Opening the Door for the New Methodology for Optimizing Functional Material Development in Technology Management Framework

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***Abstract*--As the chemical companies, functional material development is the cornerstone of sustainable competitiveness. In the technology management perspective, it is quite difficult to understand the present R&D project status within overall process. Therefore, companies struggle to allocate and organize their resources for material development. Dynamic technology management replies this need.**

In the previous work, various kind of approach to solve this need, however, it was simply difficult to explain the R&D project status as quantitative dynamic model. In this paper, we attempted to be expressed the state of the research and development process by means of quantitative physical model as modified magnetic model. we defined the R&D project as dynamic model and estimated interactions among internal elements within the company. The model can distinguish the success / failure case beyond the function of the time of the project. In addition, the visualization of the result of the model simulation gives feedback of the improvement point from the research and development process status. Our highlight is the optimization strategy for technology management framework and enable a practical feedback of optimizing functional material research and development.

I. INTRODUCTION

The chemical industry supplies a wide variety of products to many fields including the automotive, electronics, semiconductor, and photovoltaic industries. Japanese companies have succeeded in maintaining a high level of global competitiveness through technical capabilities, excellent research and development (R&D) records of accomplishment, and the exploitation of end-product manufacturer connections. Additionally, Japanese companies have developed a variety of high-tech materials. Recently, Japanese semiconductor industry and consumer product industry have lost their global competitiveness by deflation and long-term stagnation of the Japanese economy after the collapse of the bubble [1]. China and South Korean company has taken over their position. Therefore, Japan is considered a national decline. However, especially electronic material industry has hold global competitiveness now [2]. According to the bilateral trade between Japan and South Korea, Japan continues to run chronic surpluses in material segment [3]. For example, TAC film1 is the indispensable functional film to produce LCD Panel and following LCD-TV, LCD monitor, Tablet and Smart phone and others. Only two Japanese companies, Fujifilm Holdings Corporation and Konica Minolta, Inc. have dominated 100% market share of global supply in 2012. In spite of this critical position of Japanese Chemical Industry in the global market, they are underestimated undeservedly. We are interested in this fact. A process management technique is known as the management of technology (MOT). As the result of the recognition about MOT, the generalization of R&D to new business development (NBD) has been widespread. NBD is essential driver to the sustainable competitiveness of firms. Without new products to stimulate new business, companies are not sustainable. However, uncertainties of technical and market are persistent unfortunately. Businesses that sell high-tech materials are also concerned with technical uncertainties concerning the end product: the device or module is an intermediate product of the brand's consumer products. In the high-risk development for materials, it is required the product concept. The concept is to anticipate the potential needs of customers before customers recognize to their needs by themselves. An R&D project in the NBD process will begin as a product concept.

While the conventional MOT method can work well for problems with relative certainty state, it works poorly and is still challenge for problems characterized by uncertainty status. One of the biggest reasons of the uncertainty is we cannot capture well the interaction of uncertainty elements. Therefore, we focus on the interdependence of ingredients in the process. The state-of-the-art approach that differentiates the study is to apply physics principles into MOT as quantitative analysis method. A quantitative model of process management is introduced for the continuous period, focusing on the process until end of new business development from starting early research stage after idea creation. A quantitative representation of an R&D project could predict the future of the project by simulation. The current situation, and the results of the project, could be significantly improved in this study.

Many kinds of R&D management model have been studied in the passed. Those models are fundamentally conceptual model and most likely quantitative models have designed by the indicator of financial statement. Magnetic model is one of the physical models representing the state. In this paper, we attempted to be expressed the state of the research and development process by means of quantitative physical model as modified magnetic model.

The Ising model [4], a mathematical physics model of spin-polarized system, e.g. ferromagnetic and anti-ferromagnetic. It is the simple model consisting of two state variables (up-spin state and down-spin state) that occur when a small change in a parameter, such as temperature or pressure, causes a large-scale qualitative change in the state of a system. Nearest-neighbor interaction (network) creates correlative behavior. The Ising model is used to predict the potential for a phase transition. This physical phase transition model has been applied to an analysis of many complex systems including the human body, society, and economic markets to extract the universal characteristics of the system, such as the "cooperative" behavior of a large system. This paper addresses the complex MOT system by applying the Ising-based mathematical model and quantitative analysis [5]. Our mathematical model consists of three energy components. One of these components expresses the interaction energy among six factors: market, technology, cost, human resources, mental model, and design.

We study the interaction between the factors, which defines the network state of the complex system from an intelligence-network dynamics perspective. The importance of the interaction matrix among these factors is also discussed.

II. PREVIOUS WORK

Studies concerning innovation, product development projects, and NBD address MOT from different perspectives.

A. Research and product development management

Research concerning new product development (NPD[1]) began in the late 1960s when attempts were made to extract the success factors from each NPD success. One of the well-known research projects was the SHAPPO (scientific activity predictor from patterns of heuristic origins) project led by Freeman and Rothwell [6, 7] and "*the NewProd project*" led by Cooper [8, 9]. With respect to SHAPPO, the project analyzed a total of 72 success and failure cases focusing on the chemicals and materials industry. Freeman and Rothwell identified five success factors: 1) understanding customer needs, 2) marketing or promotion activity, 3) effective product development,4) effective external company communications, 5) senior managers with substantial authority, responsibility, and commitment. "*The NewProd project*", which analyzed 177 cases from the production industry using a concept model[2], studied a combination of (1) marketing activities, (2) NPD process management, (3) the characteristics of information gathering, (4) the target market, (5) the company, (6) the characteristics of NPD project management. The conclusions were that successful projects include the provision of unique products for the customer, effective marketing, and synergy between technology and production [8]. Additionally, product differentiation is a key success factor although the product development process type is different with respect to Japanese functional chemical companies [10]. However, the cited studies only verify the success factors as a necessary condition. Based on the research results concerning the success factors, the conceptualization of product development structure and mechanisms is attempted in this study.

B. The product development process management

The product development process was a popular area of study in the mid-1980s that was approached from perspectives such as process patters and process management. The linear process model has three steps, new invention, NPD, and commercialization. The fuzzy front-end (FFE) process focuses on the initial stage of NPD in a linear model. The FFE phase features product concept creation and idea generation with respect to new products [11]. More precisely, "product strategy formulation and communication, opportunity identification and assessment, idea generation, product definition, project planning, and executive reviewers" are typically conducted in the FFE stage p59, [12]. Differences in FFE activity are apparent between cases of success and failure [13]. The funnel-type stage-gate model is used to manage the R&D project process [14-20]. In this model, it is proposed that the interdependency between the R&D and marketing divisions and divided the R&D process into eight parts (target setting; idea generation; idea selection; product development; product valuation; product marketing strategy; evaluation of product performance; and product commercialization). The study summarized the roles of senior level marketing and other divisional management using three different criteria, responsibility, support, and approval. This integration of marketing and R&D is modified by [21-23].

Recently, Stage gate process model has been extended by the external interaction; Open Innovation propounded by Chesbrough [24]. Open innovation suggests that firms should interact with other firms or institute to combine their external idea and internal idea. Open innovation is not limited only idea creation. Open innovation is a kind of system to explore some combination by a various kinds of internal and external resources for the innovative opportunities. Cooperation and coordination have been found in studies to be significant in divisional communication in Japanese product development organizations. Overlapping product development phases, such as the rugby-type phase, affects product processes [25]. Clark and Fujimoto [26] studied 29 global automobile NPD cases and applied statistical analysis. The authors concluded that product integrity together with close communication is required between divisions. Moreover, a product manager emphasis on effective coordination between cross-divisional, functional, disciplinary (external integration), and internal NPD team communication (internal integration) can achieve a high level of organizational performance in product development [26].

Studies on the chemical industry revealed that product development in this field possesses unique characteristics such as (1) complex and diverse customer needs, (2) uncertainty between material product structures and the function of the material products [27], (3) difficulties in

[1] The NPD is defined new product development: the NBD is defined creating new business by applying new/existing product.

[2] The concept is divided into two components, outside situational factors (company, target market, NPD project management) and management controllable factors (marketing activity, information gathering characteristics, and NPD process management.

material evaluation. The analysis clarified three points: (1) the need to respond to customer need in the concept development stage [27], (2) the need to reduce the timing with respect to a prototype sample product, (3) accumulated technology expertise affects the success or failure of chemical industry, A vital issue for NPD is the need to assess material specifications, the production process, and the performance of the customer product for the customer [28]. Further studies of this assessment capability, dynamic valuation capability, show that it accumulates during the NPD process and this capability enhances product development performance [29]. An empirical study of a Japanese company by Kusunoki et al [30] concluded that a competitive advantage of Japanese firms is organizational process capability. Customer-oriented marketing activity is a key success factor. Tomita [31] studied a total of 51 NPD projects of 22 Japanese companies using a questionnaire survey and concluded that product concept creation from a customer perspective rather than a direct customer perspective is an effective factor for success. Kuwashima [32] studied functional chemical product development specifically, and Matsuda [33] used a classification of the two factors of market uncertainty and technology difficulty. The majority of functional product development is composed of small-market uncertainty and a low level of technology difficulty. Functional product development incorporates five process steps, the confirmation of need and specifications, material and processing method choice decisions, trial sample production and presentation to the customer, mass-production process development, and commercialization. Product development projects for imminent commercialization have been evaluated based on integrated qualitative and quantitative model studies using Monte Carlo simulations to assess business operation scenarios [34]. Product development models have been adapted from linear models. However, non-linear models have also been studied and have focused on product development.

C. A thinking point model of R&D management

A total of 103 new industrial product projects were studied incorporating a conceptual framework with six elements (the idea source, the nature of process activities, project organizational methods, the international orientation of projects, early product definition, and product launch) necessary for product success in the chemical industry by Cooper and Kleinschmidt [35]. Cooper and Kleinschmidt concluded that the quality of activity execution of the innovation process is integral to new product success. The six elements of the study framework included a detailed market study, pilot production, a pre-commercialization business analysis, preliminary market assessment, a trial sales period, and initial screening. The interactions among the six elements were beyond the scope of the study.

Innovator skill concerning the generation of ideas can also be the focus of an analysis. These key skills include the cognitive skill of associational thinking, which engages the behavioral skills of questioning, observing, networking, and experimenting [36]. The five elements of organization, technology, user/consumer, idea/concept, and a participant mental model can assist innovation teams struggling to improve innovation practices by Høussian et al [37]. Høussian and co-researchers perspective that spans research and new business development (NBD) emphasizes cross divisional communication and the five perspectives: 1) visualization of the goal, 2) visualization of the process, 3) open discussion concerning commercialization, 4) the need for individuals who can understand R&D and business, and 5) decision-making capacity for successful NBD [34].

Wind [20] proposed interdependency between the R&D and marketing divisions. The author divided the R&D process into eight parts (target setting; idea generation; idea selection; product development; product valuation; product marketing strategy; evaluation of product performance; and product commercialization) and summarized the role of the marketing division senior management, and other divisional senior management from the perspective of three different criteria including responsibility, support, and approval. This integration of marketing and R&D is modified by Gupta, Raj, and Wilemen [21-23] in a competition model using an agent-based simulation used to study the relationship between the gatekeeper and team members in complex organizational management systems [39]. The results show that well-educated engineers with a high level of communication skills exhibit unique behavioral patterns. Communication with other organizations is centered on the organizational interface. Contrastingly, an agent with a lower level of communication skill can achieve high performance through a skunkworks model that promotes proactive activities in various situations [40].

The concept of “small world networks” [41] was introduced as an attempt to capture and study nontrivial features observed in realistic social networks. The Ising model was studied on a small world network by Barrat and Weight[42]. According to statistical physics, the one-dimensional (1D) Ising model has no phase transition, but the two-dimensional (2D) Ising model in a square lattice is one of the simplest statistical models that can explain a phase transition [4, 46]. A milestone in the development of modern statistical mechanics is the exact solution of the 2D Ising model in a square lattice discovered by Onsager [46]. In higher dimensions, that is, greater than three, the free energy is calculated by simulation. However, higher-dimensional studies of nearest-neighbor links, or complex systems, have not proven sufficient.

The techno-economic network [48] provides a simple analytical framework for the innovation system. It consists of three major poles (science, technology, and market) and one minor pole (finance). These poles interact both directly and indirectly. The close interaction of main R&D activities is explained using an interactive geometric innovation process model, which consists of conception, applied research, marketing (sales and distribution), experimental development, and engineering (including production) [49].

A quantitative model approach has also been assumed in addition to concept model analysis approaches based on questionnaire surveys with statistical analysis of principal components.

D. The quantitative model

The quantitative modeling approaches of product development processes are classified as a scoring approach [50], a computational approach [51], a decision and game theoretical approach, simulation models for R&D [52, 53], heuristics for R&D project selection and resource allocation, and cognitive emulation for R&D project selection and resource allocation. The effectiveness of another approach, consisting of a quantitative model based on a management index calculated from financial statements, was discussed using simulations [54].

A structural equation model of the FFE analysis is applied to two types of FFE with direct impact by influencing the next stage or indirect impact [55]. Existing research has captured R&D from a variety of perspectives. However, few studies from an MOT perspective consider quantitative models of the management of NBD and NPD in the chemical material industry.

E. The knowledge creation model and Technology Valuation

The theory of organizational knowledge creation developed by Nonaka and his colleagues [56-63] originated in studies of information flow. The spiral of knowledge creation is referred to as the SECI (socialization, externalization, combination, internalization) model, which was first fully proposed in 1994 [57]. The model was revised in "The Knowledge Creating Company" [59] and was expanded together with *Ba* [61]. SECI model does not refer to the quantitative interaction of the each phase.

After the creation of a product concept, the idea must be considered with respect to product development towards commercialization. Therefore, technology valuation (TV) is required. A systematic survey of MOT focusing on TV was conducted by MITI in 2002 [64]. The purpose of TV is threefold: understanding business opportunity, understanding competitor trends, and determining of suitable resource investment. MOT consists of four elements: strategy, process, resources, and organization. There are six techniques corresponding to each element; target setting and TV related to strategy and project planning, pipeline management related to process and allotment design, and climate diagnosis related to resources and the organization.

Technology management technique consists of four major elements: intellectual property (IP) evaluation, qualitative technology evaluation, economic business activities using quantitative evaluation, and business strategy using quantitative evaluation. IP valuation was introduced by the patent map approach, the bibliometric method, the Tech factor, and the TRRU (technology risk reward unit). Qualitative technology evaluation is known by peer review, Business Technology Evaluation (BTE), dynamic technology strategy, SWOT analysis, core competencies, and strategy tables. Economic business by quantitative evaluation was introduced by cost-benefit analysis, the Teal method, the Savelman method, the Olsen method, the Pacifico method, the investment margin method by Fisher, the project index method, net present value, risk analysis and decision making portfolio, Monte Carlo simulation, and real option. Business strategy by quantitative evaluation was introduced by the BCG matrix, the GE-McKinsey matrix, the BMO (Bruce Merrifield and Ohe method), the familiarity matrix, strategic management of technology (SMT), strategic decision groups (SDG), the new score method, multi-function technology (MFT), technology pricing value (TPV), the risk map, analytic hierarchy process (AHP), and the strategic technology assessment review program (STAR).

These methods are appropriate for TV valuation. However, company optimization of proprietary unique resources is required in the application of any tool.

F. Design thinking in business

A new approach to business strategy using design instead of knowledge or productivity was introduced by Tim Brown, CEO of IDEO, at the World Economic Forum in Davos in 2006. Brown later published his design thinking in the Harvard Business Review [65]. Business design thinking is a human-centered way of approaching innovation. Brown defined innovation and categorized it into three factors: inspiration (exploring opportunity), ideation (the process of idea creation, formulation, and validation), and implementation (the execution of an idea). Design thinking is the non-linear process of these three factors. Design thinking is useful in the formation of product concepts and business models. [66]

Martin [67] and Leavy [68] addresses a set of concepts they termed the knowledge funnel; the distinction between abductive reasoning, validity, and reliability. The studies refer to customer dialogue to obtain information and the use of abductive reasoning to create ideas, to develop hypotheses based on those ideas, and to build prototypes to validate them. The prototypes can then be screened using business experience and logical thinking. Business design thinking, however, remains a concept model and the interaction of each process step and the criteria required to reach the next step are not defined.

NPD research began in the late 1960s. The majority of studies use empirical case studies or questionnaire surveys as the principle components, which are not sufficient to establish an empirical theoretical model. Additionally, knowledge creation with respect to new product concepts is not defined with respect to each phase of quantitative interaction.

III. METHODLOGY

A number of MOT models focusing on R&D management or innovation have been proposed. [19,27] R&D consists of many interacting elements, and it is widely accepted that innovation is a complex process [13,20]. We attempted to understand both these phenomena using a macroscopic description of the processes.

The Ising model considers all atoms are identical spin-1/2 system. In the Ising model, we consider only the z-components of each spin of atoms, and we assume that the spins can take only two orientations, + and -. Each spin can interact with its neighbor. The Ising model is used to understand phase transitions through numerical simulations using the Monte Carlo method. Here, we consider the six fundamental factors from the high-purity ammonia gas for blue or white light-emitting diode (LED) case study that were extracted from the R&D period [15]. Our modified Ising model consists of six sites, and each site can have an up (+1) or down (−1) value.

We define the state of the system as

$$\sigma = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \cdots (1)$$

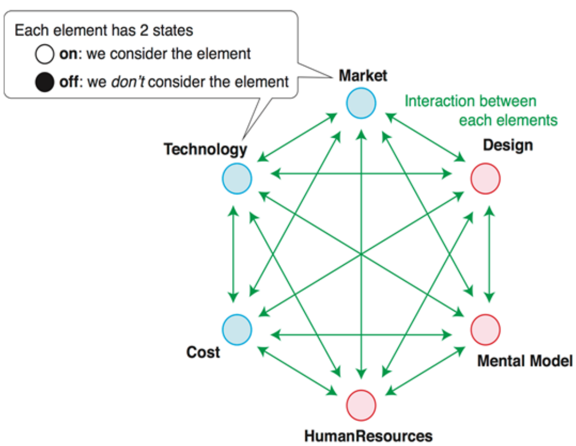

Fig.1 Interaction R&D six elements

An R&D success state (good MOT and healthy R&D activities) is interpreted as a lower energy state. The R&D element energies consider the state of R&D in the firm or the state of the R&D activities. The interaction energy is expressed by the network interaction between the six R&D elements (i.e. Market, technology, cost (Finance), Human Resources (organization), mental Model, Design). This paper focuses on six elements of R&D activities; however, there is no limit to the number of R&D elements. The six elements are the market, technology, cost, human resources, the mental model, and design. Market represents the potential market, market trends, market intelligence, the application of market development, and other market-related elements. Technology represents the product process technology, intellectual property, competing technology, originality, uniqueness, technology creativity, technology application and development, and other technology-related elements. Cost represents production productivity, business profitability, R&D financing, supply chain costs (logistics), product promotion, and other cost-related elements. Human resources represent people and organizations, internal assets such as human networks, employee expertise, R&D decision systems, new R&D project proposal systems, innovation management systems, vision, leadership, and other HR-related elements. The mental model represents R&D activity, prototype thinking, trial and error execution, abduction, grounded theory approach, customer-oriented approach, the balance of product-in and product-out thinking, and other elements related to the way of thinking in support of the execution of R&D. Design represents the business concept, the business model, the business case, the product concept, product material design, the design of the R&D process development road map, and other design-related elements.

The R&D model, which consists of *R&D activity elements*, is expressed in the form of a modified Ising model [69] as

$$[\text{R\&D energy}] = \sum_{i=1}^{\text{nsite}} (\text{R\&D element energies}) + \sum_{<i,j>} (\text{Interaction Energy}) \qquad (2)$$

The first term denotes the spin site energy, the second term denotes the site interaction energy and the third term denotes the external energy respectively. Because the external energy is constant with the same condition, such as same country, the third term can be omitted. Thus, the R&D energy can be expressed by using modified Ising model as below:

$$\mathcal{H} = \sum_{\mathrm{i=1}}^{\mathrm{nsite}} \mathcal{E}(\sigma_\mathrm{i}) - \sum_{<\mathrm{i,j}>} \frac{\sigma_i J_{ij} \sigma_j}{d_{ij}} \qquad (3)$$

Now, we consider that n_{site} is equal to six. As a result, a spin state can be represented as a six-dimensional coordinates $\boldsymbol{\sigma}$

$$\boldsymbol{\sigma} \equiv \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_6 \end{bmatrix} = \sum_{i=1}^{6} \sigma_i \boldsymbol{e_i} \qquad \sigma_i = \begin{cases} 1 \text{ (upspin case)} \\ -1 \text{(downspin case)} \end{cases} \qquad (4)$$

where $\sigma = 1$ and $\sigma_i = -1$ denotes upspin and downspin states respectively. We assume that the up-spin state is the ground state and the downspin state is the excited state

$$\varepsilon(\sigma_i = 1) < \varepsilon(\sigma_i = -1)$$

where $\boldsymbol{e_i}\ (i = 1, \dots 6)$ are the basis set of the six-dimensional space and satisfying ortho-normality,

$$\boldsymbol{e}_i, \cdot \boldsymbol{e}_j = \delta_{ij}$$

We define the sign of the interaction factor between σ_i and σ_j as J_{ij}. In our study, we ignore the self-interaction,

$$J_{ii} = 0 \ \ \forall i$$

In the $i \neq j$ case, J_{ij} is terneary, i.e.,

$$J_{ij} = \begin{cases} 1 \\ 0 \\ -1 \end{cases} \quad (5)$$

In view of the symmetry of the R&D system, the *J* matrix $J = \{J_{ij}\}$ must be a unitary (in this case the symmetric) matrix,

$${}^{t}J = J \iff J_{ji} = J_{ij}$$

We describe the interaction factor between the *i*-th R&D activity element σ_i and the *j*-th R&D activity element σ_j as F_{ij}, which is defined as the factor matrix. Using the factor matrix F_{ij}, the interaction energy between σ_i and σ_j is represented as

$$-\sigma_i F_{ij} \sigma_j$$

The interaction factor, F_{ij}, consists of two factors, the sign and magnitude of the interaction energy (similar to a vector). We describe the sign of F_{ij} as J_{ij}, which can describe a state of complex interaction:

$$J_{ij} = \mathrm{sign}(F_{ij}) = \begin{cases} 1\ (F_{ij} > 0) \\ 0\ (F_{ij} = 0) \\ -1\ (F_{ij} < 0) \end{cases} \quad (6)$$

The ternary J_{ij} value is described as:

$$J_{ij} = \begin{cases} -1 & \text{anti} - \text{parallel spin contiguous site (more stable)} \\ 0 & \text{Independent of contiguous site} \\ 1 & \text{parallel spin contiguous site (more stable)} \end{cases} \quad (7)$$

Through the *J* matrix, $J = \{J_{ij}\}$, it is possible to represent the state of the interaction between each site.

Secondly, the magnitude of the electromagnetic interaction energy, in the case of the same amount of electric (or magnetic charge), depends on the distance of the charges. Thus, we represent the magnitude of the interaction energy $|F_{ij}|$ by the distance d_{ij} between σ_i and σ_j . Therefore d_{ij} is written as

$$d_{ij} \equiv \frac{1}{|F_{ij}|} \quad (8)$$

In this way, we define the distance matrix $d = \{d_{ij}\}$, in other words, we can obtain bond lengths for each R&D activity. Due to the definition of the distance matrix, the distance matrix must also be a symmetrical matrix.

The interactions of each R&D activities, i.e., the six R&D activities ("Market", "Technology", "Cost", "Human resources", Mental Model", and "Design") are divided into two groups, LSG is measured quantitatively, such as the financial statement of the firm, and RSG is measured qualitatively. Those two groups represent qualitatively different aspects, described in two different ways. Thus, we have

Left-side Group (LSG): "Market", "Technology", and "Cost"

Right-side Group (RSG): "Human resources", Mental Model", and "Design"

The interactions between LSG elements can be measured quantitatively. However, the other interactions, between LSG and RSG or within RSG are assessed qualitatively.

The sign of the interaction factor between J_{12}, J_{13}, J_{23} are quantitatively determined according to the definitions below.

$$J_{12} = \begin{cases} -1 & \text{The operating profit on net sales below the chemical industry standard} \\ 0 & \text{The operation profit on net sales equal to the chemical industry standard} \\ 1 & \text{The operation profit on net sales avove the chemical industry standard} \end{cases}$$

$$J_{13} = \begin{cases} -1 & \text{The return on equity below the chemical industry standard} \\ 0 & \text{The return on equityequal to the chemical industry standard} \\ 1 & \text{The return on equity avove the chemical industry standard} \end{cases} \quad (9)$$

$$J_{23} = \begin{cases} -1 & \text{The return on investment cost below the chemical industry standard} \\ 0 & \text{The return on investment cost equal to the chemical industry standard} \\ 1 & \text{The return on investment cost avove the chemical industry standard} \end{cases}$$

The other *J*-matrix elements are determined by a question sheet format. The questions are answered by either "Yes" or "No". We defined the interaction factor component between σ_i and σ_j established by the k-th question as $A_{ij}^{(k)}$.

$$A_{ij}^{(k)} = \begin{cases} \text{The answer is positive for the interaction between } \sigma_i \text{ and } \sigma_j \\ \text{The answer is independant for the interaction between } \sigma_i \text{ and } \sigma_j \\ \text{The answer is negative for the interaction between } \sigma_i \text{ and } \sigma_j \end{cases} \quad (10)$$

From the answers of all those questions, we obtain the factor matrix F_{ij} between σ_i and σ_j

$$F_{ij} = \frac{1}{N_{ij}} \sum_{k=1}^{n} A_{ij}^{(k)} \quad (11)$$

where N_{ij} is the normalization factor and n is the number of questions. Normalization factor N_{ij} is written as

$$N_{ij} = \sum_{k=1}^{n} |\tilde{A}_{ij}^{(k)}| \quad (12)$$

where $|\tilde{A}_{ij}^{(k)}|$ represents the maximum value that $|A_{ij}^{(k)}|$ can take.

In Eq. (3), ε denotes the rate of net sales and R&D cost as a percentage; $0.2\,\% \leqq \varepsilon \leqq 14.61\,\%$ with an average of 3.47% as Chemical industry sector in Japan [70].

In our modified Ising model, we calculate the Ising state based on the financial statements and other factors. Because of the dependency of the financial statements at the time, the Ising states are the implicit function about the time. As the results, our model is the universal model, including the time term.

IV.CASE STUDY

High purity NH3 gas business development of Showa Denko K.K. and Taiyo Nippon Sanso Corporation [69] was selected for the comparison of the success / failure project . The Nihon Zeon (as written in ZEON) case [71] was selected to study the effect of the time factor for this modified Ising model.

TABLE 1 PARAMETER FOR ISING MODEL ABOUT SDK AND TNSC

Year of 2004	SDK	TNSC	Chemical Industry Average
ε as of Research and Development ratio on Net sales (%)	2.38	1.00	4.30
J12 operating profit on net sales (%)	7.03	6.22	7.09
J13 as of return on equity (%)	4.27	4.79	5.59
J23 as of return on Investment Cost (%)	5.68	5.45	5.81

TABLE 2 PARAMETER FOR ISING MODEL ABOUT ZEON

Year 1988	Zeon	Chemical Industry Average
ε as of the R&D ratio on Net Sales(%)	4.83	4.17
Operating profit on Net Sales(%)	8.87	9
Return on Equity(%)	6.96	7.76
Return on Investment Cost(%)	5.42	9.04
Volatility	—	25.063

V. RESULTS AND DISCUSSION

Material product development and the customer system of Zeon corporation (as Zeon)

A. Preparation of model simulation

The parameters of the model simulations are shown in Table 1

We calculate the interaction matrices for SDK and TNSC case by substituting these parameters to (9) and (10). The interaction matrix can be decomposed with the J matrix and the length matrix (Table.2). In order to define J matrix and length matrix, we use 150 questions with regard to Right-Left 9 pattern interactions, Right-Right 3 pattern interactions, Left-Left 3 pattern interactions respectively. Therefore, total 15 interaction bonds are calculated with relevant length. (Table.2)

Compared to the failure case, we use Taiyo Nippon Sanso Corporation (TNSC) result[3] as below

TABLE 3 TNSC J MATRIX

$$\begin{bmatrix} 0 & -1 & -1 & 1 & 1 & 1 \\ -1 & 0 & -1 & 1 & -1 & -1 \\ -1 & -1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & -1 & -1 \\ 1 & -1 & 1 & -1 & 0 & -1 \\ 1 & -1 & 1 & -1 & -1 & 0 \end{bmatrix}$$

TABLE 4 TNSC LENGTH MATRIX

$$\begin{bmatrix} 1.00 & 8.14 & 6.99 & 15.00 & 7.50 & 2.10 \\ 8.14 & 1.00 & 16.14 & 5.33 & 5.67 & 18.00 \\ 6.99 & 16.14 & 1.00 & 8.50 & 7.00 & 1.88 \\ 15.00 & 5.33 & 8.50 & 1.00 & 3.17 & 3.00 \\ 7.50 & 5.67 & 7.00 & 3.17 & 1.00 & 3.50 \\ 2.10 & 18.00 & 1.88 & 3.00 & 3.50 & 1.00 \end{bmatrix}$$

TABLE 5 SDK J MATRIX

$$\begin{bmatrix} 0 & -1 & -1 & 1 & 1 & 1 \\ -1 & 0 & -1 & 1 & 1 & 1 \\ -1 & -1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

TABLE 6 SDK LENGTH MATRIX

$$\begin{bmatrix} 1.000 & 0.522 & 0.758 & 1.273 & 1.250 & 1.105 \\ 0.522 & 1.000 & 16.310 & 1.231 & 1.067 & 1.125 \\ 0.758 & 16.310 & 1.000 & 2.000 & 1.400 & 1.400 \\ 1.273 & 1.231 & 2.000 & 1.000 & 1.125 & 1.091 \\ 1.250 & 1.067 & 1.400 & 1.125 & 1.000 & 1.167 \\ 1.105 & 1.125 & 1.400 & 1.091 & 1.167 & 1.000 \end{bmatrix}$$

TABLE 7 ZEON J MATRIX

$$\begin{bmatrix} 0 & -1 & -1 & 1 & 1 & 1 \\ -1 & 0 & -1 & 1 & 1 & 1 \\ -1 & -1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

TABLE 8 ZEON LENGTH MATRIX

$$\begin{bmatrix} 1.00 & 69.23 & 4.34 & 1.25 & 1.07 & 1.11 \\ 69.23 & 1.00 & 3.32 & 1.14 & 1.33 & 1.13 \\ 4.35 & 3.32 & 1.00 & 2.43 & 1.56 & 1.25 \\ 1.25 & 1.14 & 2.43 & 1.00 & 1.19 & 1.20 \\ 1.07 & 1.33 & 1.56 & 1.19 & 1.00 & 1.56 \\ 1.11 & 1.13 & 1.25 & 1.20 & 1.56 & 1.00 \end{bmatrix}$$

B. Ising state analysis

All the Ising state energies determined as Table 9, 10 and 11. The exchange energy indicates the main contribution.

We simulated 64 Ising states of TNSC, SDK and Zeon and compared as Fig. 2. The geometric positions about six elements for TNSC, SDK and ZEON cases are illustrated as Fig.3, 4, and 5 respectively.

[3] In detail preparation of parameter is mentioned in [69]

TABLE 9 ISING STATE RESULT OF TNSC

istate	spin_state	Istate	site energy	exchange energy	total energy	probability
0	[-1 -1 -1 -1 -1 -1]	0	6.0000	34.5840	40.5840	0.00022
1	[1 -1 -1 -1 -1 -1]	1	4.0000	72.4760	76.4760	0.00005
2	[-1 1 -1 -1 -1 -1]	2	4.0000	- 135.8640	-131.8640	0.21477
:		:	:		:	
63	[1 1 1 1 1 1]	63	- 6.0000	34.5840	28.5840	0.00036

TABLE 10 ISING STATE RESULT OF SDK

istate	spin_state	Istate	site energy	exchange energy	total energy	probability
0	[-1 -1 -1 -1 -1 -1]	0	14.2800	295.6620	309.9420	0.00000
1	[1 -1 -1 -1 -1 -1]	1	9.5200	-171.2100	-161.6900	0.00014
2	[-1 1 -1 -1 -1 -1]	2	9.5200	-331.4220	-321.9020	0.08372
:		:	:		:	
63	[1 1 1 1 1 1]	63	-14.2800	295.6620	281.3820	0.00000

TABLE 11 ISING STATE RESULT OF ZEON

istate	spin_state	Istate	site energy	exchange energy	total energy	probability
0	[-1 -1 -1 -1 -1 -1]	0	28.9800	121.7740	150.7540	0.00000
1	[1 -1 -1 -1 -1 -1]	1	19.3200	- 158.8300	- 139.5100	0.02762
2	[-1 1 -1 -1 -1 -1]	2	19.3200	- 154.8100	- 135.4900	0.02353
:		:	:		:	
63	[1 1 1 1 1 1]	63	- 28.9800	121.7740	92.7940	0.00000

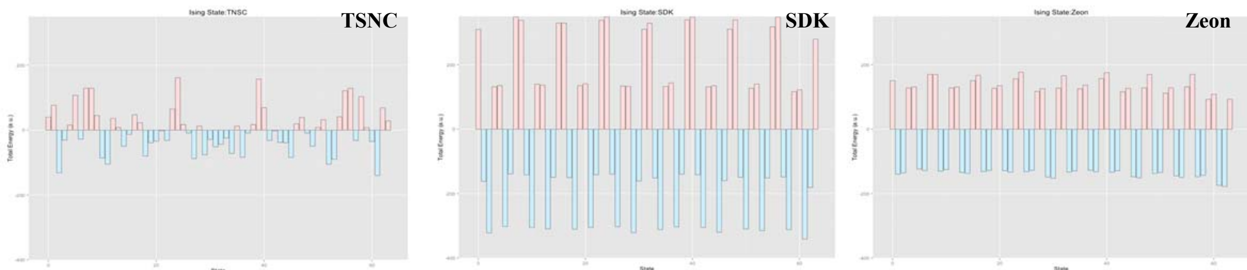

Fig. 2 Ising state energy

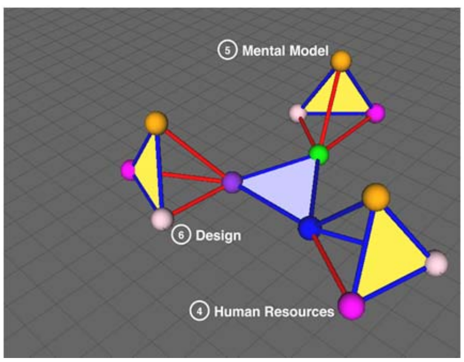

Fig. 3-1 Position of TNSC six elements based on LSG

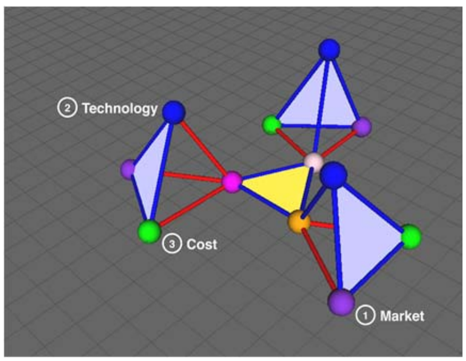

Fig. 3-2 Position of TNSC six elements based on RSG

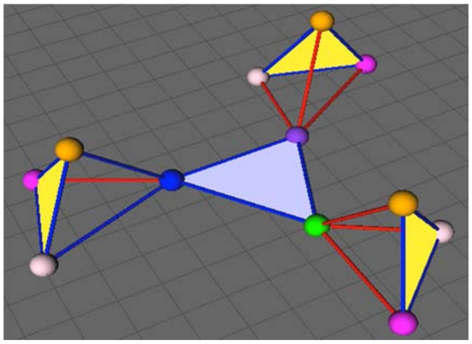
Fig. 4-1 Position of SDK six elements based on LSG

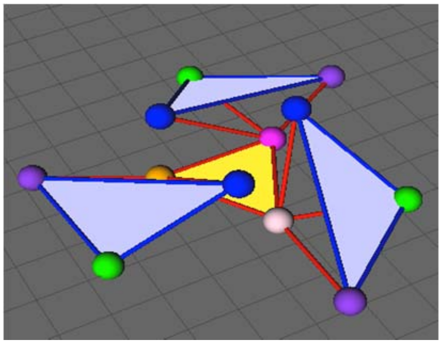
Fig. 4-2Position of SDK six elements based on RSG

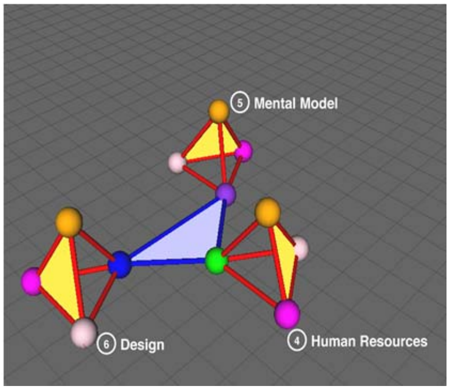

Fig. 5-1 Position of Zeon six elements based on LSG

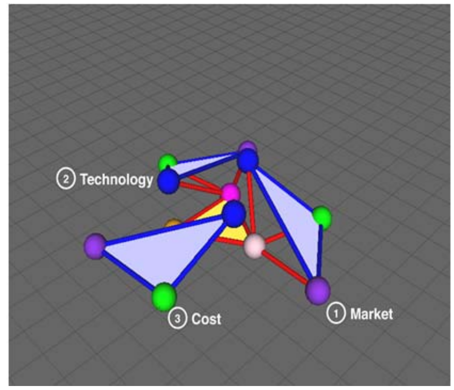

Fig. 5-2 Position of Zeon six elements based on RSG

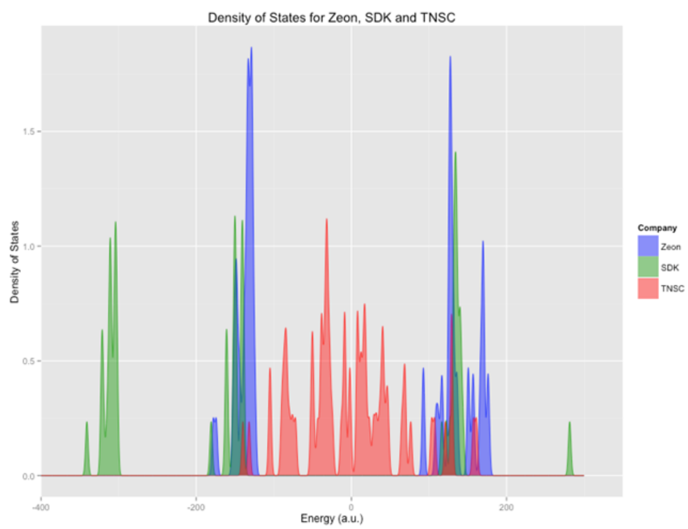

Fig. 6 Density of States (DOS) of TNSC, SDK and Zeon

SDK showed large vibration band regularly. On the contrary, TNSC showed small vibration band and un-regularly in Fig. 2. Since exchange energy is the main component of the total energy, we are focusing on the positioning of each elements and visualized as below Fig.3, 4, and 5. First, we simulated the case study of TNSC and showed the failure six elements positioning case of TNSC R&D activities in Fig.3. Fig.3-1 is based on Left Side Group (LSG): Market, Technology and Cost and Fig.3-2 is based on Right Side Group (RSG): Human Resource, Mental Model and Design. The six elements have been ordered with the same distance and the same force of interactions. We represent the norm of interaction between each element as the bond length, and the direction of interaction as colored bonds. Positive interaction and negative interactions are represented as the red bonds and the blue bond, respectively. Secondary, we simulated the case study of SDK and showed the success six elements positioning case of SDK R&D activities in Fig. 4-1 and Fig. 4-2. The last, we simulated the case study of Zeon and showed the failure six elements positioning case of Zeon R&D activities in Fig.5-1 and Fig.5-2. A good condition is defined as a red bond (positive interaction) with a short distance between elements. This formation of elements creates an equilateral triangle and indicates a well-balanced formation. For example, Fig.5.1 shows that the bond between technology and market is blue. The total position of six elements will be compressed, as one point with positive interaction is the best position. According to the comparison between Fig4 and Fig.5, we found the similarity between Fig. 4-2 and Fig. 5-2 expect the distance of each elements. On the contrary, there big difference of six elements position even if the same success case between Fig.4-1 and Fig.5-1. The distance of the three elements represents result of the company management. The blue color described the financial indicator are lower than the average of Japanese Chemical industry. The Zeon case showed shorter length and positive interaction, which is more compressed position than SDK. This means good interaction at the R&D process within the company.

We found that there are characters of Density of States (DOS) of the distinct types. In this work, Zeon has a polarized DOS consisting of 2 energy regions in Fig. 6.

Meanwhile, TNSC has a non-polarized DOS. Due to analyze to determine the characterization of DOS, we compared with DOS and 64 Ising states for each company.

In Zeon case, it is shown in Fig 7 that all 64 Ising states belong either region (a) or region(b).

$$-178.15 \leq E \leq -124.11 \in region(a)$$
$$92.476 \leq E \leq 176.786 \in region(b)$$

In other word, the intermediate region ($-124.11 < E < 94.476$) is the forbidden region. In this region, Zeon is forbidden to have the energy states. As the result, DOS of Zeon occurs polarization. the probability of the energy states in region (b) is very little. In the results of Zeon case, there is little chance to choice as the trial state in the region (b).

In SDK case, it is shown in Fig.8 that all 64 Ising states belong either region (a) , (a') or region (b), (b').

$$-340.94 \leq E \leq -302.22 \in region(a')$$
$$-180.73 \leq E \leq -138.78 \in region(a)$$
$$116.49 \leq E \leq 143.70 \in region(b)$$
$$281.38 \leq E \leq 176.786 \in region(b')$$

In other word, the intermediate region ($-138.78 < E < 116.49$) is the forbidden region. In this region, SDK is forbidden to have the energy states. As the result, DOS of SDK occurs polarization.

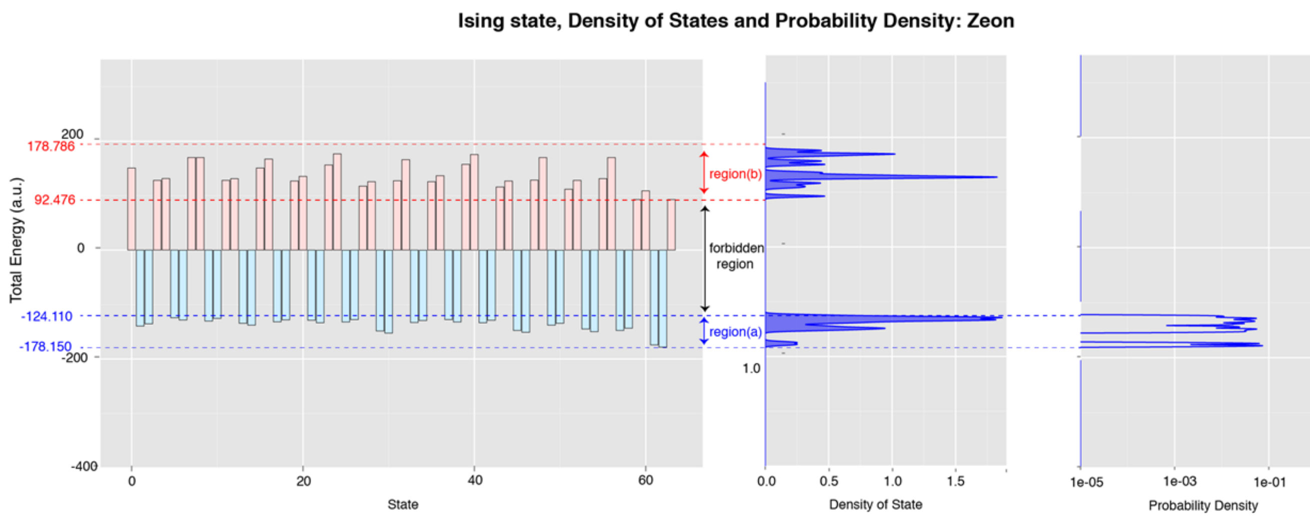

Fig. 7 Ising state, Density of States (DOS) and probability of Zeon

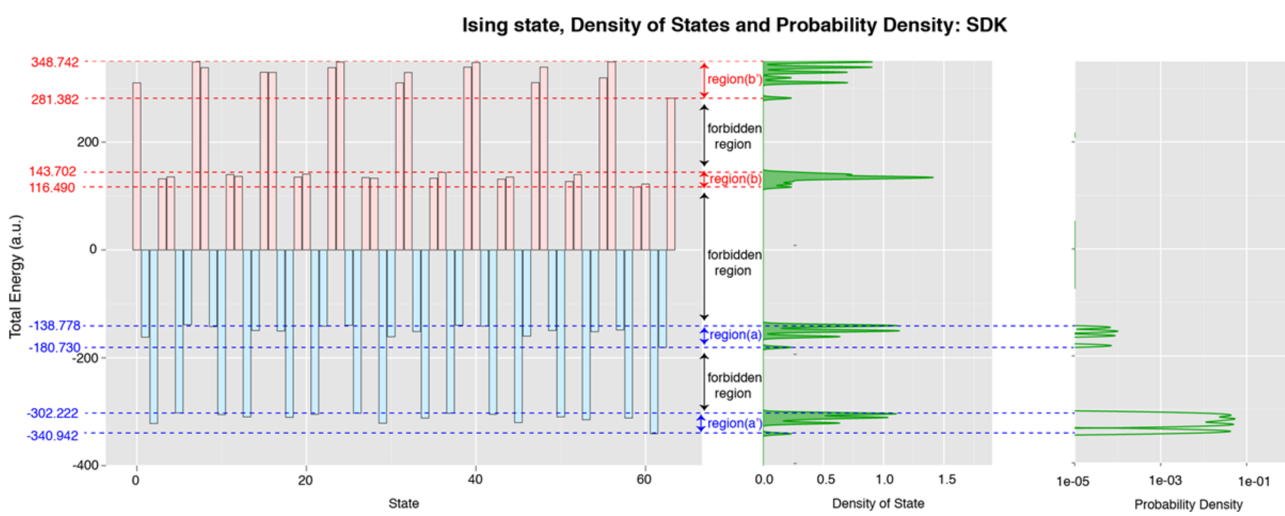

Fig. 8 Ising state, Density of States (DOS) and probability of SDK

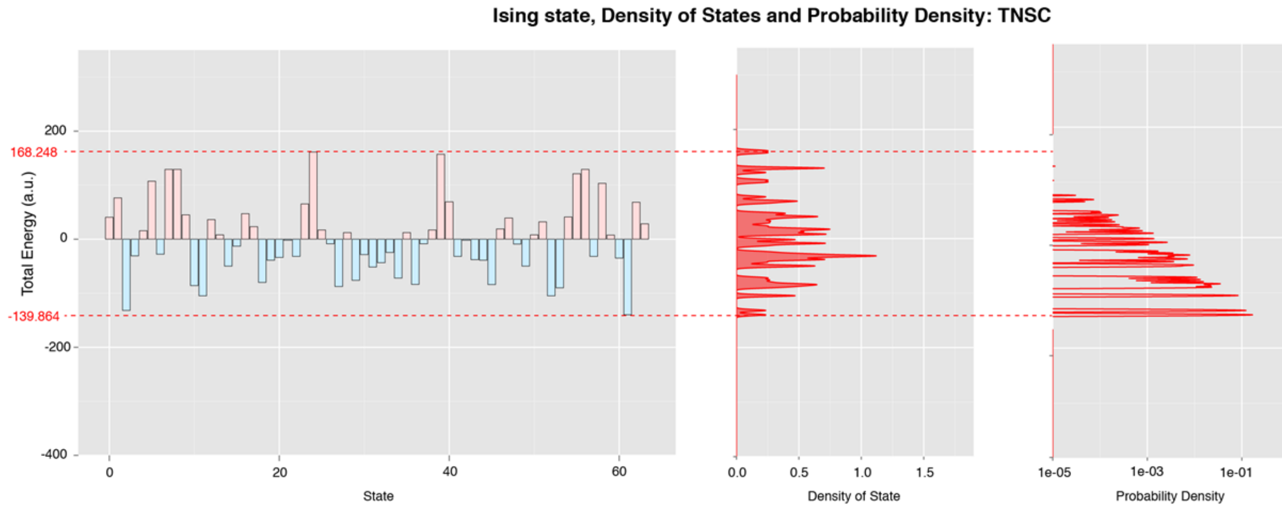

Fig. 9 Ising state, Density of States (DOS) and probability of TNSC

On the other hand, in TNSC case, Ising states are not separated with any regions,

In TNSC case, it is shown in Fig.9 that all 64 Ising states belong either region (a) or region (b).

$$-139.67 \leq E \ \leq 168.25 \ \in region$$

In the most of all energy regions, TNSC can choice various energy states as a trial state under the moderate probability. This means quite unstable of the R&D process.

By the comparison between Zeon case (Fig. 5, Fig.7) and SDK case (Fig. 4, Fig. 8), both case are success case, however, Zeon case is more energy stable (closer to the best case) than SDK case, which means the intermediate success cases. If the SDK case would be better right side interaction (Technology –HR, MM, DSG), the elements position would be the same position. This means SDK case would be better business result if SDK had improved the right side interaction (Technology –HR, MM, DSG) in those days.

VI. CONCLUSION

The goal of this study is to create a quantitative research and development process evaluation model based on a physical model by means of thinking the research and development process from research to commercialization as one system. As the result of the model simulation, it is expected both to indicate the R&D project status and to give us the feedback to improve the R&D project.

Historically, it was not enough successful achievement of understanding of the research and development state by quantitative analysis of open secondary data, such as financial statement from MOT perspective. In the research and development environment, “Human Resource”, “Information”, qualitative elements such as “Organizational Strength” also plays an important role in addition to the quantitative elements such as published financial statement. Those qualitative elements and quantitative elements have the interaction each other. Our model is the combination of the quantitative indicators and qualitative indicators. Quantitative indicator was used management indicators from the financial statements. Qualitative indicator such as corporate culture was calculated by statistical analysis of the quantitative part from a lot of YES/NO questionnaires. We defined two groups consisting of six elements: quantitative group: Market, Technology, Cost, and qualitative group: Human Resource, Mental Model, Design. And focusing on the interdependence of six elements in the research and development process. The qualitative indicator such as *J* matrix and length matrix were defined by 180 questions concerning six elements: Market, Technology, Cost, Human Resource, Mental Model and Design. In this model, it does not depend on the period of the R&D project because it uses the financial indicators of each year as parameter.

The best case should be Simulation result will be indicated that short distance of the interaction means strong interaction. Interaction has the two different types of force: pulling force (positive) and repulsive force (negative). The best Success case will be focusing on one point of the tetrahedron figure. All the distance of the interaction indicates both close to zero and positive interaction. On the other hands worse case indicated a long distance of the interaction and negative interaction. Because the lower total energy should be stable.

This model is implemented into three business cases: SDK represents as success case, TNSC represents as a failure case [69], Zeon Corporation represents a successful case of Japan’s bubble period [71]. Statistical analysis of model simulation was conducted for each business case and the state of research and development process can be visualized from this statistical analysis. As the result of the model simulation, this modified Ising model can distinguish the success case and failure case of the R&D project.

This model analysis can give us the feedback that which specific interaction has to be improved and help our understanding easier by the visualization of the project status.

According to the Fig.6, 7, 8, and 9, it is clear to distinguish from success case and failure case. Success case basically consists of two polarized peaks as Density of State and failure case consists of broadened peak, in other word, the un-polarized peak as Density of State. Additionally, the results of the model simulation indicate the critical interaction between certain elements and the results suggests certain element interactions have to improve for R&D projects. (Model simulation feedback).

It seems natural to conclude that this approach presented here can serve as a useful framework for R&D project evaluation

The issue of this modified Ising model is still a prototype. The further study of this model would be the external effect of the internal six elements. This external topic is the next research target of this study.

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