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Visualization of Research and Development Process State for Research and Development Management: Empirical Study of High-Purity NH3 Gas Business Case

Hideki Hayashida, Hiroki Funashima, Hiroshi Katayama-Yoshida
Department of Materials Engineering Science, Graduate School of Engineering Science, Osaka University, Osaka, Japan

***Abstract*--This study is part of our attempt to understand the management of technology (MOT) through the lens of quantitative model. We present here a six-dimensional quantitative analytical model (based on the Ising model, a physical phase transition model) that can be applied to the state of technology management activities with respect to the wider business context. We selected, as a case study, the new product development of a high-purity ammonia gas business for the blue light-emitting diode industry. The modified Ising model is discussed in this paper to evaluate this case study. The results of the quantitative model analysis are useful for visualizing the state of the MOT. The model could quantitatively analyze the high-purity ammonia gas of new business development together with product development and distinguish between the cases of two different companies.**

The results of the methodology indicate the R&D project status and how to improve the interaction network of the six elements of the MOT.

I. INTRODUCTION

The chemical industry supplies a wide variety of products to numerous fields, including the automotive, electronics, semiconductor, and photovoltaic industries. Japanese companies have so far maintained a high level of global competitiveness by taking advantage of technical capabilities, excellent research-and-development (R&D) records of accomplishment, and a close connection with end-product manufacturers. In addition, Japanese companies have developed a variety of high-tech materials. In recent years, a process management technique known as the management of technology (MOT), a generalization of R&D to new business development (NBD), has found widespread use.

NBD is the cornerstone of sustainable competitiveness for firms. Unless a successful new business is brought about by selling new products, companies will not be sustainable. There are, however, always technical and market uncertainties associated with it: Can the technology be made into a new product, and will that product sell in the current market? Businesses selling high-tech materials have additional technical uncertainties in the end product: the device or module is an intermediate product of the brand's consumer products. Thus, successful NBD, based on high-risk materials development, requires product concepts that meet potential customer needs before the customers themselves have recognized those needs. A R&D project in the NBD process will start from a product concept. If we could represent a R&D project quantitatively, we would be able to predict the future of the project by simulation. We could then improve the current situation and the result of the project would, as a result, be much better than the current state.

The Ising model [18], a mathematical model of ferromagnetism, is a simple model consisting of two state variables (ordered state and disordered state), which 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) gives rise to correlative behavior. The Ising model is used to predict, in some sense, the potential for a phase transition.

This physical phase transition model has been applied to 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 large system. Here, we attempt to understand the complex system MOT by applying an Ising-model based mathematical model and a quantitative analysis [14]. Our mathematical model consists of three energy components. One of these components expresses the interaction energy of six factors: market, technology, cost, human resources, mental model, and design. We studied the interaction between the factors, which define 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 on innovation, product development projects, and NBD have been made from a variety of perspectives within the scope of MOT. The funnel-type stage-gate model is useful for managing the R&D project process [5-10,18], and the effectiveness of another approach, consisting of a quantitative model based on a management index calculated from financial statements, was discussed using simulations [21]. Product development projects, aimed at imminent commercialization, have been evaluated based on studies of integrated qualitative and quantitative models using Monte Carlo simulations to assess the business operation scenarios [23]. Such studies are approached from a process management perspective. The innovator's skills for generating ideas can also be the focus of the analysis. These key skills include the cognitive skill of associational thinking, which engages the behavioral skills of questioning, observing, networking, and experimenting [11]. A communication competition model using an agent-based simulation has been used to study the relationship between the gatekeeper and team members in the organizational management of complex systems [1]. The results show that well-educated engineers with high communication skills have a unique behavioral pattern in that communication with other organizations is done around the interface of the organization. In contrast, an agent with fewer communication skills can achieve a high performance through a "skunk works model" that promotes proactive activities in various situations [24].

The concept of "small world networks" [26] 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 [2]. 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 [18,22]. A milestone in the development of modern statistical mechanics is the exact solution of the 2D Ising model in a square lattice discovered by L. Onsager [22]. In higher-dimensions, i.e., greater than three, the free energy is calculated by simulation. However, higher-dimensional studies of nearest-neighbor links, i.e., complex system, have not been sufficient. The techno-economic network[3] 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 major R&D activities was explained using an interactive geometric innovation process model, which consists of conception, applied research, marketing (sales and distribution), experimental development, and engineering (including production) [4].

The quantitative modeling approaches of product development processes are classified as scoring approach [16], computational approach [17], decision and game theoretical approach, simulation models for research and development [12], heuristics for R&D project selection and resource allocation, and cognitive emulation for R&D project selection and resource allocation.

Existing research has captured R&D from a variety of perspectives. However, few studies from a MOT perspective consider quantitative models of the management of NBD and new product development in the chemical material industry.

III. METHOD AND MODEL INDUCTION

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

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

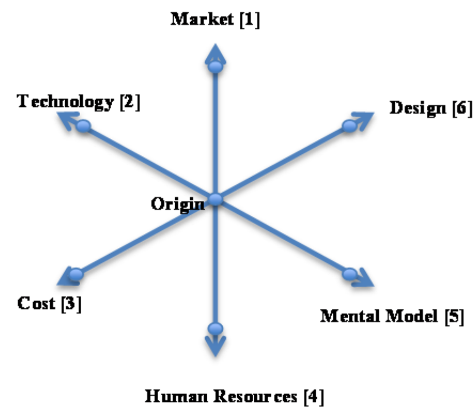

Fig.1 The six fundamental factors

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). We represent the states of R&D activity as coordinates in the six-dimensional topological space. In this paper, we focus on the six elements of R&D activities; however, there is no limit on the number of R&D elements.

In general, the Ising model is described by

$$\mathcal{H} = -2\sum_{<i,j>} J_{ij} s_i s_j - \sum_{i=1}^{nsite} g\mu_B \, s_i \mathbf{H} \qquad (2)$$

As the Hamiltonian for the spin s_i, s_j of the electrons with the orbiting the *i*-th and *j*-th sites, respectively.

Here J_{ij} is exchange correlation energy between the *i*-th site electron and *j*-site electron, g is the Landé g-factor, μ_B is the Bohr magneton, and **H** is the external magnetic field. Ising model is defined as the heat equilibrium physics model, therefore the time dimension of phase state shows thermodynamic equilibrium state, which means the infinite environment.

The R&D model, which consists of *R&D activity elements*, is expressed in the form of a modified Ising model [24] as

$$[\text{R\&D energy}] = \sum_{i=1}^{nsite} (\text{R\&D element energies}) + \sum_{<i,j>} (\text{Interaction Energy}) \qquad (3)$$

The first term denotes the spin site energy and the second term denotes the site interaction energy respectively. Thus the R&D energy can be expressed as

$$\mathcal{H} = \sum_{\mathrm{i=1}}^{\mathrm{nsite}} \mathcal{E}(\sigma_\mathrm{i}) - \sum_{<\mathrm{i,j}>} \frac{\sigma_i J_{ij} \sigma_j}{d_{ij}} \quad (4)$$

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

$$\boldsymbol{\sigma} \equiv \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_6 \end{bmatrix} = \sum_{i=1}^{6} \sigma_i \boldsymbol{e}_i \qquad \sigma_i = \begin{cases} 1 \text{ (upspin case)} \\ -1 \text{(downspin case)} \end{cases} \quad (5)$$

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

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

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

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

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.,

$$J_{ij} = \begin{cases} 1 \\ 0 \\ -1 \end{cases}$$

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,

$${}^tJ = J \ \Leftrightarrow \ J_{ji} = J_{ij}$$

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 $A_{ij}^{(k)}$.

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

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

$$F_{ij} = \frac{1}{N_{ij}} \sum_{k=1}^{n} A_{ij}^{(k)} \quad (10)$$

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

$$N_{ij} = \sum_{k=1}^{n} |\tilde{A}_{ij}^{(k)}| \quad (11)$$

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 [25].

IV. THE MODIFIED ISING MODEL (R&D STATE MODEL)

A. Visualization of the interaction energy

The discussion in previous section defined the *J*-matrix and the distance matrix. These matrices characterize the interactions in our R&D management system. Therefore, we would like to visualize these matrices. First, we discuss their geometry and implementation. To represent the state of the system as a diagram, the six elements keep a distance from the other elements independently. In Euclidean geometry, any two points can be connected by a straight line. Thus, in the case of two elements, a state can be represented as a straight line where both ends are elements. In the case of three elements, a state can be represented as a triangle. In the case of four elements, a state can be represented as a tetrahedron. In general, in the n elements case, a state can be represented as an *(n-1)* dimensional solid where all vertices are elements.

We consider a model with six elements. Thus, each state can be represented as a 5-dimensional solid. For the visualization, we opened up the 5-dimensional solid as a substitute for a real 5-dimensional solid, which would be hard to visualize. In our model, the six elements can be divided into two side groups, LSG and RSG. Thus, "Market", "Technology", and "Cost" belong to LSG while "Human Resources", "Mental Model", and "Design" belong to RSG. We choose one side group as a base, either LSG or RSG. Because a base includes three elements, a base state is represented as a triangle. Next, we represent a state with a vertex of a triangle connected to other elements that do not belong to that base. Because this is a 4-elements case, this state is represented as a tetrahedron. By performing this operation at each vertex of the triangle, we could open up the 5-dimensional solids.

B. Implementation of the Visualization

Before we implement the real case such as Showa Denko K.K. (SDK) and Taiyo Nippon Sanso Corporation (TNSC), at the beginning , we tried to simulate some scenario using this model. Fig. 2-1 and Fig. 2-2 show the result of this simulation case of R&D activities. Fig. 2-1 is based on LSG and Fig. 2-2 on RSG. The six elements have been ordered with the same distance and the same force of interactions.

As discussed previously, we represent norm of interaction between each elements as the bond length

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

and direction of interaction as colored bond, i.e. positive interaction and negative interactions are represented as red colored bond and blue colored bond respectively. A good condition defined as red colored bond (positive interaction) and shorter distance. This formation of the elements makes up an equilateral triangle. This indicates a well-balanced formation. For example, in Fig.2-1case, we can see that the bond between technology and market are blue colored. Thus in this figure, it means that the technology process acts for the market process negatively.

V. BUSINESS CASE STUDY – SHOWA DENKO K.K. (SDK) AND TAIYO NIPPON SANSO CORPORATION (TNSC)

We applied our model to a business case study, involving Showa Denko K.K. (SDK) and Taiyo Nippon Sanso Corporation (TNSC). Both these cases are relevant to high-purity NH_3 gas global business for Blue/White LED applications. In addition, we know that SDK was successful while TNSC was not. In 1998, the GaN based-LED is in the emerging stage for Blue/White LED applications. SDK, one of the largest diversified chemical companies in Japan, and TNSC, one of the diversified gas supplying companies in Japan, both supplied high-purity NH_3 gas to Nichia Corporation and Toyoda Gosei Co., Ltd. for their GaN epitaxial processing using metal organic chemical vapor deposition (MOCVD). Both SDK and TNSC are relevant companies in the specialty gas industry in Japan. Specialty gases are indispensable process materials in the front-end process. High-purity ammonia gas is used to form the thin nitride layer in GaN LEDs. GaN films are grown epitaxial using MOCVD through the chemical reactions of NH_3 gas on a sapphire substrate. The GaN epitaxial wafer is then diced to form small blue LED chips.

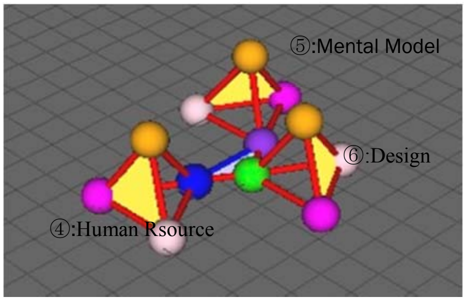

Fig. 2-1 Position of the six elements based on LSG

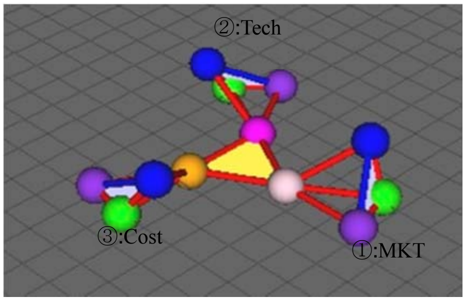

Fig. 2-2 Position of the six elements based on RSG.

The colored balls (Market: violet, Technology: navy, Cost: green, Human Resources: red-violet, Mental Model: orange, Design: pink) represent elements, and the colored bars (red: +1, blue: -1, white:0) represents factors of the J matrix. The lengths of the bars represent the distances between elements and the base color (light violet: LSG and light yellow: RSG) represents the element group.

The GaN-based LED was applied to make white LED for LCD backlight applications, such as for mobile phones. This application was at that time in its early stages. It was believed that LED displays and LED lightning could become a reality. There was a potential for LEDs to be applied for general lighting purposes in the future; however, the sales of high-purity ammonia gas was a niche business, and there was still some doubt about the potential growth of the high-purity NH_3 gas business.

SDK has 30.8% global market share in 2012, but TNSC has less than 5%[28]. The reasons are 1) SDK has a global business plan based on a vision from the beginning. 2) SDK has good communication both internal and external. As the result, SDK has succeeded in developing to meet customer requirements. 3) SDK created strong value proposition based on good product concept.

VI. RESULT

A. Preparation of model simulation

With regard to parameter of model are as in table 1.

B. Result of simulation

At first, we calculate the interaction matrices for SDK and TNSC case by substituting these parameter 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)

Secondly, we calculate the all Ising state for each system by substituting the interaction matrix and the research and development ratio to (4). There are 6 elements for each system, thus, number of total Ising state for each system consists of only 64 states. Thus we calculate the Hamiltonian by using the interaction matrices and the research and development ratio on net sales exactly. In result, we can get all Ising state for SDK and TNSC cases.

VII. DISCUSSION

A. Ising state analysis

We implemented the modified Ising model for our R&D state model, and applied it to the case studies. We obtained the each of the *J* matrix and of the distance matrix for each. Fist of all, we simulated the Ising state of Energy and summarized as Table. 3.

The energy state of SDK is over two times lower than TNSC. This result indicates the quantitative difference between the success case and the failure case.

TABLE 3. COMPARISON OF <E> STATE

	SDK	TNSC
<E> (a.u)	-9.42	-3.97

B. Elements position analysis

Next we consider the R&D state <E> of a ratio occupied by six R&D element energy and that of interaction energy. In this case study, the Interaction energy term is important that we cannot neglect it. In the case of SDK, the effect of interaction is obviously larger than six R&D element energy, because the variance of interaction energy for each state is 131.9 and that is 3 times larger than that of six element energies (=37.1). In TNSC case, the relationship magnitude between variance of the interaction of the six element energy and that of interaction energy is a similar as that of SDK case. As the result of these, we have concluded that the effect of the energy of interaction is larger than six R&D element energy.

Next, we visualize the interaction between each six elements. The successful case of SDK is shown as Fig.3 and the failure case of TNSC is shown as Fig.4.

TABLE 1.PARAMETERS FOR MODEL SIMULATION

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.PARAMETERS FOR MODEL SIMULATION

SDK J matrix

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

SDK length matrix

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

TNSC J matrix

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

TNSC length matrix

$$\begin{bmatrix} 1.000 & 0.303 & 1.250 & 3.500 & 15.000 & 2.625 \\ 0.303 & 1.000 & 1.148 & 2.667 & 8.000 & 9.000 \\ 1.250 & 1.148 & 1.000 & 16.000 & 7.000 & 7.000 \\ 3.500 & 2.667 & 16.000 & 1.000 & 3.600 & 4.800 \\ 15.000 & 8.000 & 7.000 & 3.600 & 1.000 & 7.000 \\ 2.625 & 9.000 & 7.000 & 4.800 & 7.000 & 1.000 \end{bmatrix}$$

The Red color bond means positive interaction so that the distance between items is shorter the better and triangle is smaller the better. The Blue color bond means negative interaction. Therefore the distance between item is longer the better. However, the mixed color bond cannot simply define by the distance and shape of triangle. For example, compared to Fig.3-1 and Fig.4-1, it is apparently that both SDK and TNSC were bonded by all blue colored bond within LSG and the LSG (Market: violet, Technology: navy, Cost: green) triangle size of TNSC is smaller than SDK. This means that both SDK and TNSC were not in a good financial condition compared to the condition of average Japanese chemical company. Also, the size of LSG triangle indicated that TNSC was worse condition than SDK in those days.

Within SDK, most of the interaction consists of red colored (+1) bond and distance seems to be the same. In addition, the triangle of RSG (Human Resources: red-violet, Mental Model: orange, Design: pink) seems to be the same. This means SDK was the good condition of internal and external communication. In other words, SDK technical marketing and R&D team kept good communication. They had installed customer oriented R&D in order not to be a good financial situation. However, the interaction between elements of TNSC case is shown of both red colored bond and blue colored (-1) bond.

Compared to the distance of HR and Mental Model (Fig.3.2 and Fig.4.2), Both SDK and TNSC connected by red colored bond. This means that they have customer-oriented activity. But the distance of TNSC was almost double as SDK. This means that SDK could established tight connection as an organization not only for Marketing & Sales but also for R&D and shared common perceptions of R&D as an organization.

The distances of SDK between Design-(Market-Technology-Cost) are shorter than TNSC. Design is the direct effect element for planning new business development. Therefore TNSC was not in a good condition for New Business development. This can explain the fact that TNSC initially could not understand emerging technology and growing big LED / LED lighting market for high-purity NH3 gas. They could get almost the same emerging market information from Nichia by selling high-purity NH3 gas, but they did not take additional R&D for high purity NH3 gas. One year later, they understood the emerging market and SDK had supplied specific high-purity NH3 gas but they could not get any further technical information from the market (customer). SDK had already protected their high-purity NH3 gas technology.

Also, compared to Fig.3-2 and Fig.4-2, TNSC is apparently different from SDK. The triangle of TNSC is much more deformation. This means TNSC had not a good communication combination between internal activities (right side group based activities) and external activities (right side group activities).

The deformation of the element position of SDK is much less than that of TNSC. The distances between the elements of SDK are almost the same. However, those of TNSC are much longer than those of SDK are. In other words, the model solid of SDK consists of one equilateral triangle and three equilateral tetrahedra, but that of TNSC consists of one deformed a triangle and deformed tetrahedra. The element distances of SDK (Fig.3-1) are shorter than those of TNSC (Fig. 4-1). Because of our work, the SDK case seems to be a compressed formation. In addition, Fig. 3-2 and Fig. 4-2 are apparently different (pink (Design)-blue (Technology), pink-green (Cost), and pink-violet (Market)). TNSC thought almost the same way as SDK from a market oriented perspective. However, TNSC was in a state where business design related activity did not work. It is clear that the area of the triangle of RSG of TNSC is large, unlike SDK. Both of the LSGs of interactions are almost the same.

The interactions of TNSC show that the interaction between right and left does not link well (mixed red and blue colored bond). Especially on the right side, the interactions of each elements show as blue bars. This means that they thought of the interactions, but something creates a negative impact for the interaction between certain elements. The TNSC of RSG interaction from pink (Design) in Fig 4-2 shows blue colored bond. This means that there was a shortage of R&D talented people in TNSC.

The colored bonds of SDK are usually red, however, for TNSC they are red, blue. That means SDK can do better in R&D management. In addition, the TNSC case gives us information about which interaction has to be improved to better the R&D management.

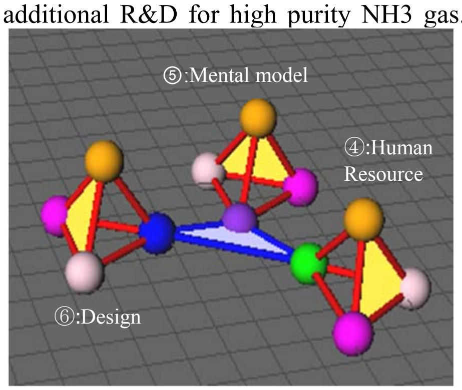

Fig.3-1 SDK Position of six elements based on Left-Side Group

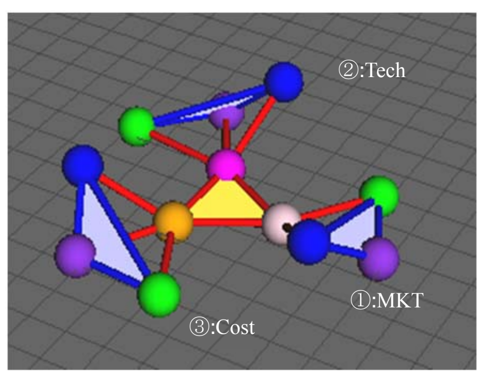

Fig.3-2 SDK Position of six elements based on

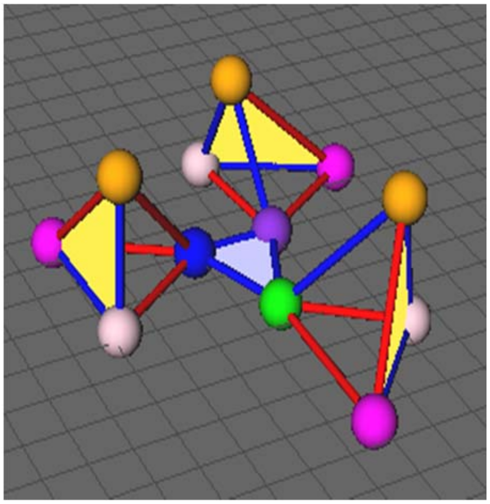

Fig.4-1 TNSC Position of six elements based on Left-Side Group

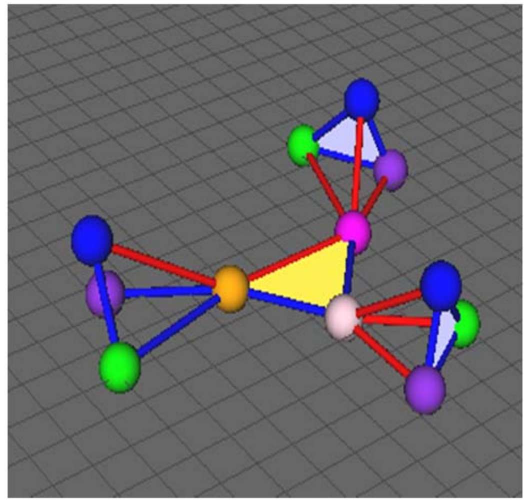

Fig.4-2 TNSC Position of six elements based on Right-Side Group

C. Deformation analysis

First of all, we consider the distance between all elements. (Fig. 5) The tetrahedron consists of the six sides and we evaluate the deformation as the normalized variance of the length of the sides.

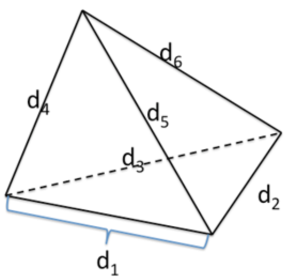

Fig.5 Distance between each elements

The variance of the length of sides is written as

$$\sigma^2 = \sum_{i=1}^{6} (d_i - < d >)^2 \qquad (11)$$

and the normalized variance is given by

$$\widehat{\sigma^2} \equiv \frac{\sigma^2}{< d >^2} = \frac{1}{< d >^2} \sum_{i=1}^{6} (d_i - < d >)^2 = \sum_{i=1}^{6} \left(\frac{d_i - < d >}{< d >} \right)^2 \qquad (12)$$

We have summarized the normalized variance $\frac{\sigma^2}{<d>^2}$ for $\frac{\text{TSNC}}{\text{SDK}}$ case in Table. 2. It is difficult to explain by the combination with blue bond connection (negative interaction). Therefore in this analysis, we only focus on RSG.

The smaller of the $\hat{\sigma}^2$ is the better, since if there is no deformation, the value is zero. Concerning SDK, the RSG (Human Resources-Mental Model-Design) $\hat{\sigma}^2 = 0.012$ is nearly equal to zero, which means a good status of the Human Resources-Mental Model-Design triangle. In other words, experienced experts are leading the R&D project and the activities of RSG are well balanced. In addition, the ratio of TNSC/SDK refers to the degree of deformation of TNSC compared with SDK. The RSG-TNSC/RSG-SDK shows apparent deformation ($\frac{\sigma^2}{<d>^2}$ for $\frac{\text{TSNC}}{\text{SDK}} = 135$). We can explain this by R&D of TNSC has been performed in an incongruous condition compared with the SDK case.

VII. CONCLUSION

Historically, it was not enough successful achievement of understanding of R&D state by the quantitative analysis by secondary data, such as financial statement. That is the reason we attempt to take an approach of combination of qualitative analysis together with conventional quantitative analysis.

In this paper, we propose a methodology for understanding MOT as a complex system and applied the modified Ising model. We achieved the first time to visualize R&D process status by this modified Ising model. The model could quantitatively analyze the high-purity ammonia gas of new business development together with product development and distinguish between the cases of two

TABLE. 4 COMPARISON OF DEFORMATION
(MKT:Market, Tech:Technology, HR:Human Resource, MM: Mental Model, DSG: Design)

	SDK		TNSC		TNSC/SDK	
Right -side group -Triangle (HR-MM-DSG)	σ2	$\frac{\sigma^2}{< d >^2}$	σ2	$\frac{\sigma^2}{< d >^2}$	$\frac{\sigma^2\text{TNSC}}{\sigma^2\text{SDK}}$	$\frac{\sigma^2}{< d >^2}\text{TNSC} \Big/ \frac{\sigma^2}{< d >^2}\text{SDK}$
	0.014	**0.012**	**128.427**	**1.609**	**9185.143**	**135.743**

different companies. The exchange correlation matrix (6×6) is a dominant feature of this dynamic quantitative model. The salient features of the methodology developed are its ability to (1) understand an R&D project status, (2) get feedback the status of the interaction of each elements to improve an R&D project, and (3) explain real business case. In other words, applying this model can provide (1) It is possible to see the status of the future of research and development of its own. (2) It will be visualized which interaction has to be improvement in order to be better success of the current Research and Development project. in order to be more success for the current Rresearch and Development project. (3) we can understand the success factor of which interaction is the critical when we apply this model to manufacturing company, especially chemical company of the research and development project. if we calculate with internal corporate data other than secondary data, which Ninomiya mentioned [21], the reliability of the quantitative part of the simulation result is increased.

The simulation results reveal that some site interactions are critical; however, as this approach is still in its early stages, a more detailed analysis and further discussions are required.

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