_i - A_i) - \theta(\alpha_i - B_i))) \quad .$$

We introduce a regularization of the modularity matrix by use of a new parameter T to modify the step functions such that

$$\theta(\alpha - A) = \lim_{T\to+0} 1 - \frac{1}{1+e^{\frac{(\alpha-A)}{T}}}.$$

When T is large, finding the solutions from outside the permissible ranges is easier. This new parameter T signifies a capability to find unknown solutions for product design and also a possibility to realize the small performance of product even outside permissible ranges. This regularization is similar to the fuzzy information axiom (Kulak and Kahraman, 2005). Concretely, $Kf_{ij} = diag\,(\alpha_i)$ is regularized as $Kf_{ij}(T) = diag\,(\alpha_i(T))$ such that

$$\alpha_i\{\theta(\alpha_i - A_i) - \theta(\alpha_i - B_i)\} = \lim_{T\to 0} \alpha_i(T) \qquad \text{for} \quad \alpha_i(T) = \alpha_i \left\{ \frac{1}{1+e^{\frac{(\alpha_i - B_i)}{T}}} - \frac{1}{1+e^{\frac{(\alpha_i - A_i)}{T}}} \right\}.$$

After regularization, the modularity matrices on DP for functional requirements and constraints are defined by replacing Kf_{ij} and Kc_{ij} to $Kf_{ij}(T)$ and $Kc_{ij}(T)$, where $Kc_{ij}(T)$ is similarly defined from Kc_{ij}.

Then, the modularity matrix G_{ij} for both functional requirements and constraints is defined as the intersection of modularity matrices for functional requirements and constraints as function design by use of the step function $\theta(\cdot)$, which is a new theoretical definition of DSM (Tokunaga and Fujimura 2016):

$$G_{ij} = \sum_{l,k,m=1}^{n} \alpha \cdot \left[\theta\left(\alpha - A_{iklmj}\right) - \theta\left(\alpha - B_{iklmj}\right) \right],$$

$$[A_{iklmj}, B_{iklmj}] = [\left(\partial f_k / \partial X_i\right)^{-1} \cdot A_k \cdot \left(\partial f_k / \partial X_l\right), \left(\partial f_k / \partial X_i\right)^{-1} \cdot B_k \cdot \left(\partial f_k / \partial X_l\right)]$$

$$\cap \quad [\left(\partial C_m / \partial X_l\right)^{-1} \cdot P_m \cdot \left(\partial C_m / \partial X_j\right), \left(\partial C_m / \partial X_l\right)^{-1} \cdot Q_m \cdot \left(\partial C_m / \partial X_j\right)].$$

As a definition of modularity, if the matrix elements of the modularity matrix are diagonal or block diagonal, then the related product design is understood to be "modular." If the upper triangular matrix elements of the modularity matrix are zero, then the product design is "hierarchical." If the upper triangular matrix elements of the modularity matrix are not zero, then the product design is "integral." In this doctorial thesis, we adopt the definition of modularity proposed by Baldwin et al. (2014), which is expressed by the use of a transitive closure of the modularity matrix to a successive power.

Realistically, small probability to realize product design exists even outside the permissible ranges and the probability to realize product design inside the permissible ranges becomes smaller as compensation. Then, the product design can be applicable to wider functional requirements and we introduce a new parameter T as applying more functional requirements outside the permissible ranges.

The new parameter T signifies the capability to find unknown solutions for product design as function design even outside the known permissible ranges. The change of the new parameter T can impact the number of product designs to be realized by the change of permissible ranges as well as the change of the number of modules through a shift of the units of permissible ranges, which is really caused by technology advances.

Product design should be adjusted in the permissible ranges of functional requirements between A_i and B_i, which expresses design flexibility, and should be impacted by the new parameter T as a phase of technology. Mathematically, the modularity matrix can be regularized using the new parameter T to modify the step functions smoothly, as in Figure 5.1, with $T = 0$ and $T = 1$. Here, we denote α_i, A_i, and B_i as α, A, and B, respectively, as representative for overall product design. The probability for the distribution function of functional requirements is defined as $(P_B - P_A)$ as follows:

$$P_B = \frac{1}{1+e^{\frac{(\alpha-B)}{T}}} \;, \qquad P_A = \frac{1}{1+e^{\frac{(\alpha-A)}{T}}} \;,$$

which can be identified as the distribution function for a fermion.

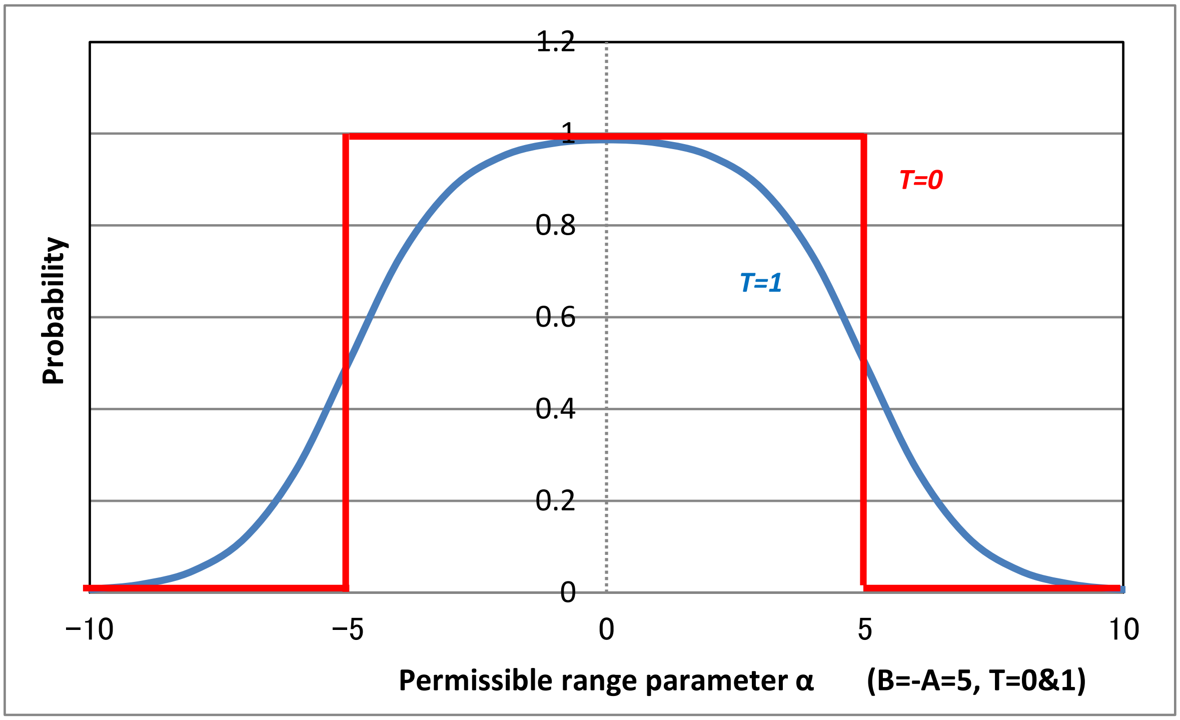

Figure 5.1: Probability for the distribution function before and after regularization

Given that the product design can be independently determined by modularity, the permissible ranges and the new parameter T, it is natural to introduce an entropy to count the number of independent product designs as one indicator of product value. From the same analogy between dynamics of product design and Fermi-Dirac statistics, we introduce the "entropy" based on Fermi-Dirac statistics (also, "Fermi-Dirac entropy") from statistical mechanics (Kubo, 1965) for a grand-canonical ensemble of fermions by identifying the matrix elements of the modularity matrix as energy for fermions, which means "an ability to do work" in statistical mechanics. As a short review of statistical mechanics for Fermi-Dirac statistics, we can see Appendix C. For example, in the case of one module, the Fermi–Dirac entropy S for the modularity matrix (we call "entropy of design") is defined as follows:

$$S(\alpha, A, B) = \log\left(\frac{1+e^{-\frac{(\alpha-B)}{T}}}{1+e^{-\frac{(\alpha-A)}{T}}}\right) + \frac{\alpha}{T}\left\{\frac{1}{1+e^{\frac{(\alpha-B)}{T}}} - \frac{1}{1+e^{\frac{(\alpha-A)}{T}}}\right\} + \frac{1}{T}\left\{\frac{A}{1+e^{\frac{(\alpha-A)}{T}}} - \frac{B}{1+e^{\frac{(\alpha-B)}{T}}}\right\} \quad .$$

From the law of entropy maximization, we propose the following principle of modularity: "*Whenever approaching the best product design, the entropy of design increases.*" We draw the entropy of design by the size of the permissible range [*A, B*], i.e., $(B - A)$ as the intersection of functional requirements and constraints in Figure 5.2 when we set $B = -A$, $T = 1$, and $\alpha = B/2$, which can be generally selected as a positive number to mean an improvement of the product design from the initial value.

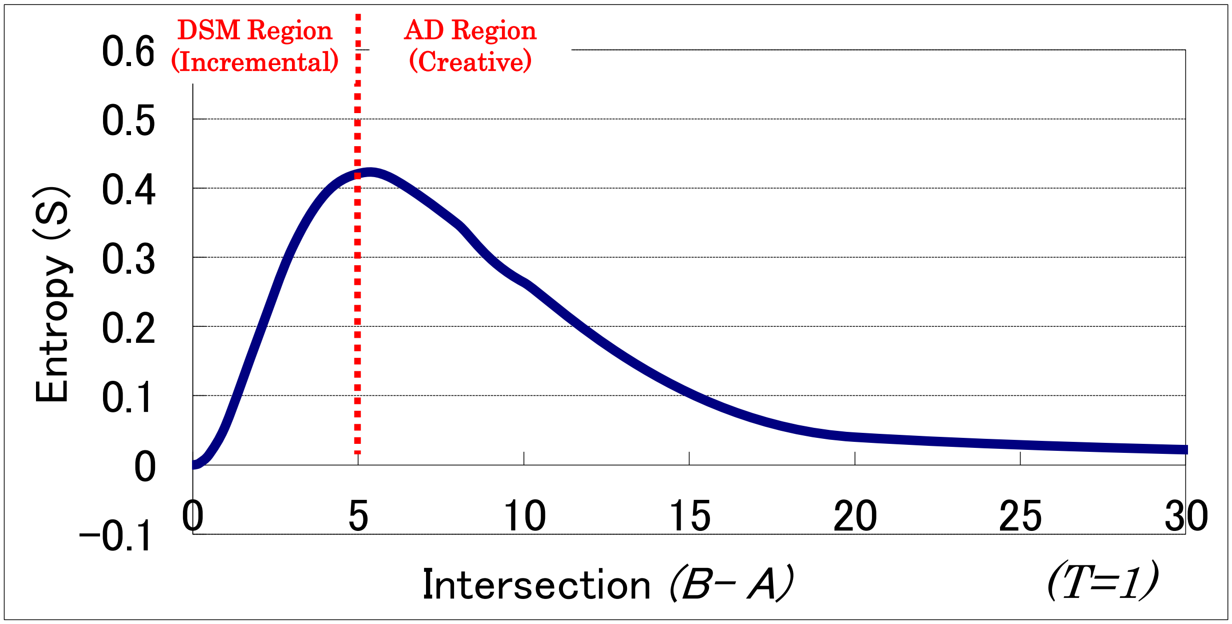

Figure 5.2: Entropy of design by the size of the intersection [*A, B*]

We verify an equivalence between DSM and AD through the modularization. We study two different limits of the entropy of design for *B/T*, smaller or larger. Here, we set $A=-B$ for simplicity. As the first limit of small *B/T*, where the constraint is strong, the entropy of design is expanded as

$$S \approx \frac{\alpha B}{2T^2}.$$

Therefore, for small B/T, the entropy of design is proportional to the size of interaction B. This is logically the same as the modularization of DSM by real option theory (Baldwin and Clark, 2000) such that the size of interaction B is similar to the standard deviation σ in real option theory.

As the second limit of large *B/T*, where the constraint is weak, the entropy of design is approximated as follows.

$$S \approx -\log\left(\frac{1}{1+e^{\frac{\alpha-B}{T}}}\right) = -\log \hat{P},$$

where $\hat{P}$ can be interpreted as a probability by which the system satisfies functional requirements without constraints. Therefore, for large *B/T*, the entropy of design is approximated to a logarithm of the probability to realize the system. This is logically the same as the modularization of AD by information axiom (Suh, 2001). Finally, regarding applicable cases of DSM and AD, DSM is applicable only to the cases of small *B/T*, where the constraint is strong, whereas AD is applicable only to the cases of large *B/T*, where the constraint is weak.

Thus, it is shown that the entropy of design is logically equivalent to real option theory at one region near zero size of the intersection (what we refer to as the “DSM region,”) and the information axiom in the other region near infinity in size of the intersection (what we refer to as the “AD region”) (Tokunaga and Fujimura, 2016). The summary of the relationship between DSM and AD is shown in Figure 5.3.

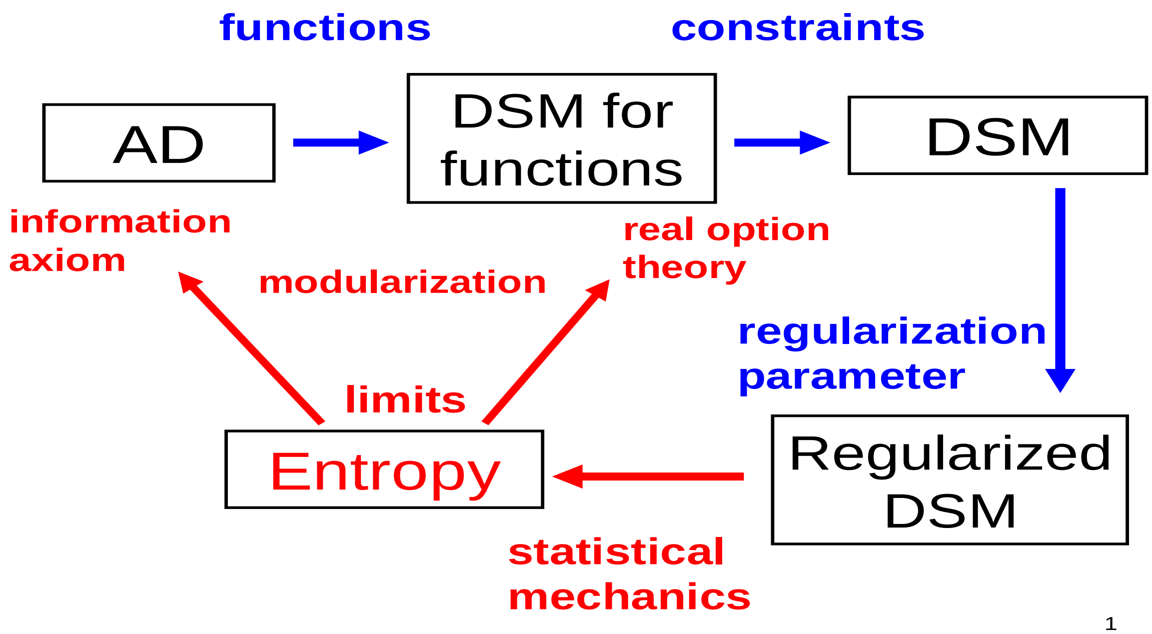

Figure 5.3: Relationship between DSM and AD

Next, we study the cases of many modules with constraints. When the matrix elements of modularity matrix are rescaled, the modularity matrix for functional requirements is

$$Gf_{ij} = \sum_{k=1}^{n} \left(\partial f_k / \partial X_i\right)^{-1} \cdot \alpha_k \cdot \left[\theta(\alpha_k - A_k) - \theta(\alpha_k - B_k)\right] \cdot \left(\partial f_k / \partial X_j\right)$$

$$= \sum_{k=1}^{n} \alpha \cdot \left[\theta\left(\alpha - \left(\partial f_k / \partial X_i\right)^{-1} \cdot A_k \cdot \left(\partial f_k / \partial X_j\right)\right) - \theta\left(\alpha - \left(\partial f_k / \partial X_i\right)^{-1} \cdot B_k \cdot \left(\partial f_k / \partial X_j\right)\right)\right],$$

where we choose $\alpha_k = \alpha$ for all *k*. Similarly, the modularity matrix for constraints is

$$Gc_{ij} = \sum_{k=1}^{n} \gamma \cdot \left[\theta\left(\gamma - \left(\partial C_k / \partial X_i\right)^{-1} \cdot P_k \cdot \left(\partial C_k / \partial X_j\right)\right) - \theta\left(\gamma - \left(\partial C_k / \partial X_i\right)^{-1} \cdot Q_k \cdot \left(\partial C_k / \partial X_j\right)\right)\right],$$

where we choose $\gamma_k = \gamma$ for all *k*, and the parameters γ_k are between P_k and Q_k, denoted as $[P_k, Q_k]$. By choice of a measure of delta function, the modularity matrix for both functional requirements and constraints is

$$G_{ij} = \sum_{l=1}^{n} \int \frac{d\gamma}{\gamma} \cdot \delta(\gamma - \alpha) \cdot Gf_{il} \cdot Gc_{lj} = \sum_{l,k,m=1}^{n} \alpha \cdot \left[\theta\left(\alpha - A_{iklmj}\right) - \theta\left(\alpha - B_{iklmj}\right) \right],$$

where the intersections are defined as

$$[A_{iklmj}, B_{iklmj}] = [\left(\partial f_k / \partial X_i\right)^{-1} \cdot A_k \cdot \left(\partial f_k / \partial X_l\right), \left(\partial f_k / \partial X_i\right)^{-1} \cdot B_k \cdot \left(\partial f_k / \partial X_l\right)]$$

$$\cap \ [\left(\partial C_m / \partial X_l\right)^{-1} \cdot P_m \cdot \left(\partial C_m / \partial X_j\right), \left(\partial C_m / \partial X_l\right)^{-1} \cdot Q_m \cdot \left(\partial C_m / \partial X_j\right)].$$

When we identify every matrix element in the modularity matrix as the energy for ground-canonical ensemble of fermions with the same energy α and the same temperature T, the entropy of design for many modules with constraints is written as a sum of entropy of design, denoted as S_{ij} for every matrix element;

$$S = \sum_{i,j,k,l,m=1}^{n} S_{ij}(\alpha, A_{iklmj}, B_{iklmj}) \ .$$

The entropy of design represents a value or performance of products with many modules. From the principle of entropy maximization, we propose a new principle of modularity: *"The Principle of Entropy Maximization" states that as approaching the optimal performance of a product, the entropy of design increases.*

We study cases of two modules in one system and can write the matrix elements of functional requirements and constraints as

$$\left(\partial f_i / \partial X_j\right) = \begin{pmatrix} a & b \\ c & d \end{pmatrix}, \quad \left(\partial C_i / \partial X_j\right) = \begin{pmatrix} p & q \\ r & s \end{pmatrix},$$

where we assume that $ad - bc > 0, ps - qr > 0, a,b,c,d,p,q,r,s \geqq 0$. When $b = c = q = r = 0$, the product design is called "modular." When $b \neq 0$ or $q \neq 0$, the product design is called "integral." When $b = q = 0$ and $c \neq 0$ or $r \neq 0$, the product design is called "hierarchical." For two modules in one system, we write the entropy of design as

$$S = S(\alpha, A_{11111}, B_{11111}) + S(\alpha, A_{22222}, B_{22222}) + \Delta S \text{ ,}$$

$$[A_{11111}, B_{11111}] = [A_1, B_1] \cap [P_1, Q_1], \;\; [A_{22222}, B_{22222}] = [A_2, B_2] \cap [P_2, Q_2] \text{ ,}$$

where ΔS is the sum of contributions from the off-diagonal matrix elements of the modularity matrix. Here, we study the contributions of constraints to change modularity. In the case that $q \neq 0$, $r = 0$, and $b = c = 0$, where the product design is integral,

$$\Delta S = S(\alpha, A_{11112}, B_{11112}) - S(\alpha, A_{11122}, B_{11122}) \text{ ,}$$

$$[A_{11112}, B_{11112}] = [A_1, B_1] \cap [(q/p) \cdot P_1, (q/p) \cdot Q_1],$$

$$[A_{11122}, B_{11122}] = [A_1, B_1] \cap [(q/p) \cdot P_2, (q/p) \cdot Q_2] .$$

In the case that $r \neq 0$, $q = 0$, and $b = c = 0$, where the product design is hierarchical,

$$\Delta S = S(\alpha, A_{22221}, B_{22221}) - S(\alpha, A_{22211}, B_{22211}) ,$$

$$[A_{22221}, B_{22221}] = [A_2, B_2] \cap [(r/s) \cdot P_2, (r/s) \cdot Q_2] ,$$

$$[A_{22211}, B_{22211}] = [A_2, B_2] \cap [(r/s) \cdot P_1, (r/s) \cdot Q_1] .$$

When the permissible ranges of functional requirements are suitably large, modularity can change by the sizes of $[P_1,Q_1]$ and $[P_2,Q_2]$. We then state the principle of modularity for the sizes of modularity matrix elements. If $[P_i,Q_i] \subset [P_{i+1},Q_{i+1}]$ for small ranges or $[P_{i+1},Q_{i+1}] \subset [P_i,Q_i]$ for large ranges, the product design can become hierarchical. If $[P_{i+1},Q_{i+1}] \subset [P_i,Q_i]$ for small ranges or $[P_i,Q_i] \subset [P_{i+1},Q_{i+1}]$ for large ranges, the product design can become integral. If the sizes of $[P_i,Q_i]$ and $[P_{i+1},Q_{i+1}]$ are similar, the product design can become modular. Therefore, we find that the principle of entropy maximization defines modularity, which we call the principle of modularity. This principle seems similar to the GA-based clustering for weighted DSM by use of the information theoretic method (Yu et al. 2007), which does not include constraints explicitly.

We draw the entropy of design for two modules with constraints in Figure 5.4 when we set $\alpha = T = 1$ and $P_1 = -Q_1 = P_2/2 = -Q_2/2$, where the sizes of constraints increase in order. In Figure 5.4, the blue line with circles is in the modular case $q = r = 0$; the red line with squares is in the integral case $q/p = 1/2$; and the green line with triangles is in the hierarchical case $r/s = 1/2$. In Figure 5.4, we see that the value of a product is higher when the product design is hierarchical, in a narrow range of constraints, or more integral in a wide range of constraints. Thus, constraints can change the modularity to increase the value of a product.

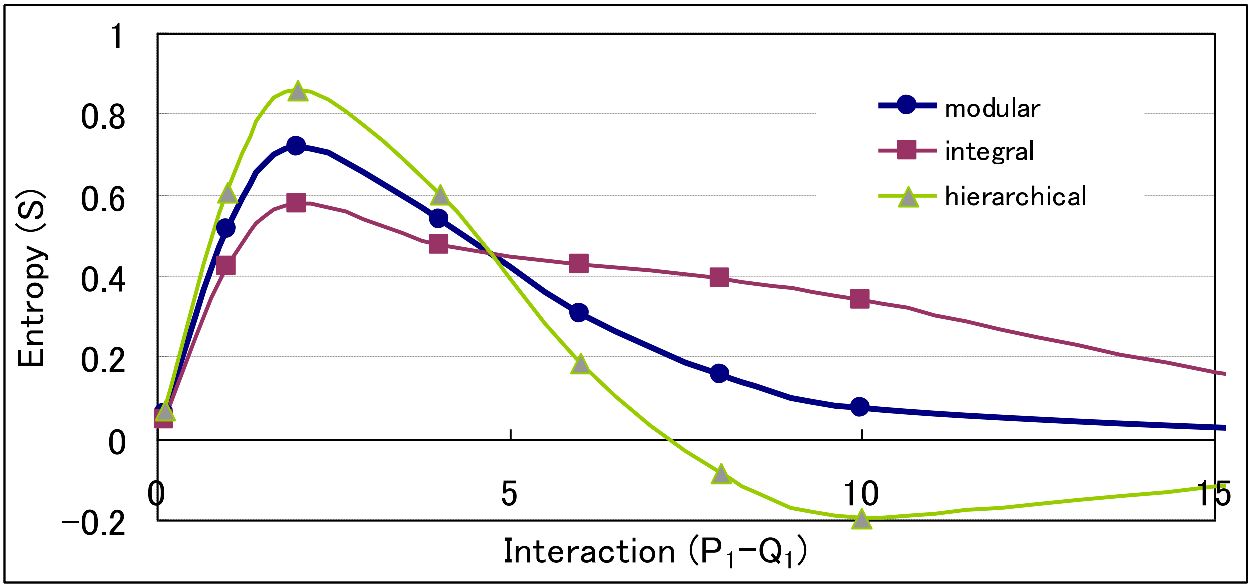

Figure 5.4: Entropy of design in modular, integral, and hierarchical cases

About the number of modules in one system, we study cases that the number of modules can be optimized in a finite number to maximize the value of product. We consider simple cases to add sets of two modules in one system with integration "c_i" as $\left(\partial f / \partial X\right)_{\{2i+1,2i+2\}} = \begin{pmatrix} a_i & 0 \\ c_i & d_i \end{pmatrix}$, where $c/d = 1/2$, $\alpha = 7$, $T = 1$, $B_n = -A_n = nB_1$, and $B_1 = 1$, and the other off-diagonal matrix elements of modularity matrix for functional requirements are zero when the constraints are weak and modular. In Figure 5.5, we plot entropy of design for the number of modules and can see an optimized number of modules in one system. When the number of modules increases beyond the optimized number, it becomes difficult to realize the system without much cost.

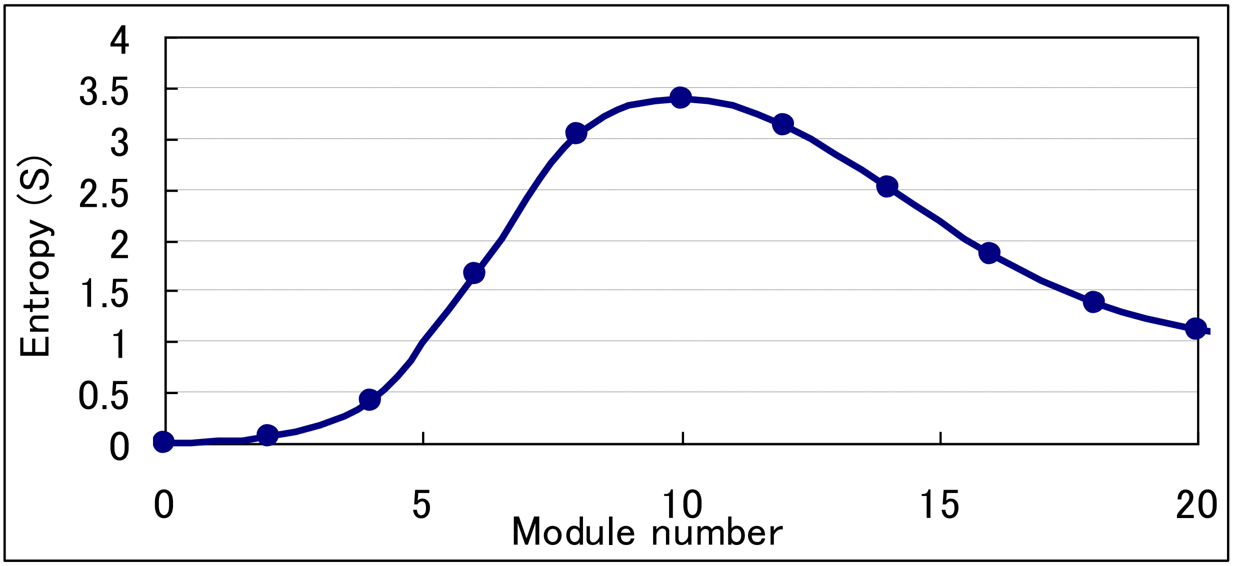

Figure 5.5: Optimized number of modules

6 Entropy of Design as Shannon Entropy in Product Design

In this section, we study the dynamics of product design as function design in the case with a change of permissible range of functional requirement and/or constraint even in only one module, although we have considered the overall product design with many modules in section 4 and section 5. It is natural to introduce information theory, especially Shannon entropy, because product design is a bundle of solutions (information) determined by the permissible ranges of functional requirements and constraints.

From Kubo's textbook (1965), the entropy of design as Fermi-Dirac entropy is written as follows:

$$S(\alpha, A, B) = S(P_B, P_A) = H(P_B) - H(P_A),$$

$$H(P) = -P \log P - (1 - P) \log (1 - P).$$

This is one kind of Shannon entropy (1948), which is the average amount of information entropy for probability P or (1 − P) (such as a coin flip) as one of the general relationships between information theory and statistical mechanics shown by Jaynes (1957). P_B and P_A denote probabilities to realize states that exist only below B and A by the scale unit of T. When $\alpha > 0$ and $B = -A$, P_A is further from 1/2 than P_B (Figure 6.1), and then $S = H(P_B) - H(P_A) \geqq 0$.

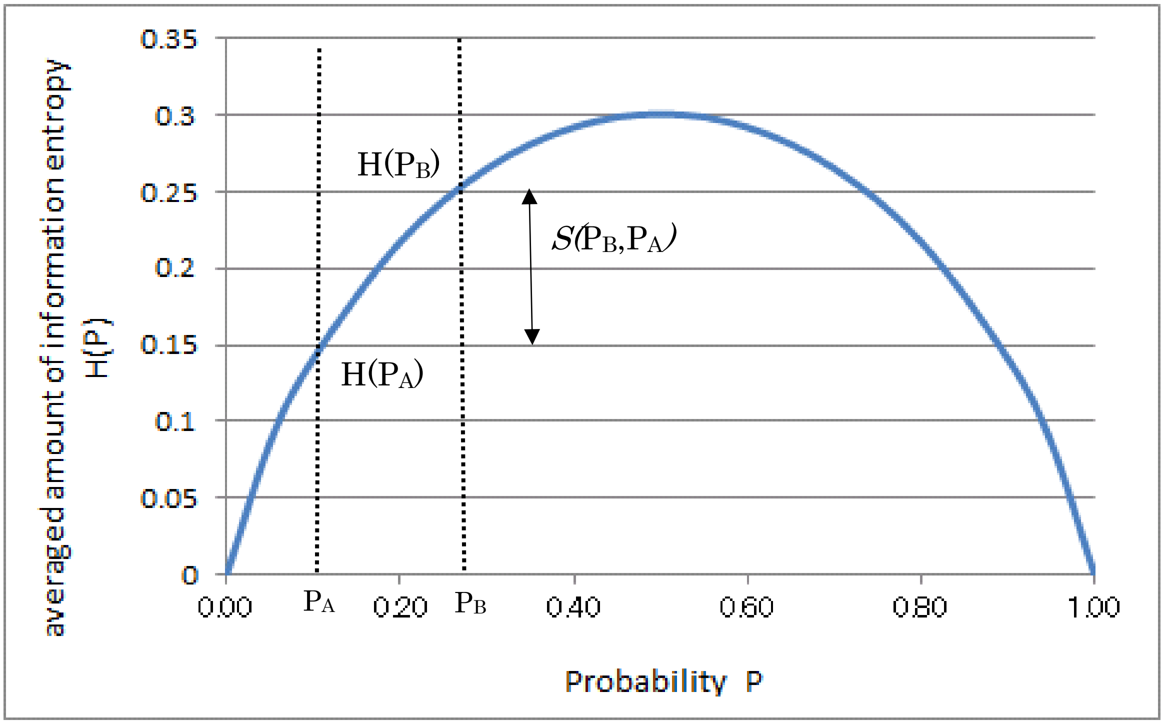

Figure 6.1: Average amount of information entropy in the case of a coin flip

Since the Shannon entropy S (P_B, P_A) is the number of possibilities that satisfy $P_B - P_A$ in information theory, the Shannon entropy for modularity matrix in product design (we also call entropy of design) expresses the number of the possibilities that satisfy both functional requirements and constraints, which mean the same as the Fermi–Dirac entropy. The entropy of design only depends on the probabilities P_B and P_A, and hence it is logically similar to information axiom proposed by Suh (2001), which is determined by information contents for probabilities to satisfy functional requirements under constraints such as productivity and cost. Therefore, we can confirm that "***entropy of design can also be formulated as one of Shannon entropy***," which would be natural because product design can be expressed as a set of solutions (information). Thus, Shannon entropy for the modularity matrix in product design (also, entropy of design) expresses a bundle of information as the number of the possibilities that satisfies both functional requirements and constraints. As with the real option theory (Baldwin and Clark 2000), a higher entropy of design indicates the possibility to realize a wider product design.

In information theory, it is natural to consider cases where the sizes of permissible ranges are discretized, because realistically, the permissible ranges in product design are often considered as discrete values. For example, the permissible ranges of functional requirements can be discretized for three categories of beginners, the public and professionals. In the case with only one module, we can set $Q_1 = -P_1$, $T = 1$, and $\alpha = Q_1/2$ as the intersection of functional requirements and constraints, when the size of the permissible range of the functional requirement is larger than that of the constraint. When the order of constraints is set as the size of constraints $(Q_1 - P_1) = 30$, 29,…, 6, 5 by one additional kind of constraint, the entropy of design increases by a definite value along the dimension of the constraint in the AD region (Figure 6.2). Therefore, we confirm that the entropy of design as Shannon entropy from information theory expresses the number of the satisfied constraints to be measured by a unit of resolution in a phase of technology, namely T, even in only one module.

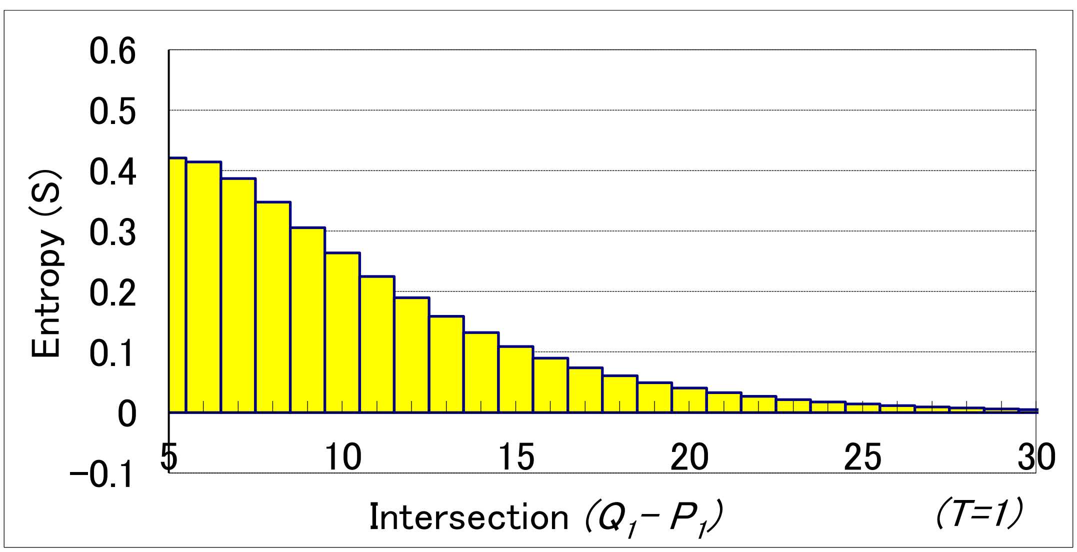

Figure 6.2: Entropy of design with discretized constraints in the AD region

7 Applications of Entropy of Design to Product Design

In this section, we investigate the coverage of a change of function design, including the change in product architecture, for the entropy of design.

For simplicity, we assume that one product is composed of two modules. Here, the two modules are realized as two different actual designs, described by the design parameters $\{X_1\}$ and $\{X_2\}$ with only one parameter in each module to satisfy two functional requirements $\{f_1(X)\}$ and $\{f_2(X)\}$. In this simple case, the modularity matrix is 2x2 for the product architecture. Then, we can examine how large the coverage of the function design is for the entropy of design in the design space. For example, we can calculate the coverage of function design for the entropy of design in the design space in the case that the modularity matrix is diagonal or lower triangle. The matrix elements of functional requirements and constraints are denoted as

$$\left(\partial f_i / \partial X_j\right) = \begin{pmatrix} a & b \\ c & d \end{pmatrix}_{ij}, \quad \left(\partial C_i / \partial X_j\right) = \begin{pmatrix} p & q \\ r & s \end{pmatrix}_{ij},$$

where we assume that $ad - bc > 0$, $ps - qr > 0$, $a, d, p, s > 0$, $b = q = r = 0$, and $c = 0$ (modular) or $c/d=1/2$ (hierarchical). The entropy of design with two modules is as follows (Tokunaga and Fujimura, 2016):

$$S = S(B_{11111}/2, A_{11111}, B_{11111}) + S(B_{22222}/2, A_{22222}, B_{22222})$$

$$+ S(B_{22111}/2, A_{22111}, B_{22111}) - S(B_{21111}/2, A_{21111}, B_{21111}),$$

$$[A_{11111}, B_{11111}] = [A_1, B_1] \cap [P_1, Q_1], \quad [A_{22222}, B_{22222}] = [A_2, B_2] \cap [P_2, Q_2],$$

$$[A_{22111}, B_{22111}] = [(c/d)\cdot A_2, (c/d)\cdot B_2] \cap [P_1, Q_1], \ [A_{21111}, B_{21111}] = [(c/d)\cdot A_1, (c/d)\cdot B_1] \cap [P_1, Q_1].$$

In the hierarchical case, the non-diagonal matrix element of the modularity matrix contributes to the positive third term in the entropy of design, such as functional benefits, and the negative fourth term in the entropy of design, such as transaction costs.

In Figure 7.1, we depict the entropy of design for two modules as indifference curves with $S = 0.43, 0.48, 0.52, 0.60, 0.70$ by two permissible ranges, $[A_{11111}, B_{11111}]$ and $[A_{22222}, B_{22222}]$ with $T = 1$ in the modular case. The higher entropy of design is realized by the product design with the smaller permissible ranges when technology is constant, which can be limited by the permissible ranges of process technology (Fujimura, 2000; Suh, 2001). In addition, when both of the two permissible ranges are in the AD region, more satisfied functional requirements and constraints can contribute to realizing higher product value.

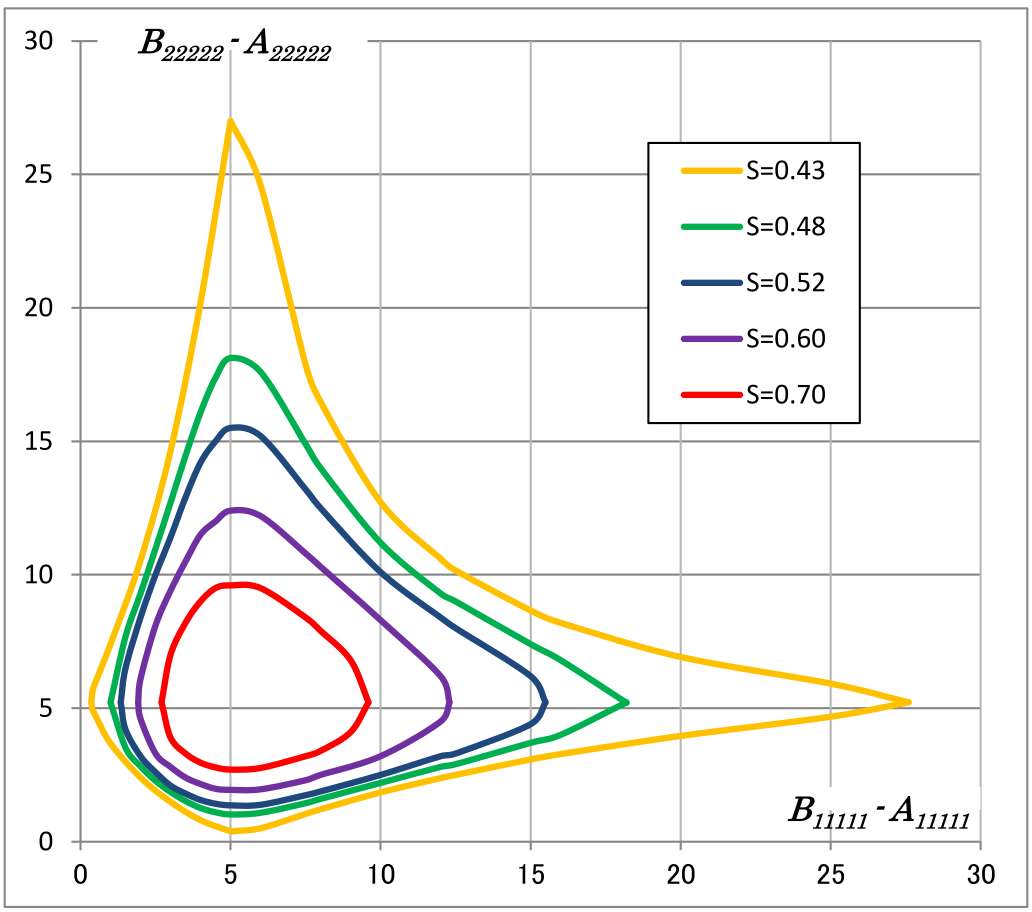

Figure 7.1: Indifference curves of entropy of design with $S = 0.43–0.70$ in the modular case

In Figure 7.2, we depict the entropy of design for two modules as indifference curves with $S = 0.43, 0.48, 0.52, 0.60, 0.70$ by two permissible ranges $[A_{11111}, B_{11111}]$ and $[A_{22222}, B_{22222}]$ with $T = 1$ in the hierarchical case with $c/d=1/2$. As one direction of product design, we should start to develop the product design related to $[A_{22222}, B_{22222}]$ for $[A_{11111}, B_{11111}]$ as hierarchical with $c/d=1/2$ in order to achieve higher product value efficiently from the origin. In comparing the indifference curves in the modular case (Figure 7.1) and the hierarchical case (Figure 7.2), we find that modularity can change the permissible ranges to realize the expected entropy of design. As a note, the local maximum in the right of Figure 7.2 means to increase the product value by focusing on a specific functional requirement, although it must be compared with the market value in Section 8.

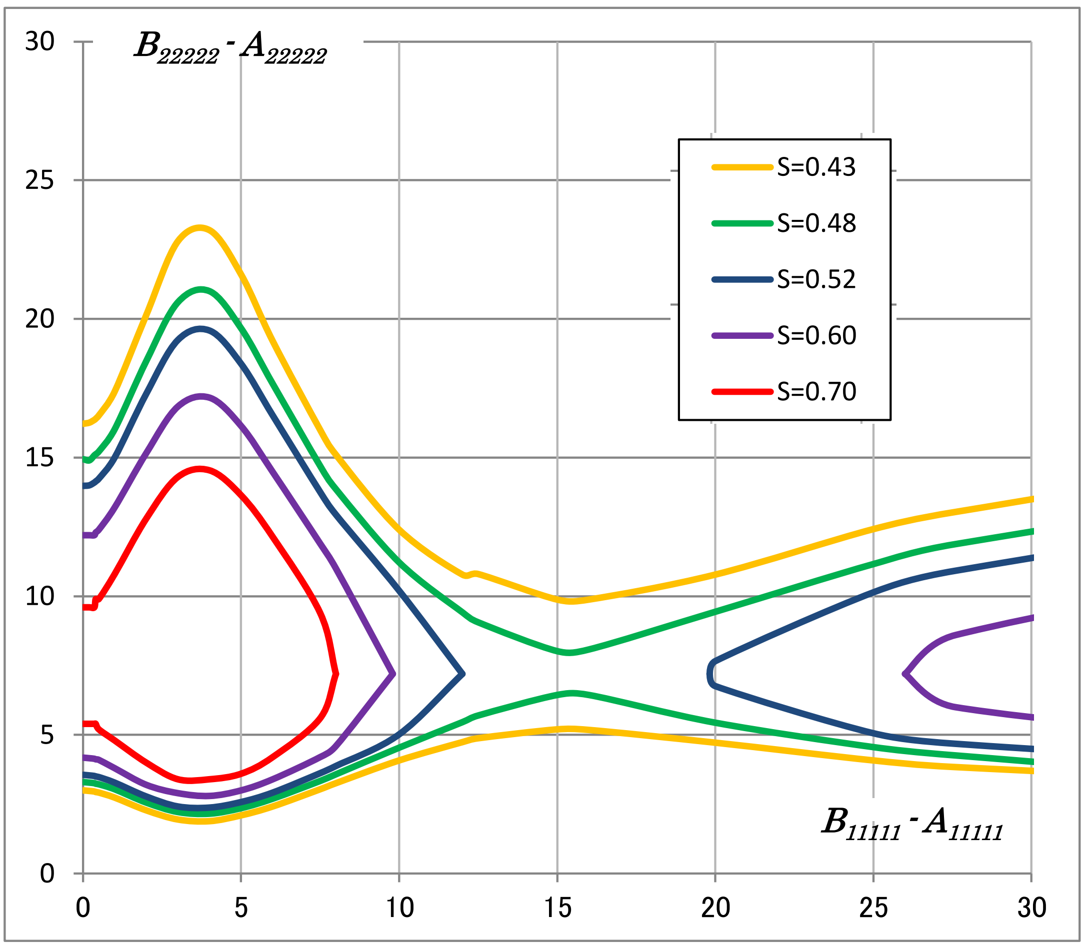

Figure 7.2: Indifference curves of entropy of design with $S = 0.43–0.70$ in the hierarchical case

A shift of the parameter *T* as a phase of realization technology rescales the axes of two permissible ranges, which means relative coefficients of the axes for the entropy of design**.** We can draw the indifference curves for the entropy of design with $T=0.5$, $T=1$ and $T=2$ in the modular case with $S=0.52$ in Figure 7.3, which shows that technology advance allows design flexibility in modularity design as wider permissible ranges to realize the expected product value. In this case, the progress of technology to satisfy the function requirements can compensate the lack of realization capability because by using upgraded technology, even enterprises with low realization capability to realize the product with the function design in the half of permissive range of D1 can realize the same market value as the product in the permissive range of D2. A progress of technology advance *T* can compensate for a lack of “skill”, expressed by $[A_{11111}, B_{11111}]$ and $[A_{22222}, B_{22222}]$. This suggests one ideal direction of technology management theoretically on how technology can impact product value.

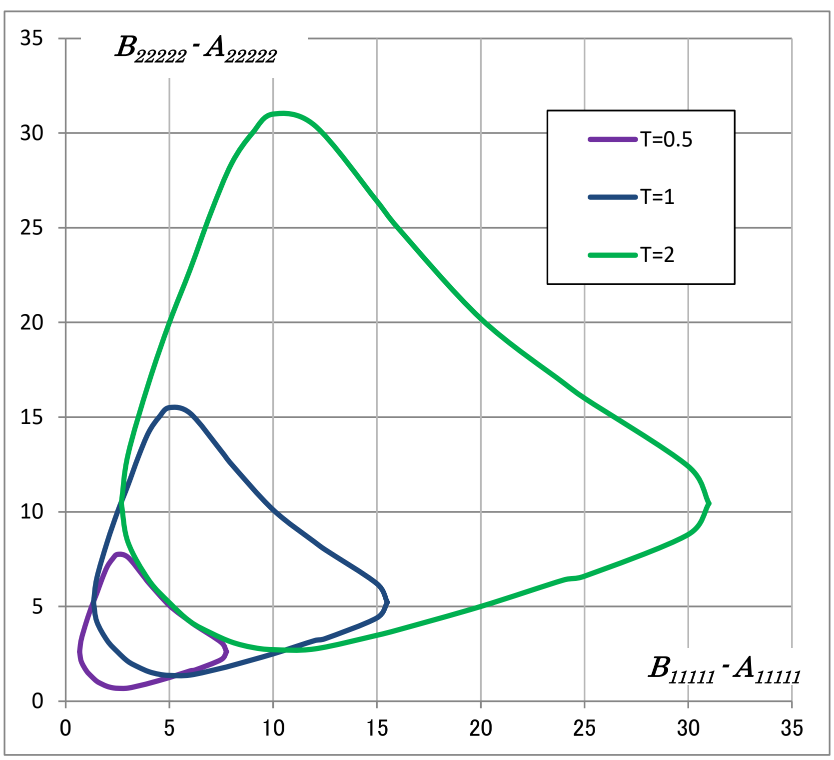

Figure 7.3: Entropy of design with $T=0.5$, $T=1$ and $T=2$ in the modular case with $S=0.52$

8 Entropy of Design and Utility Function as Market Value

In this section, we propose a mapping from entropy of design to utility function in the market, and study some examples in which the utility function determines the best product design in a phase of technology advance even in various modularity cases as modularity design by comparing the entropy of design mapped to the market with utility function.

There have been many studies on mapping customer needs in the market to the product design. We can approximately measure customer needs/attributes using functional requirements, and customer needs/attributes are, in general, denoted as functions of functional requirements as $n_i(f_k)$ for $i,k = 1,2,\ldots n$. Here, customer needs/attributes mean the kinds of benefit for the product in the market. Since we consider only a small transformation around the initial value, functional requirements in product design can be mapped to customer needs in the market through the mapping of $\partial n_i / \partial f_j$ as a square matrix. Here, we call the mapping $\partial n_i / \partial f_j$ as the extended Lancaster's consumption technology matrix, or "seeds translation matrix", to connect the market and product design, although the Lancaster's consumption technology matrix (Lancaster, 1966) is generally a mapping between goods and their characteristics. Since we can measure customer needs (shortly CN) by use of Functional Requirements (FR), here we study only a small transformation around an initial value on FR such that $\Delta n_i(f_k) = \alpha_i$. The characteristics defined by Lancaster can also introduce a kind of utility function of the characteristics as preference in the market (Lancaster, 1966; Arguea et al., 1994; Blow et al., 2008). After FR are redefined as linear functions by combining with $\partial n_i / \partial f_j$, the permissible ranges of CN can be approximately mapped to the different permissible ranges of FR through B_i and T, for examples, drawn by three rectangles in the right of Figure 8.1, which means a marketing activity to effectively distinguish the FR from the CN through marketing research.

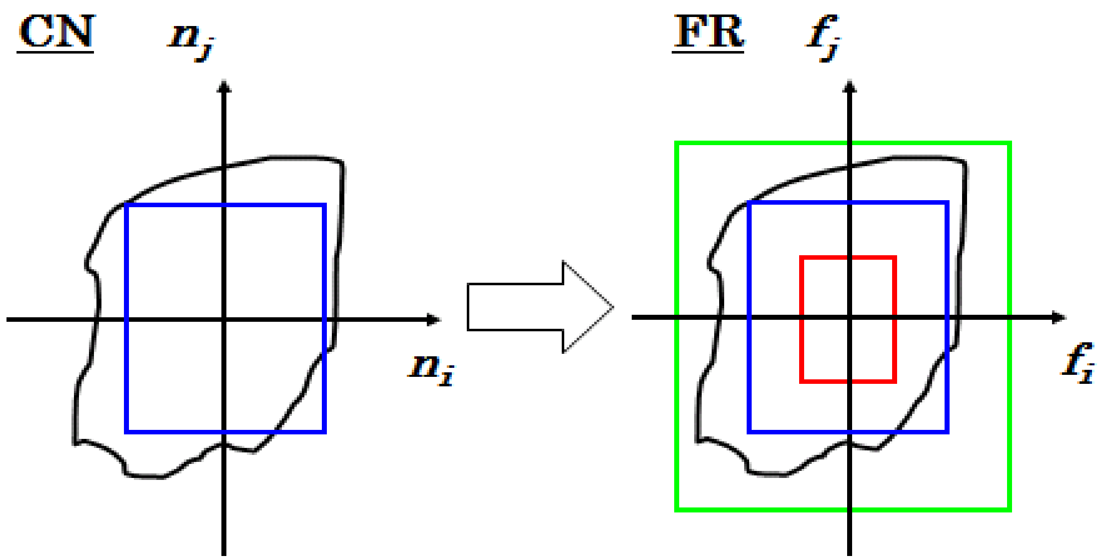

Figure 8.1: Mapping from CN to FR

Therefore, the relationship between customer needs in the market and functional requirements /design parameters/constraints in product design is shown in Figure 8.2. As a viewpoint of customer needs, the regularization parameter T means market uncertainty (Herstatt et al. 2004), as a difference between CN in the market and FR, which manufacturers know. For example, at the DSM limit when B_i are small, the market uncertainty by T can be decreased by use of marketing research to achieve higher product value, which is logically similar to Rogers' Innovation Diffusion Theory (1962).

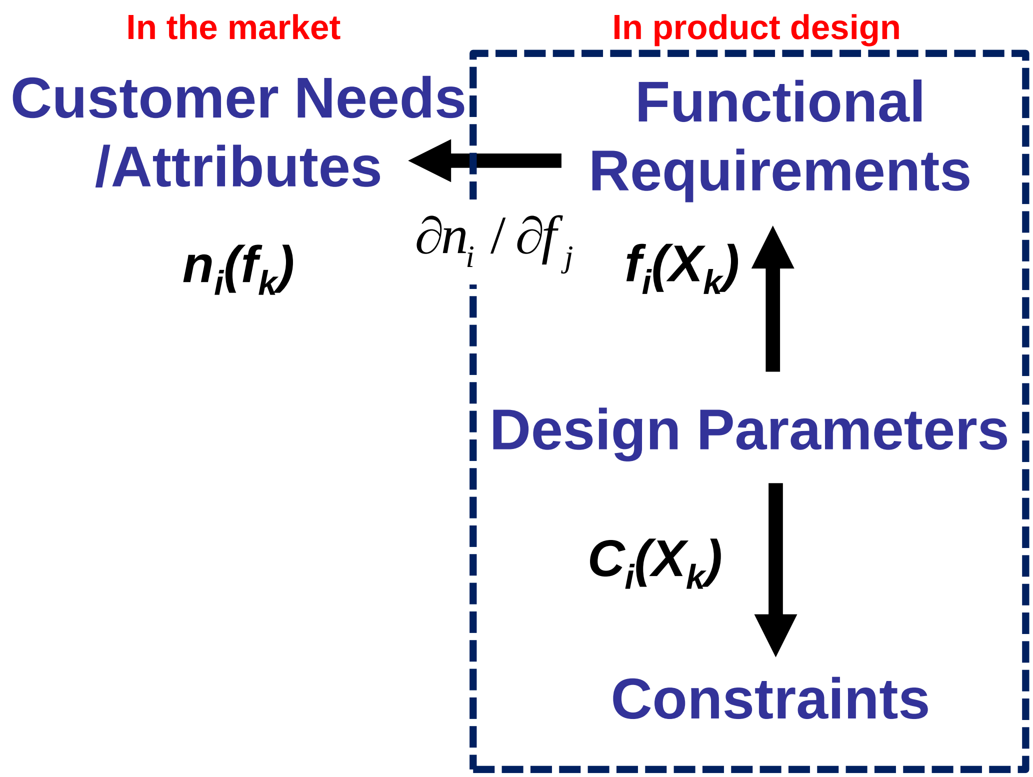

Figure 8.2: Customer needs in the market mapped to functional requirements in product design

We study a simple example case that the utility function as market value can be identified as the entropy of design in the modular case with $S = 0.43, 0.48, 0.60, 0.70$ in the DSM region, which looks downward and convex like the definition of utility function in Mankiw's textbook on economics (2011). Here we simply set the seeds transition matrix as a unit matrix. Then, the sizes of permissible ranges, [A_{11111}, B_{11111}] and [A_{22222}, B_{22222}], mean the performances of the functional requirements in the market as a point, denoted as α_1 and α_2, as the coverage of actual design in the market space, which is the same as *"each version of the product is a point in an N-dimensional space of attributes"* in the real option theory of Baldwin and Clark (1994). When we put the entropy of design with S=0.52 in the modular case, the product design with S=0.52 can cover the ranges of performance for modularity design as the market value in market space. In comparing the utility function and the entropy of design, we can find the best product design with many varieties, which fundamentally clarifies that increasing the entropy of design, like the real option value in the market (Baldwin and Clark, 2000), means to cover wide permissible ranges in product design surrounded by the forefront of technology. Concretely, the modular system in product design is ideally independent from any ambiguity of process technology to realize the utility function with less than $S=0.52$, which is one reason why product design often tends to be modular (Ulrich, 1995; Baldwin and Clark, 2000). In addition, to realize the entropy of design beyond utility function with $S=0.60$ for all performances in the DSM region, technology advance should happen toward $T=1.25$ from $T=1$ to cross the expected market value with $S=0.60$ in the DSM region. The entropy of design expresses the technology landscape for the product value to find the best product design from the wide permissible ranges (Kauffman, 1996; Kauffman et al., 2000). Thus, comparing the entropy of design and the utility function can support decision making for directions of product design as "*max utility function subject to decision variables satisfy constraints*" (Gilboa, 2010).

When we put the entropy of design with $S=0.52$ in the hierarchical case with $c/d=1/2$ and $T=1$, the ranges of performance as modularity design in the market space can be modified to be asymmetric for both axes. To achieve the expected market value beyond $S=0.60$, we can find the existence of permissible ranges on the indifference curve of the entropy of design in product design with $S=0.52$ in the DSM region, where the performance α_1 is larger than α_2. Thus, even in the same phase of technology with $T=1$, we find that the change of modularity as product design from modular to hierarchical can realize the higher market value as utility function in the permissible ranges with larger performance α_1 than α_2.

Therefore, we conclude that ***the entropy of design and the utility function in the market can determine the best product design for creating market value in a phase of technology even in any modularity case***. This theoretically consistent formulation opens "*an opportunity for these communities to work together in marketing to product domains governed by complex technological constraints*" (Krishnan and Ulrich, 2001) and provides theoretical proof to meet customer needs with product design, such as conjoint analysis (Green et al., 1981), mass customization (Pine, 1993; Tseng et al., 1996), target cascading (Michalek et al., 2005), and the market-driven approach (Kumar et al., 2009).

9 Conclusions and Future Work

We have proposed a new theoretically consistent formulation to define functional requirements and constraints with permissible ranges and the modularity as the mappings (Figure 1.1) from design parameters with the impact of technology advances to maximize utility function with customer needs through the entropy of design in product design, which is related to utility function as market value through the "seeds translation matrix." As a basic idea of this theoretically consistent formulation, we have differentiated the concept of design as "actual design", "function design" and "modularity design". In addition, it has been essential to introduce the applicability of product design with the new parameter T as a phase of technology advance. We have shown that the dynamics of product design through the modularity matrix and beyond the static design process in DSM and AD are analogous to Fermi-Dirac statistical mechanics in physics and Shannon entropy in information theory. Also, we have demonstrated the equivalence of DSM on PC for functional requirements and AD for modularity matrices and modularization, and have proposed a relationship among three modularity matrices on DP, PC, and FS by showing hierarchy of constraints. Also, we have discussed that from the analogy of econophysics, the principle of modularity can be an extension of the utility theory in economics. The theoretically consistent formulation to realize the highest market value can determine design directions to optimize functional requirements and constraints in product design through modularity design. Especially, it has been shown that a modular system is more flexible for technology advances to cover the wide permissible ranges of product design than other systems. As one conclusion, the theory suggests that we should manage modularity and technology advance separately and simultaneously by understanding the market coverage of product design. Thus, we have found the process of product design as modularity design in Figure 9.1 to increase the coverage of customer needs for utility function in the market space, which are determined by performance of the product as the intersection of functional requirements and constraints on the design space.

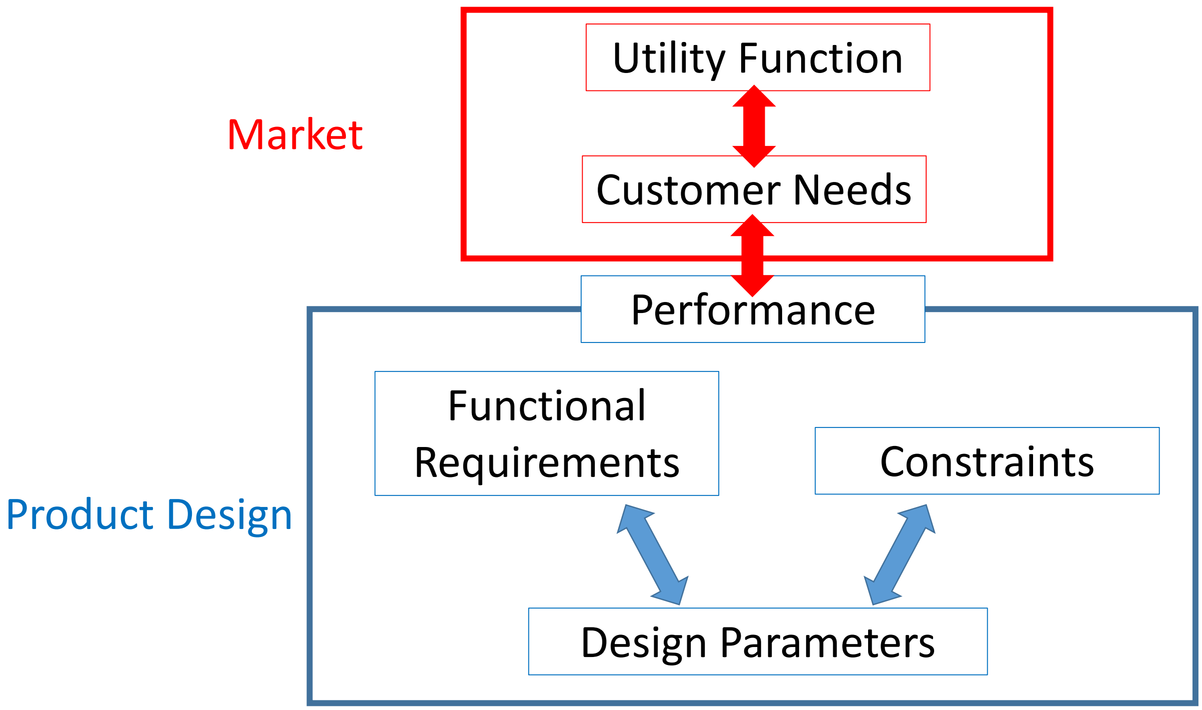

Figure 9.1: Process of product design as modularity design to create market value

The theoretically consistent formulation suggests how to simultaneously manage technology advances on both research (long-term) and development (short-term) beyond the current business to avoid a risk of sudden business failures in the future. It has been shown that disruptive innovation is caused by leading companies' lack of effort to re-study a trade-off among functional requirements and develop product performance along existing value standards using a familiar product realization technology.

As an important future work, this theoretically consistent formulation will make a prediction for future innovations by simulating the value of product design, although it has not been clear yet that the product design maximizing the entropy of design is equivalent to that of the maximum product value in the real world. Here we assume that functional requirements, constraints, design parameters, utility function, customer needs, technology advance and seeds transition matrix are known as functions. Also, since this theoretically consistent formulation has not been quantitatively demonstrated in the real world yet, it would be interesting to apply the modularity matrix in product design and the entropy of design to various case studies in industries such as supply chain, business ecosystem, competitive advantage and product positioning for the assembly and process industry. Soon, it will also reveal the dynamics of creativity from the theoretically consistent formulation. Although this theoretically consistent formulation addresses an application of statistical mechanics for fermions to business, we anticipate that a similar new analogy of physics will be developed to be useful for future innovations.

Acknowledgments

The author is thankful to Shigeki Saito, Shuzo Fujimura and Miki Mizuno for their full support on his proceeding the academic research and this doctorial thesis. The author is also grateful to Carliss Y. Baldwin, Tyson R. Browning, Kazuaki Inaba, Yuya Kajikawa, Celine Mougenot, Yukari Nagai, Mayuko Nakamaru, Shoiti Ninomiya, Taro Sugihara, Masaharu Tsujimoto, Eiichi Yamaguchi, his colleagues in Mitsui Chemicals and people at the Department of Innovation Science, School of Environment and Society, Tokyo Institute of Technology, for their helpful comments and encouragements. This work was partially supported by JSPS Grants-in-Aid for Scientific Research.

References

Abbas, A. E. 2006. Maximum Entropy Utility. *Operations Research*, *54*(2), 277-290.

Adner, R. 2002. When are technologies disruptive? A demand-based view of the emergence of competition. *Strategic Management Journal*, *23*(8), 667-688.

Akao, Y. 1972. New product development and quality assurance–quality deployment system. *Standardization and Quality Control*, *25*(4), 7-14.

Arguea, N. M., Hsiao, C., Taylor, G. A. 1994. Estimating consumer preferences using market data—an application to US automobile demand. *Journal of Applied Econometrics*, *9*(1), 1-18.

Arthur, W. B. 2009. *The nature of technology: What it is and how it evolves*. Simon and Schuster.

Baldwin, C. Y. 2008. Where do transactions come from? Modularity, transactions, and the boundaries of firms. *Industrial and corporate change*, 17(1), 155-195.

Baldwin, C. Y., Clark, K. B. 1994. Modularity-in-design: An analysis based on the theory of real options. *Harvard Business School*.

Baldwin, C. Y., K. B.Clark. 2000. Design Rules: The Power of Modularity. MIT Press, Cambridge, MA.

Baldwin, C., MacCormack, A., Rusnak, J. 2014. Hidden structure: Using network methods to map system architecture. *Research Policy*, *43*(8), 1381-1397.

Barberà, S., Hammond, P., Seidl, C. Eds. 2004. *Handbook of Utility Theory: Volume 2 Extensions*. Springer Science & Business Media.

Bayus, B. L. 2008. Understanding customer needs. *The Handbook of Technology and Innovation Management, S. Shane, ed., Wiley, West Sussex, UK*, 115-141.

Bernardo, J. M. 1979. Expected information as expected utility. *The Annals of Statistics*, 686-690.

Blow, L., Browning, M., Crawford, I. 2008. Revealed preference analysis of characteristics models. *The Review of Economic Studies*, *75*(2), 371-389.

Blumrich, F. J. 1970. Design. *Science*, *168*(3939), 1551-1554.

Browning, T. R. 2001. Applying the Design Structure Matrix to System Decomposition and Integration Problems: a Review and New Directions. Engineering Management, 48, 3, 292-306.

Browning, T. R. 2016. Design structure matrix extensions and innovations: a survey and new opportunities. *IEEE Transactions on Engineering Management*, *63*(1), 27-52.

Buderi, R. 2000. *Engines of tomorrow: How the worlds best companies are using their research labs to win the future*. Simon and Schuster.

Christensen, C. M. 1997. *The innovator's dilemma: when new technologies cause great firms to fail*. Harvard Business Review Press.

Danilovic, M., Browning, T. R. 2007. Managing complex product development projects with design structure matrices and domain mapping matrices. *International Journal of Project Management*, 25(3), 300-314.

Darooneh, A. H. 2006. Utility Function from Maximum Entropy Principle. *Entropy*, *8*(1), 18-24.

Dong, Q., D. E. Whitney. 2001. Designing a Requirement Driven Product Development Process. Proceedings of ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conferences, DTM-21682:1-10.

Eppinger, S. D. 1991. Model-based Approaches to Managing Concurrent Engineering. Journal of Engineering Design, 2, 4, 283-290.

Eppinger, S. D., T. Browning. 2012. Design Structure Matrix Methods and Applications. MIT Press, Cambridge, MA.

Eppinger, S. D., Ulrich, K. T. 1995. *Product design and development*. McGraw-Hill Higher Education.

Fine, C. H. 1998. Clockspeed: winning industry control in the age of temporary advantage. *Massachusetts: Perseus Books Reading*.

Finke, R. A., Ward, T. B., Smith, S. M. 1992. Creative cognition: Theory, research, and applications.

Fishburn, P. C. 1970. *Utility theory for decision making* (No. RAC-R-105). Research Analysis Corp, McLean VA.

Fixson, S. K. 2005. Product architecture assessment: a tool to link product, process, and supply chain design decisions. *Journal of operations management*, *23*(3-4), 345-369.

Foster, R. N. 1988. *Innovation: The attacker's advantage*. Summit Books.

Fujimura, S. 2000. Handotai Rikkoku Futatabi (in Japanese). Nikkann-Kogyo Shin-bun-sha.

Gans, J., King, S., Mankiw, N. G. 2011. *Principles of microeconomics*. Cengage Learning.

Gero, J. S. 1990. Design prototypes: a knowledge representation schema for design. *AI magazine*, *11*(4), 26.

Gilboa, I. 2010. *Rational choice*. MIT press.

Green, P. E., Srinivasan, V. 1978. Conjoint analysis in consumer research: issues and outlook. *Journal of consumer research*, *5*(2), 103-123.

Green, P. E., Carroll, J. D., Goldberg, S. M. 1981. A general approach to product design optimization via conjoint analysis. *The Journal of Marketing*, 17-37.

Green, P. E., Srinivasan, V. 1990. Conjoint analysis in marketing: new developments with implications for research and practice. *The Journal of Marketing*, 3-19.

Hatchuel, A., Weil, B. 2009. CK design theory: an advanced formulation. *Research in engineering design*, *19*(4), 181.

Hauser, J. R., Clausing, D. 1988. The house of quality. *Harvard business review*, *66*(3).

Hauser, J., Tellis, G. J., Griffin, A. 2006. Research on innovation: A review and agenda for marketing science. *Marketing science*, *25*(6), 687-717.

Herstatt, C., Verworn, B., Nagahira, A. 2004. Reducing project related uncertainty in the" fuzzy front end" of innovation: a comparison of German and Japanese product innovation projects. *International Journal of Product Development*, *1*(1), 43-65.

Jacobides, M. G., Winter, S. G. 2005. The co-evolution of capabilities and transaction costs: Explaining the institutional structure of production. *Strategic Management Journal*, 26(5), 395-413.

Jaynes, E. T. 1957. Information theory and statistical mechanics. *Physical review*, *106*(4), 620.

Kauffman, S. 1996. *At home in the universe: The search for the laws of self-organization and complexity*. Oxford university press.

Kauffman, S., Lobo, J., Macready, W. G. 2000. Optimal search on a technology landscape. *Journal of Economic Behavior & Organization*, *43*(2), 141-166.

Krishnan, V., Ulrich, K. T. 2001. Product development decisions: A review of the literature. *Management science*, 47(1), 1-21.

Kubo, R. 1965. Statistical Mechanics: An Advanced Course with Problems and Solutions. North-Holland, Amsterdam.

Kulak, O., Kahraman, C. 2005. Fuzzy multi-attribute selection among transportation companies using axiomatic design and analytic hierarchy process. *Information Sciences*, 170(2), 191-210.

Kulak, O., Cebi, S., Kahraman, C. 2010. Applications of axiomatic design principles: A literature review. *Expert Systems with Applications*, *37*(9), 6705-6717.

Kumar, D., Chen, W., Simpson, T. W. 2009. A market-driven approach to product family design. *International Journal of Production Research*, *47*(1), 71-104.

Lancaster, K. J. 1966. A new approach to consumer theory. *The journal of political economy*, 132-157.

Lindemann, U., Maurer, M., Braun, T. 2009. *Structural complexity management.* Springer.

Loucopoulos, P., Karakostas, V. 1995. *System requirements engineering*. McGraw-Hill, Inc..

Luo, J., Whitney, D. E., Baldwin, C. Y., Magee, C. L. 2009. *Measuring and Understanding Hierarchy as an Architectural Element in Industry Sectors*. Harvard Business School.

Michalek, J. J., Feinberg, F. M., Papalambros, P. Y. 2005. Linking marketing and engineering product design decisions via analytical target cascading*. *Journal of Product Innovation Management*, *22*(1), 42-62.

Michelena, N. F., Papalambros, P. Y. 1995. Optimal model-based decomposition of powertrain system design. *Journal of mechanical design*, *117*(4), 499-505.

Moreau, C. P., Dahl, D. W. 2005. Designing the solution: The impact of constraints on consumers' creativity. *Journal of Consumer Research*, *32*(1), 13-22.

Ortega, P. A., Braun, D. A. 2013. Thermodynamics as a theory of decision-making with information-processing costs. In *Proc. R. Soc. A* (Vol. 469, No. 2153, p. 20120683). The Royal Society.

Pine, B. J. 1993. *Mass customization: the new frontier in business competition*. Harvard Business Press.

Rogers, E. M. 1962. Diffusion of innovations. *Diffusion of innovations.*

Shannon, C. E. 1948. A mathematical theory of communication.

Smith, E., Foley, D. K. 2008. Classical thermodynamics and economic general equilibrium theory. *Journal of economic dynamics and control*, *32*(1), 7-65.

Steward, D. V. 1981. The design structure system: a method for managing the design of complex systems. *Engineering Management, IEEE Transactions on*, (3), 71-74.

Suh, N. P. 2001. Axiomatic Design: Advances and Applications. Oxford University Press, New York.

Tang, D., Zhang, G., Dai, S. 2009. Design as integration of axiomatic design and design structure matrix. *Robotics and Computer-Integrated Manufacturing*, 25(3), 610-619.

Terwiesch, C., Ulrich, K. T. 2009. *Innovation tournaments: Creating and selecting exceptional opportunities*. Harvard Business Press.

Tokunaga, T., S, Fujimura. 2013. Equivalence of Design Structure Matrix and Axiomatic Design. In *Reducing risk in innovation: Proceedings of the 15th International DSM Conference Melbourne, Australia, 28-30 August 2013*. 73-81.

Tokunaga, T., S, Fujimura. 2013. Equivalence of Design Structure Matrix and Axiomatic Design. *Transactions of Japan Society of Mechanical Engineers*.

Tokunaga, T., S, Fujimura. 2014. Principle of Modularity. *Transactions of the Academic Association for Organizational Science*.

Tokunaga, T., S, Fujimura. 2015. The Principle of Modularity. In *DSM 2015: Modeling and managing complex systems-Proceedings of the 17th International DSM Conference Fort Worth (Texas, USA), 4-6 November 2015*.

Tokunaga, T., Fujimura, S. 2016. A Unified Theory of Design Structure Matrix and Axiomatic Design for Product Architecture. *The Journal of Modern Project Management*, *3*(3).

Tokunaga, T., S, Fujimura. 2017. Product Design and Utility Function. *Transactions of the Academic Association for Organizational Science*, *6*(1), 126-131.

Tokunaga, T., Fujimura, S. 2017. Product Design for Innovation. *Proceedings of Japan Creativity Society, Tokyo, 9-10 September 2017.*

Tokunaga, T., Fujimura, S. 2018. Dynamics of Product Design for Creating Market Value. *Proceedings of International Conference on Creativity and Innovation, Osaka, 10-12 September 2018.*

Tseng, M. M., Jiao, J., Merchant, M. E. 1996. Design for mass customization. *CIRP Annals-Manufacturing Technology*, *45*(1), 153-156.

Ulrich, K.T. 1995. The role of product architecture in the manufacturing firm. *Research policy*, 24(3), 419-440.

Ulrich, K. T. 2011. Design is everything? *Journal of Product Innovation Management*, *28*(3), 394-398.

Ulrich, K. T., Ellison, D. J. 1999. Holistic customer requirements and the design-select decision. *Management Science*, *45*(5), 641-658.

Urban, G. L., Hauser, J. R. 1980. *Design and marketing of new products*. Prentice hall.

Utterback, J. M. 1996. *Mastering the dynamics of innovation.* Harvard Business Press.

Von Neumann, J., Morgenstern, O. 1945. Theory of games and economic behavior. *Bull. Amer. Math. Soc*, *51*(7), 498-504.

Yassine, A., Braha, D. 2003. Complex concurrent engineering and the design structure matrix method. *Concurrent Engineering*, *11*(3), 165-176.

Yassine, A., D. R. Falkenburg. 1999. A Framework for Design Process Specifications Management. Journal of Engineering Design, 10(3), 223-234.

Yassine, A. A., Naoum-Sawaya, J. 2017. Architecture, performance, and investment in product development networks. *Journal of Mechanical Design*, *139*(1), 011101.

Yu, T. L., Yassine, A. A., Goldberg, D. E. 2007. An information theoretic method for developing modular architectures using genetic algorithms. *Research in Engineering Design*, *18*(2), 91-109.

Appendix A: Derivative of Modularity Matrix

We consider small transformations of modularity matrix for initial values, which is written as tensors $G_{ij,k} = \partial_k G_{ij}$. This is one way to study global information of modularity in base vector space. $G_{ij,k}$ for functional requirements on DP is calculated as follows.

$$G_{ij,k} = \frac{\partial G_{ij}}{\partial X_k}$$

$$= \sum_{m,l,p,q} -\left(\frac{\partial f_m}{\partial X_i}\right)^{-1} \cdot \frac{\partial^2 f_m}{\partial X_k \partial X_l} \cdot \left(\frac{\partial f_p}{\partial X_l}\right)^{-1} \cdot Kf_{pq} \cdot \frac{\partial f_q}{\partial X_j}$$

$$+ \sum_{m,k,p,q} \left(\frac{\partial f_m}{\partial X_i}\right)^{-1} \cdot Kf_{ml} \cdot \frac{\partial f_p}{\partial X_l} \cdot \left(\frac{\partial f_p}{\partial X_q}\right)^{-1} \cdot \frac{\partial^2 f_m}{\partial X_k \partial X_q}$$

$$- \sum_{m,l} \left(\frac{\partial f_m}{\partial X_i}\right)^{-1} \cdot \delta_{ml} \frac{\partial f_m}{\partial X_k} \cdot \frac{\partial f_l}{\partial X_j}$$

Here, we note that the third term of $G_{ij,k}$ does not change the modular structure.

For example, we consider a case that modular structure changes by small transformations of initial values. Design parameters and functional requirements are set as $\{X_1,X_2\}$ and $\{f_1,f_2\}$, and $Kf=diag(\alpha_1,\alpha_2)$. If $\partial f_2 / \partial X_1 |_{X0} = 0$, $G_{21}=0$, which means zero lower triangular matrix element of DSM. Only if $\partial^2 f_2 / \partial X_k \partial X_l |_{X0} \neq 0$, $G_{21}=0$ and $G_{21,k} \neq 0$, which changes the modular structure. These conditions are satisfied, when $f_2(X_1,X_2)= g(X_2)(X_1-X0_1)^2+h(X_2)$ for arbitrary functions of X_2 such as $g(X_2)$ and $h(X_2)$. Then, the modularity can change on the boundary of permissible ranges.

By use of the tensor $G_{ij,k}$, we can know changes of modular structure of modularity matrix around initial values. For example, if the matrix elements of $G_{ij,k}$ are more large than G_{ij}, the modularity can be rapidly changed in base vector space, which may be the case for immature technology and products.

Appendix B: Mathematical Description of Modularity Matrix

We try to write in mathematical words, the definition of modularity matrix for functional requirements and constraints, more exactly.

First, Design Parameter space is a subset of $\mathbb{R}^n$ such that D $\subset$ $\mathbb{R}^n$, where X_i $\in$ X for $X \in D$ such that $X = {}^t(X_1, ..., X_n)$. A functional requirement f is a C^∞class regular mapping : $D \rightarrow D$ such that $f(X) = {}^t(f_1(X), ..., f_n(X))$, where $f_i : D \rightarrow \mathbb{R}$ for all $i \in \{1, ...n\}$.

Next, we choose an initial value $X0 \in D$ and $X0_i \in \mathbb{R}$. $\frac{\partial f_i}{\partial X_j}(X)$ is a partial derivative of $f_i(X)$ for X_j, and we express $\frac{\partial f_i}{\partial X_j}(X0)$ by substituting the initial value such as $X_i = X0_i$. $\left(\frac{\partial f}{\partial X}\right)$ is a following matrix as

$$\begin{pmatrix} \frac{\partial f_1}{\partial X_1}(X0) & \cdots & \frac{\partial f_1}{\partial X_n}(X0) \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial X_1}(X0) & \cdots & \frac{\partial f_n}{\partial X_n}(X0) \end{pmatrix}.$$

$\left(\frac{\partial f}{\partial X}\right)_{ij}$ is (i,j) element of $\left(\frac{\partial f}{\partial X}\right)$. $\left(\frac{\partial f}{\partial X}\right)^{-1}$ is an inverse matrix of $\left(\frac{\partial f}{\partial X}\right)$. $\left(\frac{\partial f}{\partial X}\right)^{-1}_{ij}$ is (i,j) element of $\left(\frac{\partial f}{\partial X}\right)^{-1}$, which depends only on the initial value.

We define permissible ranges for functional requirements such that $(Kf)_{ij} = diag(\alpha_1, ..., \alpha_n)$. Here, $\alpha \in U$ for $U \subset \mathbb{R}^n$ and $\alpha_i \in \mathbb{R}$ such that $\alpha = {}^t(\alpha_1, ..., \alpha_n)$.

Modularity matrix for functional requirements is a *n x n* matrix such that

$$(Gf)^{(\alpha)}_{ij} = \sum_k \left(\frac{\partial f}{\partial X} \right)^{-1}_{ik} \sum_m (Kf)_{km} \left(\frac{\partial f}{\partial X} \right)_{kj} \quad .$$

Also, as a set, modularity matrix for functional requirements is written as $\left\{ (Gf)^{(\alpha)} \big|_{\alpha \in U} \right\} \subset \mathbb{R}^{n2}$.

Second, a function C for constraints is a C^{∞}class regular mapping: $D \rightarrow D$ such that $C(X) = {}^t(C_1(X),...,C_n(X))$, where $C_i : D \rightarrow \mathbb{R}$ for all $i \in \{1,...n\}$. $\frac{\partial C_i}{\partial X_j}(X)$ is a partial derivative of $C_i(X)$ for X_j , and we express $\frac{\partial C_i}{\partial X_j}(X0)$ by substituting the initial value such as $X_i = X0_i$. Moreover, $\left(\frac{\partial C}{\partial X} \right)$ is a following matrix as

$$\begin{pmatrix} \frac{\partial C_1}{\partial X_1}(X0) & \cdots & \frac{\partial C_1}{\partial X_n}(X0) \\ \vdots & \ddots & \vdots \\ \frac{\partial C_n}{\partial X_1}(X0) & \cdots & \frac{\partial C_n}{\partial X_n}(X0) \end{pmatrix} .$$

$\left(\frac{\partial C}{\partial X} \right)_{ij}$ is (i,j) element of $\left(\frac{\partial C}{\partial X} \right)$. $\left(\frac{\partial C}{\partial X} \right)^{-1}$ is an inverse matrix of $\left(\frac{\partial C}{\partial X} \right)$. $\left(\frac{\partial C}{\partial X} \right)^{-1}_{ij}$ is (i,j) element of $\left(\frac{\partial C}{\partial X} \right)^{-1}$.

We define permissible ranges for constraints such that $(Kc)_{ij} = diag(\gamma_1,...,\gamma_n)$. Here, $\gamma \in V$ for $V \subset \mathbb{R}^n$ and $\gamma_i \in \mathbb{R}$ such that $\gamma = {}^t(\gamma_1,...,\gamma_n)$.

Modularity matrix for constraints is a *n x n* matrix such that

$$(Gc)^{(\gamma)}_{ij} = \sum_k \left(\frac{\partial C}{\partial X} \right)^{-1}_{ik} \sum_m (Kc)_{km} \left(\frac{\partial C}{\partial X} \right)_{kj} \quad ,$$

Also, as a set, modularity matrix for constraints is written as $\left\{ (Gc)^{(\gamma)} \Big|_{\gamma \in V} \right\} \subset \mathbb{R}^{n2}$.

Modularity matrix for both functional requirements and constraints is

$$\left\{ (G)^{(\alpha,\gamma)} \right\} = \left\{ (Gf)^{(\alpha)} \times (Gc)^{(\gamma)} \Big| (Gf)^{(\alpha)}, (Gc)^{(\gamma)} \in \left\{ (Gf)^{(\alpha)} \Big|_{\alpha \in U} \right\} \wedge \left\{ (Gc)^{(\gamma)} \Big|_{\gamma \in V} \right\} \right\} \quad .$$

As a note, the existence of modularity matrix supposes that $\left\{ (Gf)^{(\alpha)} \Big|_{\alpha \in U} \right\} \wedge \left\{ (Gc)^{(\gamma)} \Big|_{\gamma \in V} \right\} \neq \phi$.

Appendix C: Short Review of Statistical Mechanics

We shortly review statistical mechanics of Fermi-Dirac Statistics in physics. We consider grand-canonical ensemble for fermions, where the system can exchange energy *E* and number of particles with heat bath of temperature T, energy ε=α and chemical potential μ=B. A distribution for the average number of particles and the entropy are as follows.

$$n_f = \frac{1}{1+e^{\frac{(\alpha-B)}{T}}}$$

$$S = \log\left(1+e^{-\frac{(\alpha-B)}{T}}\right) + \frac{\alpha+B}{T}\left\{\frac{1}{1+e^{\frac{(\alpha-B)}{T}}}\right\}$$

Next, we introduce ghost fermions with negative values against the fermions. Then, from statistical mechanics (Kubo, 1965), a partition function *Z* for a grand-canonical ensemble system with fermions and ghost fermions is defined as

$$Z = Z(\alpha, A, B) = \frac{1+e^{-\frac{(\alpha-B)}{T}}}{1+e^{-\frac{(\alpha-A)}{T}}}.$$

The Fermi–Dirac entropy can be written by the density of state *W* as Boltzmann's formula:

$$S(\alpha, A, B) = \log W = \log(e^{-E-\hat{G}}/Z),$$

$$E = \alpha\left\{\frac{1}{1+e^{\frac{(\alpha-B)}{T}}} - \frac{1}{1+e^{\frac{(\alpha-A)}{T}}}\right\},$$

$$\hat{G} = \frac{A}{1+e^{\frac{(\alpha-A)}{T}}} - \frac{B}{1+e^{\frac{(\alpha-B)}{T}}} = A\,P_A - B\,P_B.$$

Since the entropy of design for modularity matrix in product design is Fermi–Dirac entropy in thermodynamics for fermions, the entropy of design for modularity matrix in product design satisfies the first law of thermodynamics (Kubo, 1965):

$$T\,dS = -dJ + dE - d\hat{G},$$

$$J = -T \cdot \log Z\,,$$

with $S \to 0$ at $T \to 0$, although the entropy of design can be negative as a difference from a product value of the initial product design. We conclude that **quantities that satisfy thermodynamics exist in product design”**, which is consistent with econophysics of Smith and Foley (2008).