Graduate education for multi-disciplinary system design and management

— Developing leaders of large-scale complex systems —

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"System Design and Management" program, a study that integrates humanities and sciences by crossing many disciplines, is essential to foster talented persons who can lead in the development and operation of large-scale complex systems that are symbiotic, safe and secure. The subject of the new graduate school education is large-scale complex technological and social systems, with an education curriculum that provides practically oriented lectures through which students can acquire the capacity to consider systems, the faculty to design systems in line with system life cycles, and the ability for system management. By collaborating with industries and related stakeholders such as domestic and international educational research institutions, we designed an educational curriculum and recruited faculty members, developed educational facilities and research centers, recruited students, provided education, and moreover designed the method of publishing accomplishments. As for the establishment of the graduate school in April 2008, the educational curriculum was formed to provide students with opportunities to acquire must-learn capability and knowledge that were classified into six groups. The validity of the education method was confirmed based on verification of the students' self-evaluation, evaluation by the external evaluation committee and accomplishments by students such as papers, after the first two years of graduate education.

Keywords **:** System design and management, large-scale complex system, multi-disciplinary

1 Introduction

The Japanese universities and graduate schools mainly provide "the education for single disciplines" and "*Type 1 Basic Research*, which is a research to strategically discover, clarify, and formulate universal knowledge by investigating an unknown phenomenon[1]". The conventional education and research have been effective for training people with highly specialized knowledge over the years. However, the specialization and segmentation of discipline may not be appropriate for training people who can respond to issues that may stretch across different fields[2].

On the other hand, some of the recently instigated systems are producing various problems that cannot be dealt with by specialized and segmented disciplines. For example, there are difficulties in dealing with the unforeseen accidents and failures that may occur in the power generation system and aerospace system, or there are difficulties in safety design in the development of automobiles and robots. These difficulties emerge because of the increased size and complexity of the systems[3]. At the same time, the issues of earth environment, which was created as a side effect of the culture of modern science and technology, have become the most urgent issues in modern society. This means that it is difficult to design a system appropriately, if the issues of safety in the individual system and the issues of earth environment are dealt separately. To realize a system that can concurrently solve the issues of different time-space dimension, as exemplified by safety and symbiosis, it is necessary to accurately understand the complex interaction between the diverse values that have different categories and scales, such as the safety issues, environment issues, and the system and the relationship of various elements that compose the system. It is necessary to grasp the relationship among the systems, to systematize the transdisciplinary academics to design a whole system, and to provide education from the perspective of the integration of the system. However, sufficient education has not been provided in Japan on the method of problem solving across several different disciplines that may occur in the development and the operation of the diverse products in industry.

In Europe and the United States, systems engineering has played a certain role in problem solving across several different disciplines. In Japan, systems engineering is understood narrowly as engineering for the IT systems, but it is actually engineering for the analysis and synthesis of all systems including mechanical, IT, and social systems. According to the international society for systems engineering, International Council on Systems Engineering (INCOSE), systems engineering is defined as "a method and approach that stretch across several disciplines to realize a system successfully"[4]. Particularly in the United States, the education for the systems engineering defined by INCOSE is systematically practiced in 75 universities and graduate schools including the Massachusetts Institute of Technology, Stanford University, Naval Academy, and Air Force Institute of Technology[5].

In providing the education at universities and graduate schools, it is necessary to perceive the demands of the

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industrial world. According to the “Result of Questionnaire Survey on the Human Resources Wanted by the Companies”[6] of the Educational Issues Committee, Nippon Keidanren, the items shown in Table 1 are given as expectations for the human resource training at the universities and graduate schools of sciences. This is a questionnaire result of 520 companies on what they expect in terms of human resource training by the universities and graduate schools (science departments, faculties, majors) from the standpoint of engineer recruitment. The top five items with most responses are shown. In this questionnaire, each company may select up to three responses. From this result, it can be seen that the demand is for the universities and graduate schools to produce people who are capable of utilizing advanced expert knowledge, responding to the rapidly changing social situation, creating and managing the next-generation systems.

Given such a social background, the Keio University established the Graduate School of System Design and Management (SDM) in April 2008. At this graduate school, a unique, practice-oriented educational curriculum unseen in any other graduate school has been created to train people, who already are specialists or have business experience, to become capable of designing large-scale complex systems, taking in consideration the social demands such as symbiosis and safety. In other words, the people trained here will be capable of leading *Type 2 Basic Research*[1] and application research, and such human resources before could not be trained in conventional Japanese graduate schools. The large-scale complex systems include not only the technological systems such as power generation and aerospace systems, but also social systems such as the financial system, medical system, community, corporate organization, and NPO.

Our objective is to build the system design and management science (SDM science), a discipline system to creatively design and thoroughly manage the large-scale complex systems, and to provide graduate school education to train people who are capable of leading the construction and operation of large-scale complex systems. In this paper, we present the scenario for establishing the graduate school to realize our set goal, the elements selected to provide the graduate school education, and the results of the integration of the elements. We shall also present the evaluations by the students and the external evaluators, discuss the evaluations, and address the future issues.

Table 1 Expectations for universities and graduate schools from industry

Response	Companies
To have students acquire specialized knowledge	340 companies
To train the students to organize their thoughts by gathering knowledge and information	287 companies
To have the students acquire basic knowledge of other disciplines related to their specialties	231 companies
To provide education with relevancy to the real society, in addition to theories	162 companies
To have the students experience working in teams on certain topics	119 companies

2 Scenario

The Keio University established a graduate school for SDM education after a long period of deliberation. In 1996, a system design engineering department was established in the Graduate School of Science and Technology, to conduct education and research on system design engineering transcending the framework of engineering disciplines such as mechanical, electrical, information, architecture, and others. It continues to train engineers with both the abilities for basic knowledge and integrated perspectives. In 2008, the Graduate School of SDM was established independently of the Graduate School of Science and Technology for the education and research on SDM science, a discipline that fuses humanities and sciences and surpasses the framework of technology and social sciences such as science, engineering, economics, and political science.

In establishing the Graduate School of SDM, we interviewed the people involved in large-scale complex systems in Japan and abroad, on the current issues in developing and operating the large-scale complex systems, and also sought the demands of industry for graduate school education. As a result, we found that the demand for the graduate school education was almost the same as the ones described in Table 1. The format of the graduate school education was designed based on: the design method for large-scale complex systems such as automobile, robot, and plant that developed in the Japanese industry, as well as the systems engineering that developed mainly in Europe and the US; the system design methodology built by the Keio University in the 21st Century COE Program “System Design: Paradigm Shift from Intelligence to Life”[7][8]; and knowledge and methods necessary for the design and management of the social systems. The masters program was established with the educational objective of training people who can lead the construction and operation of the large-scale complex systems through a vocational graduate school type education, placing emphasis on interaction between the faculty and students or among the students themselves. The doctoral program was established with the educational objective of training specialists of SDM science with emphasis on research.

To realize our goal of the graduate school education for issues that stretch across multiple disciplines, collaborations with various interested parties (or stakeholders) are important. The relationship between the scenario set to realize the goal and the major stakeholders are shown in Fig. 1. The input and output between the stakeholders and the Graduate School of SDM are shown by arrows, and the items particularly emphasized by the School are underlined and capitalized. In this figure, society/industry, who is one of the stakeholders, represents all others except the “academia (education and research institution)” in the “industry-government-academia” and include all sorts of social organizations such as the government, local governments, and NPOs. Details of the scenario are as follows.

(1) Preparation of educational curriculum

Considering the social and industrial issues and the demands for the graduate school education, an educational curriculum is prepared by setting the abilities that the student must acquire to handle large-scale complex systems and by building the system of SDM science as a discipline system that enables nurturing such abilities. Collaboration will be done with the universities and graduate schools in Japan and abroad for the single discipline education, as necessary.

(2) Faculty recruitment

Based on the educational curriculum, the faculty members who can promote the research of SDM science and provide lectures for the courses are recruited. Particularly, faculty members with experiences in companies or overseas, as well as first-class experience in development and operation of large-scale complex systems are employed.

(3) Preparation of educational facilities

The educational facilities that promote communication and group learning by faculty members and students are prepared. To emphasize the close collaboration between society and education research, the facility should be located in a place with good access by public transportation. A communication system will be established to support discussions and conferences among students and faculty members in remote areas and with other institutions in Japan and abroad.

(4) Preparation of research center

The research center is set up to solve the social and industrial issues by application of SDM science, to utilize the obtained findings, and to further advance the SDM sciences through collaboration with other education and research institutions, international institutions, and academic societies.

(5) Recruitment of students

To enable learning based on exchange of diverse human resources, people with specialties in some disciplines of science and engineering, social sciences, or humanities are recruited (the ratio of people with specialties in so-called sciences to humanities will be 1:1, and the ratio of people with business experiences to new college graduates will be 2:1). Foreign students are actively recruited to enhance the international consciousness of the Japanese students, and to spread SDM sciences to students who are non-native speakers of Japanese.

(6) Education

The education for SDM science is executed mainly through hands-on experience and group learning of

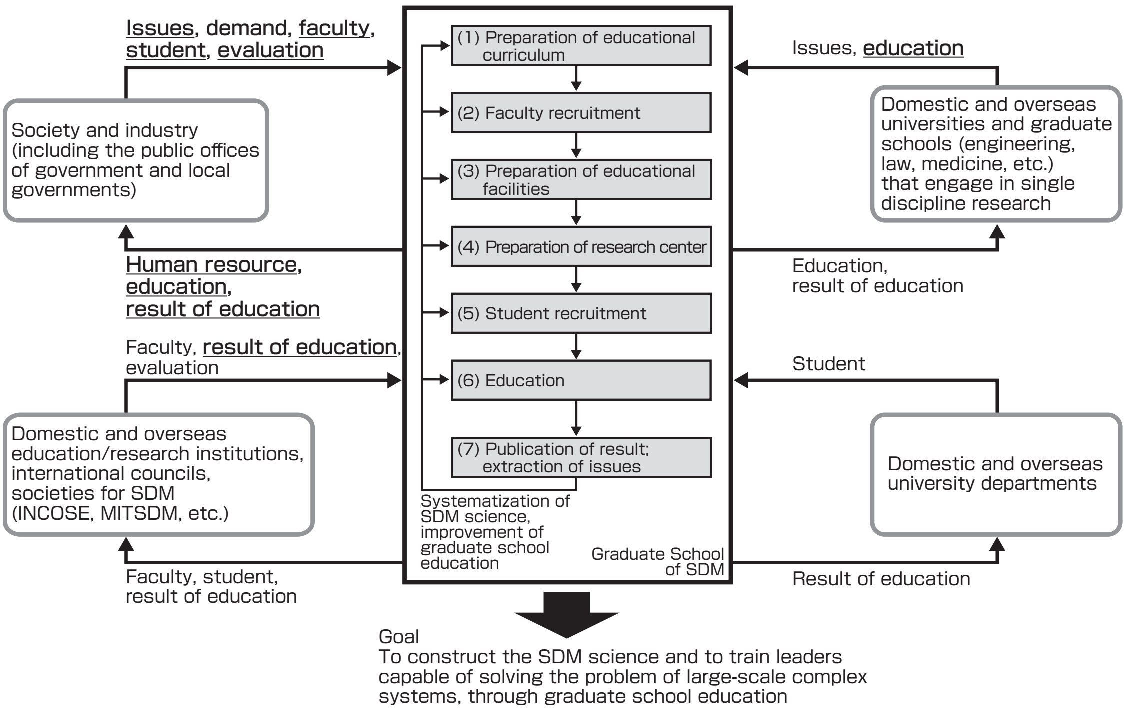

Fig. 1 Scenario for achieving the goal and the relationships with the stakeholders

unsolved issues in society. In addition, SDM seminars and lectures are actively done for business people in industry who are not participating as students, to train leaders of large-scale complex systems and to extract social issues and demands for graduate school education. Also, the opportunities for faculty development[Term 1] are regularly and frequently provided to increase the educational ability of the faculty members.

(7) Publication of results; extraction of issues
The abilities acquired by the students through the graduate school education and the findings obtained by the faculty members are presented to the stakeholders, and are evaluated. Also, evaluations will be done by students attending the Graduate School of SDM. The issues are extracted by analyzing the evaluations, and the education is improved based on the results.

The above scenario will not end in one cycle. It is a spiral-up[Term 2] scenario where the improvement of the graduate school education and further development of SDM science are conducted regularly for each steps from (1) to (6), based on the result of "(7) Publication of results; extraction of issues".

3 Establishment of the Graduate School

In opening the Graduate School of SDM, issues in industry and demands for graduate school education were extracted based on interviews with over 100 companies in Japan and abroad. As a result, the abilities and knowledge that the students must acquire to handle the large-scale complex systems were categorized into six groups as shown in Fig. 2. The horizontal axis shows the range of the related disciplines, while the vertical axis shows the scale and complexity of the system in question. This indicates that a leader who handles the large-scale complex systems must have the abilities of system design and system management, and should have the foundations for systemic thinking and communication. It also means that the students must be already versed in some

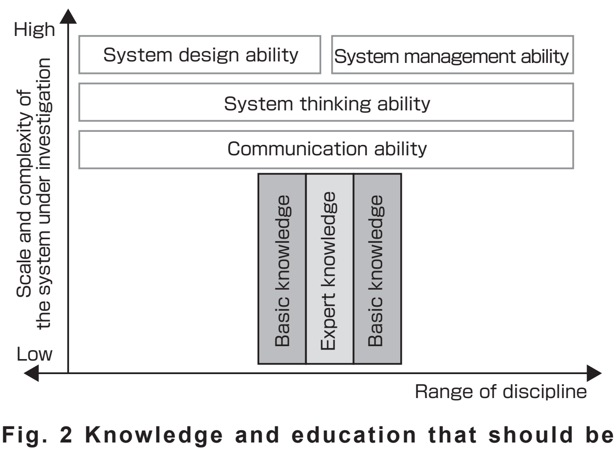

Fig. 2 Knowledge and education that should be acquired by the students

specialty and possess basic knowledge for the disciplines related to their specialty. The abilities and knowledge are defined as follows.

A) System design ability:
The ability to understand the real issues and demands of the diverse stakeholders such as user, customer, society, and environment, and to creatively suggest a solution to the issues while taking into consideration the total consistency in each lifecycle phase from conceptualization, development, operation, and disposal of the system (the design includes the proposal of concept and solutions in all designs, from technological system design, artistic design, organizational design, social design, to the grand design of management and policy)

B) System management ability:
The ability to respond to the changes in environment due to the progress of the project and the advancement of lifecycle, and to consistently carry out the system design and to manage and operate the system to fulfill the demands of the stakeholders such as the user and customer

C) System thinking ability:
The ability to capture the whole picture of the system and the essence of the issue in a transdisciplinary, birds-eye-view, and systematic perspectives, by looking at the interdependency and the interrelationship of the phenomena, as well as the independent phenomenon

D) Communication ability:
The ability to communicate one's thought to others, understand the thoughts of others, and to solve the problem by forming a team with diverse human resources

E) Expert knowledge:
Deep knowledge in certain fields of engineering or social sciences (desirable to have knowledge of multiple fields)

F) Basic knowledge:
Basic knowledge of other disciplines related to the specialty

The education at the graduate school established for the elements selected to realize the goal and the integration of these elements will be explained below.

3.1 Educational curriculum

The outline of the courses is shown in Table 2. For the abilities and knowledge that the students should acquire through education, those related to the courses are marked with ○ and those with particularly strong relations are marked with ◎ . The courses that differ according to the student's specialty are marked with △ . The individual subjects included in the recommended subject group and the elective subject group are listed in Table 3.

The basics of the four abilities that the students must learn will be taught mainly in the required subjects, and are supplemented with the recommended subjects. In the cases where the contents to be learned are different according to the student's specialty, they could be learned through the elective or recommended subjects. Since the disciplines are diverse, the students may take courses of the universities and graduate schools outside of the Graduate School of SDM to learn the expert or basic knowledge of certain fields. Particularly, the collaborations are done with the Graduate Schools of Science and Engineering and Business Administration within the Keio University, for supplementary courses to provide educational opportunities.

The credits of the courses are two credits per course for almost all courses with few exceptions. Figure 3 shows the structure of the master's program curriculum. The numbers in the parentheses indicate the credits of the courses necessary to obtain the degree. The requirement for the master's program is to complete 30 credits or more courses, including eight credits in core subjects, four credits in design project ALPS (active learning project sequence), and two credits in SDM research. The master's degree can be obtained after taking six credits or more of recommended subjects of technology, two credits or more of recommended subjects of social science, or two credits or more of recommended subjects of technology, and six credits or more of recommended subjects of social science. To allow active participation of the students, the course will be 14 sessions, 90 minutes per session, with ample opportunities for group learning, hands-on practice, and discussions. To actively

Table 2 Correspondence of educational curriculum and ability/knowledge

Abilities and knowledge to be acquired by students	Required subject group: Core subject: Introduction to systems engineering	Required subject group: Core subject: System architecting and design	Required subject group: Core subject: System integration	Required subject group: Core subject: Project management	Required subject group: Design project ALPS	Required subject group: System design and management research	Recommended subject group (technology, social sciences) 12 courses	Elective subject group (technology, social sciences) 16 courses	(Subjects of other departments and other universities)
System design ability	◎	◎	◎	○	◎	◎	○		
System management ability	○	○	○	◎	◎	◎	○		
System thinking ability	◎	◎	◎	○	◎	◎	○	○	
Communication ability				◎	◎	○	◎	○	
Expert knowledge in a certain area					○	◎	△	△	◎
Basic knowledge in disciplines related to the specialty					○	○	△	△	◎

accept foreign students, courses will be in English as well as Japanese mainly for required subjects.

The educational curriculum for the required subjects will be described. To teach the basic knowledge considered to be international standard, four textbooks are selected in accordance to the Certified Systems Engineering Professional (CSEP), which is an international qualification for systems engineering, and the Project Management Professional (PMP), which is an international qualification for project management. The textbooks included the one for core subjects[9], a book for the three courses except project management[4], a book for project management[10], and a book used in ALPS[11].

Table 3 Recommended subjects and elective subjects

Group	Category	Subject
Recommended subject group	Technology subjects	System environment
		Human factor
		Risk management of engineering system
		Dependable system
		System life
		Digital manufacturing system
		Model based engineering and architecting
	Social science subjects	Introduction to international affairs
		Communications
		Human relations
		System management
		Ethics for system design engineers
Elective subject group	Technology subjects	Mathematical modeling and statistics
		Mathematical technique of prediction and optimization
		Mathematical technique of dynamics analysis and control
		Database management system under network environment
		Software safety engineering and reliability
		Software engineering
	Social science subjects	Fundamental of accounting, marketing and economics
		Introduction to legal issues for engineers
		System simulation technique
		Global standardization strategy
		Methodology of creative decision making
		Business intelligence
		Design philosophy for policy and regulation
		Political economy of International systems
		Methodology and management of socio-critical system
		Special lectures on system design and management

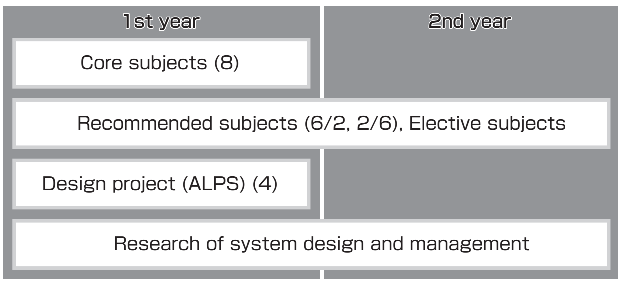

Fig. 3 Framework of master's program curriculum

Since there are many faculty members with business experience as well as knowledge and abilities in the large-scale complex systems, many courses reflect the business experiences. For example, in a core subject “System integration”, the textbook is used to introduce the processes and methods that are being systematized in the field of systems engineering. Then, the faculty members who had participated in the development of the automobile and satellite introduce the actual case of problem solving, explain the gap between theory and reality, and conduct hands-on exercises using the case studies. The students learn the differences in the system integration of mass-produced automobile and custom-produced satellite, as well as the design method developed in Japan.

3.1.1 Introduction to systems engineering

The basics of strategic systems engineering according to the V-model[Term3] in the system development process is presented. Lectures and exercises are done on system thinking, requirement analysis, functional physical breakdown, and architecting[Term 4], to learn the basics of SDM which aims to meet diversified social requests. In the exercise, the students form teams to realize some specific system such as “automatic cleaning system that can be remotely operated by the user while not at home”. Several faculty members will be in charge of the lectures. The students interview the faculty members who play the role of customers to extract the issues and needs, create the specification for each development process from system requirement to shipment, and develop the system along the development process. The other teams are considered to be the competitors, and all teams work to realize the system. Figure 4 shows the remote-controlled automatic cleaning system created by one of the teams. The image on the left is the service screen on the web to conduct remote control, and the photograph on the right is the cleaning system developed based on Roomba 577 of the iRobot Corporation.

3.1.2 System architecting and design

This is a course on the architecting and design of the problem-solving structure and detailed structure as well as visualization from multiple viewpoints in response to social demands. Group discussions will be held on the architecting and design of the research topics of the students.

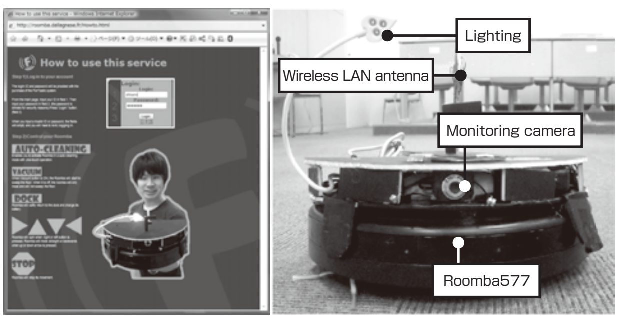

Fig. 4 Automatic cleaning system

3.1.3 System integration

This is a course on the discipline system for the process of breaking down into elements and to integrate them as a system. Lectures are given on the creation of requirement specs of a system, analysis, design, operation verification, and adequacy check of the specs. Practical group exercise will be done and discussions will follow.

3.1.4 Project management

This is a course on the basics of project management. Specifically, it will be lectures and exercises on the management of large-scale complex systems, basics and practice of logistics (personnel and procurement), and methods of cross management and project management. Figure 5 shows the exercise in tower construction using paper. The students work in teams, determine the roles including the project manager, and the preparation for tower construction is carried out according to the management process of PMP. The price of the paper and the cost of labor per student per hour are set, and the teams complete for a stable and high tower construction within a set budget and schedule. This will be followed by the evaluation of the project management of each team.

3.1.5 Design project ALPS

This is an international collaboration group project with Stanford University and the Massachusetts Institute of Technology, and the course is given in English. Under topics such as “Enhancing Senior Life in Japan” (2008) or “Sustainable Community” (2009), about four or five workshops (two days each) are conducted a year in addition to group learning between the workshops. The students join a team of five to eight members to experience the whole process of system lifecycle, and finally present a system proposal and engage in discussion[11][12]. Figure 6 shows the flow of the annual workshops and the group learning. The faculty members of the three universities adjust the lectures and methods of ALPS almost every month including through teleconferencing. This course is deeply related to the core subjects, and it is designed so the students can learn the lectures through the main course and will be able to apply the

Fig. 5 Project exercise of building tower using paper

knowledge learned in the lectures to this course. The details of the ALPS course are presented in Reference [12].

3.1.6 System design and management research

This corresponds to the research for the master's thesis. However, unlike conventional individual research, the group conducts the transdisciplinary research in project format, and the students are encouraged to engage in research that matches the social demands such as safety, symbiosis, and social coexistence. Each student writes a thesis for the part of the project that he/she is responsible.

3.2 Faculty member

Twelve full-time faculty members for the Graduate School of SDM as well as dozens of special research faculty and invited faculty members are employed. One of the characteristics is that there are many members with business experiences in industry. The faculty members employed include people with business experiences and advanced knowledge and abilities in large-scale complex systems in technological systems such as aerospace, nuclear power, automobile, information, and precision machines, as well as social systems such as finance, policy, treasury, and agriculture. The requirement for recruitment is that they must be able to give lectures in English to give courses for foreign students and to promote collaboration with educators and researchers of overseas education and research institutions.

To provide students the global trend of the academic world related to SDM science and to increase the knowledge of the faculty members as part of faculty development, about 10 lecturers are invited from abroad. These lectures are mostly on core subjects and can be heard as intensive courses or as remote conference lectures.

3.3 Preparation of educational facilities

To promote communication and group learning among students and faculty members, the classes are set up in the free seating style[Term 5], and each student is given a personal locker to store educational and experiment materials. Unlike the conventional laboratory where the spaces between the students and the faculty members are divided by partitions, there is no specific seat for any student, and the students use the rooms and seats according to their purpose such as communication and group learning. The faculty room is concentrated in a segment of the floor to enhance frequent communication among the faculty members.

An e-learning system is set up where all lectures are recorded on video by staff members, and these can be delivered online along with the lecture materials. This will enable education opportunities to students who cannot be physically present at the lectures. The teleconferencing system is introduced in several conference rooms to enable discussions and meetings with students and faculty members in remote areas and with other institutions.

To handle large-scale complex systems, it is necessary to improve the abilities in simulation and modeling technologies to support system design and system management. Therefore, the environment where the student can freely use the software for such technology through the network is offered. Also, large-scale workstation for concurrent design[Term 6] and concurrent design room composed of several high-definition displays are prepared (Fig. 7). There, the students can bring their own terminals to create designs for various systems through the network.

3.4 Research center

The SDM Research Center of the Graduate School of SDM was established as a research center to advance the SDM science by solving the diverse issues in the industrial world by application of SDM science and to accumulate the findings obtained. This center was established to solve the various issues through the collaboration of industry and academia, and the faculty members can establish a laboratory in the Center to solve some specific issues. The collaborator can obtain the information related to SDM science and may use the facilities of the Graduate School of SDM.

To solve the issues of large-scale complex systems, collaboration with education institutions transcending the framework of disciplines and international collaborations are necessary. Therefore, in collaboration with the Graduate

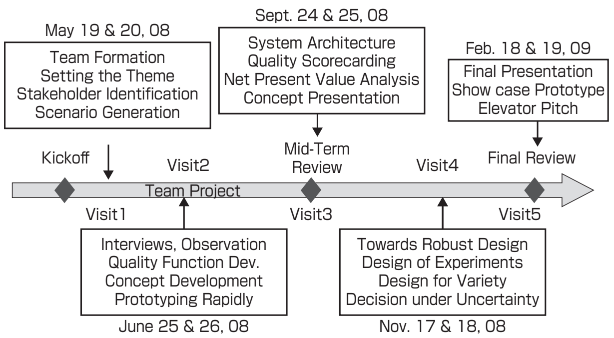

Fig. 6 Work flow of group training in the annual workshop

Fig. 7 Concurrent design room

School of Science and Technology, Keio University, the Global COE Program "Center for Education and Research of Symbiotic, Safe and Secure System Design" of the Ministry of Education, Culture, Sports, Science and Technology was started in 2008, to study the system design considering the social values such as symbiosis and safety, as well as to promote education and research of the researchers with such social values.

The following list shows some of the research topics at the Graduate School of SDM. The systems include home appliances, information, financing, insurance, human, education, and others.

- Thermal/Acoustic trade-off design for consumer electronics in a distributed design environment[13]
- A case study of the effects of platform software selection on information system maintenance cost[14]
- Transforming seamless positioning technology into a business using a system design approach[15]
- The evaluation of the alliance systems designed by "Enterprise Currencies" in Japan[16]
- Claim-payment failures of Japan's insurance companies and designing better payment architecture[17]
- A method for analyzing fundamental kinesiological motions of the human body by applying interpretive structural modeling[18]
- Capstone experience for multi-disciplinary system design and management education[12]

To be constantly aware of the global trend of academics related to SDM science and to contribute to academics through the education at the Graduate School of SDM, the School will participate in INCOSE and the Council of Engineering Systems Universities (CESUN), an international organization for systems engineering education. The faculty members will be dispatched to the meetings regularly, and the School will host the APCOSE (Asia-Pacific Conference on Systems Engineering)[19] to enhance the knowledge level of the students and the faculty.

3.5 Students

The student recruitment by the Graduate School of SDM is announced at various organizations of industry, government, and academia, and request is submitted to industry to dispatch the employees as students. As a result, after entrance examinations held three times a year, we were able to accept students almost exactly as in the set scenario. One of the characteristics is that the students are composed of wide-ranging age, diverse fields, and multiple nationalities. Students were admitted in spring and autumn semesters for the academic years (AY) of 2008 and 2009, and as of AY 2009, there were 138 students in the master's program and 46 in the doctoral program. The ages of the students varied from the 20s to 60s, and the average was 32 years old for master's students (Fig. 8) and 42 years old for doctoral students (Fig. 9). Their majors included science and engineering, law, political science, economics, literature, trade, agriculture, and physical education. Many students had business experiences, the percentages being 66 % for the master's student and 89 % for the doctoral students (Fig. 10). The occupations of those with business experiences were diverse: manufacturing, communication, consulting, information, aerospace, financing, real estate, public office, architecture, energy, system, medicine, mass communication and publishing, and law (Fig. 11). About 20 % of the students were non-Japanese including foreign students from overseas universities. As in the initial objective, it has become a place of learning based on the exchange of diverse human resources consisting of students and faculty members with diverse specialties.

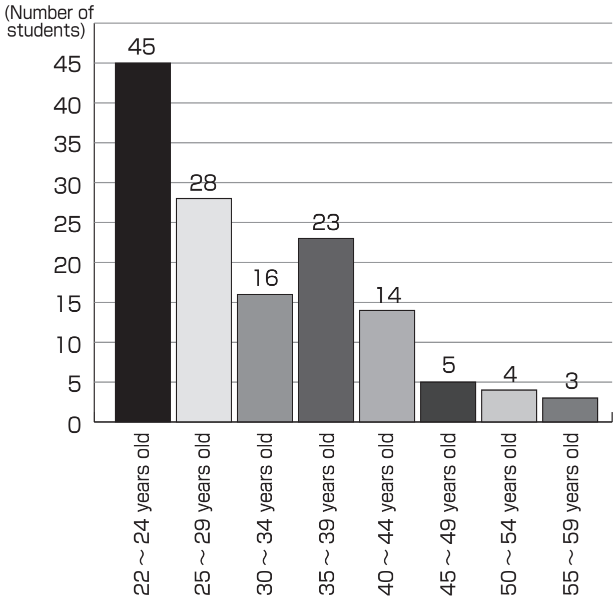

Fig. 8 Age distribution of master's students

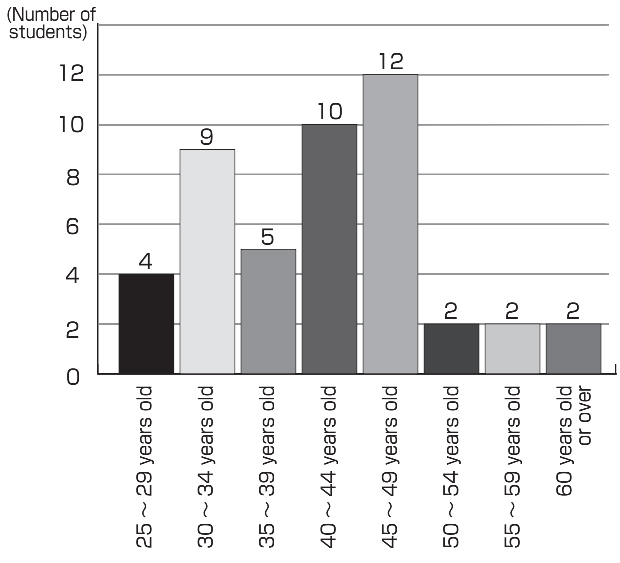

Fig. 9 Age distribution of doctoral students

3.6 Education

As mentioned earlier, since many faculty members have business experiences in large-scale complex systems, the education format is designed to reflect their experiences. Also, since there are many students who already have specialized knowledge and business experiences, there are several courses designed to seek ways to solve problems in industry or to systematize part of SDM science. For example, a faculty member with experience in the financial system may propose the topic, "What are the verification methods in the social system? What are the advantages and disadvantages of each method?" and the discussions are deepened during each session. In addition, the independence of the students is emphasized, and the students are encouraged to organize sessions where they invite students or exterior lecturers with some particular specialties as needed.

To improve the abilities and knowledge of each faculty member, opportunities for faculty development are set several times a month. The findings and issues obtained through the education experience of the faculty members are presented, and discussions are conducted regularly to share the findings and to improve education and research.

To provide learning opportunities to working students who cannot attend during office hours, the Japanese lectures of the core subjects are given on Saturdays and weekday evenings (19:00-20:30). Since most of the foreign students are full-time students who do not work, the English lectures for the core subjects are given during the weekdays. For the employees of industry who are not students, seminars and lectures for SDM science are conducted to help train the leaders of design and management of the large-scale complex systems. This is useful for the extraction of the industrial issues and the demands for graduate school education.

3.7 Publication of results; Extraction of topics

The results of the education are actively publicized, and the opportunity to be evaluated mainly by industry and the opportunity to apply the results in industry are sought. For example, in ALPS, each team proposes a service or product for a given topic in the final session. About 10 entrepreneurs, company people, and research institution people are asked to judge the proposals from the perspective of practical application in society.

For the evaluation of the courses, questionnaire survey is conducted of the students at the final session for each course. The evaluations of the course can be viewed only by the faculty members and others in charge, while the students' evaluations on overall graduate school education are shared by all faculty members, to extract the issues and the improvements are reflected in the programs next year. Also, a system is set up where five people of industry working on the development and operation of the large-scale complex systems are asked to participate as members of the external evaluation committee, to regularly conduct external evaluation of the education at the Graduate School of SDM.

4 Results to present and future issues

Two years have passed since the opening of the Graduate School of SDM. The results and evaluation to present as the students completed the program in March 2010, and the future issues will be described below.

4.1 Result of group learning by diverse human resources

In ALPS, group projects were done by the teams over the year, and many students were able to learn the diverse ways of thinking and methods for clarifying the social demand systematically and to create and realize the ideas through experience. As a specific example, the idea and the result created by a certain team will be introduced.

The team worked on the 2009 ALPS topic "Sustainable Community" and suggested a system for hydroponic

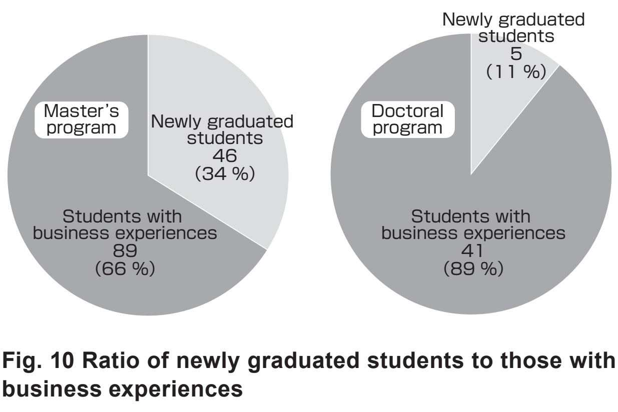

Fig. 10 Ratio of newly graduated students to those with business experiences

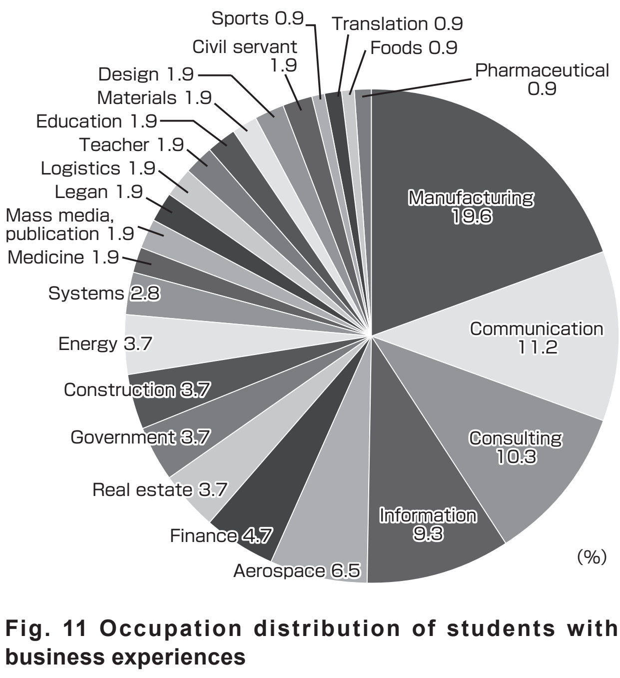

Fig. 11 Occupation distribution of students with business experiences

cultivation using the abandoned schools in the metropolitan area as a method to simultaneously solve the issues of abandoned school buildings due to low birthrate, lack of successors of agriculture, and unimproved unemployment rate of young people. Figure 12 shows part of the proposal created by this team (Roppongi Vege & Fruits). The strengths of this proposal was the construction of a sustainable business model that fulfilled the consumer demands for fresh, safe, and secure foods, as well as the demands of young people who wish to have stable income in the city. To create this proposal, the team conducted market research, questionnaire survey to the stakeholders, and interviews. Then they did a prototyping in a test plant based on the methods and knowledge learned at ALPS, and investigated the possibilities. As a result, the project won the award in the "Student Entrepreneur Championship" of the Tokyo Metropolitan Government and the Tokyo Metropolitan Small Business Center, and the Kanto Bureau of Economy, Trade and Industry Director Award in the "Campus Venture Grand Prix" organized by The Nikkan Kogyo Shimbun, Ltd. Currently, several more students have joined the team, and are considering its business development and are making adjustments with the local government and related companies. This is one example where the students acquired the ability to extract the demand from the real society and to design a system throughout its lifecycle from conceptualization, operation, to disposal, through the education at the Graduate School of SDM.

Also, it was confirmed that the concept of the Graduate School of SDM where group learning and group discussions are emphasized was effective in many courses other than ALPS. The students with diverse backgrounds understand each other's backgrounds, discuss the knowledge obtained in the course, and work together on an issue, and this results in high educational effectiveness.

4.2 Education by collaboration of multiple disciplines

The courses that transcend the framework of disciplines are realized in various forms through the collaborations of the faculty members, and feedbacks from students are obtained. As one example, the faculty members with specialty in technology give courses in "System Simulation Method" to conduct design and verification of system using the simulation method for the "Call Triage[Term 7] Emergency System" handled by the research group consisting of the faculty members with specialty in social sciences. The analysis and investigation for improving this system in terms of technological and sociological aspects are done. For example, it has become possible to carry on a more specific and specialized discussion on the legal limitations that become issues when attempting technologically optimal solution or the limits of what can be solved technologically in the current legal limitations. It can be said that an effective education can be done through collaboration of disciplines that normally rarely come together. In "System Life Theory", education on system design method learned from the environmental adaptation of organisms is done, and lectures and exercises are given on the design theory considering the unforeseen circumstances that can not be solved with conventional systems engineering. This is one example where SDM science can be applied to social and human system design transcending the systems engineering.

Fig. 12 Case study of a proposal at ALPS (Roppongi Vege & Fruits)

4.3 Master's research and doctoral research

Unique researches on the design and management of various systems including the recommendations for design and policy of management, as well as design of services and products are being done at the master's and doctorate level. Particularly,

Table 4 Example of master's research topics for AY 2009

Research topics
Measurement of CO_2 reduction effect by battery sharing alongside solar power generation
Carbon tax design using LCA for the diffusion of clean energy vehicle
System design for symbiotic city-rural society centering on biomass energy technology
Evaluation of sustainability of copper supply with consideration for recycling in Japan
Proposal for safety management system in large-scale chemical plant
Risk management for software development project with project description language
System design of lower limb protection of passengers using semi-active knee bolster
Renewal of global maritime safety policy for the stabilization of international maritime transportation system
Survey of relationship of corporate performance and corporate customs and cultures in manufacturing
Survey of motivation of employees of local governments – For the construction of lively organizational culture
Research on the motivation of young engineers – Using the microgravity experiment project conducted jointly by multiple universities as an example
Clarification of values for social relevancy in subjective happiness
Research on the strategy to introduce ultrahigh-speed plastic optical fiber network for homes to China
Research on the future prospect of electronic books and the structural change in the print media industry
Investigation and plan for verification test for the business model for launch space vehicle using the ocean – for realization of Japanese manned spacecraft

there are many research topics on conglomerate values such as symbiosis, safety and security, and social coexistence. Table 4 shows some examples of the master's research topics conducted in AY 2009. The target systems include diverse systems from technological to social systems, but the master's researches have the common points: designing and managing a system that matches the demand of the stakeholders while considering the system lifecycle; and then to write up the verification of the result and confirmation of the efficacy as a research thesis. These are the characteristic of the research at the Graduate School of SDM. The doctoral dissertations on SDM science are also beginning to appear [20].

4.4 Collaboration with industry and overseas institutions

Seminars and lectures are regularly given to the people of industry. An agreement was concluded on SDM science with the Japan Aerospace Exploration Agency (JAXA), and collaborations in education and research are being done. As one activity, seminars on SDM science are given to the employees of JAXA, and about 93 people participated in AY 2008. Various issues occurring in the space development field were clarified, the courses systematized at the Graduate School of SDM were given, and discussions were held on the solutions of the individual issues. The result of the questionnaire survey of the participants showed high satisfaction in the seminars. Particularly, high marks were seen for the overall, comprehensive viewpoint as a system.

Collaboration with overseas institutions is actively promoted, other than the aforementioned ALPS courses and workshops with Stanford and MIT. Collaborative agreements were signed on the mutual use of educational curriculum with Delft University of Technology (The Netherlands), Stevens Institute of Technology (U.S.A.), Swiss Federal Institute of Technology Zurich (Switzerland), Institut National des Sciences Appliquées (France), and others. Master's students are exchanged with TU Delft for a successful international collaborative education. We have received request for support for the construction of SDM sciences to meet the demand of the industries of the respective countries from Khalifa University of Science, Technology and Research (Abu Dhabi, UAE), Amet University (India), and Egypt-Japan University for Science and Technology. We have become aware that there is a worldwide demand for SDM education.

4.5 Evaluation by the students

A survey was conducted to 36 second-year master's students who matriculated in spring semester, AY 2008, on the abilities that they thought improved in one year of education at the Graduate School of SDM, and the level of the satisfying experience. As a comparison, similar survey was conducted to 23 second-year master's students of the Mechanical Engineering Department, Graduate School of Science and Technology, Keio University. The survey was a six-step evaluation for each item. The t-test for each item was conducted based on the survey results of the two graduate schools. The items that showed significant difference in the evaluation with significance level 1 % are shown in Fig. 13. For each item, the graph on top shows the average values and standard deviation of the survey of the students of SDM, and the graph on bottom shows the average values and standard deviation of the survey of the students of Science and Technology.

The result shows that the education and research curriculum at the Graduate School of SDM fulfills the expectation for the universities and graduate schools of science by industry, as shown in Table 1, at the level of the self-evaluation of the students. The low self-evaluation by the SDM students on "writing ability to create the papers and reports that are logical and understandable" is an issue that must be resolved in the future. It is thought that the self-evaluation for writing ability was low since the subject of the questionnaire were master's students who just entered their second year, and since the first-year students went through the SDM education where emphasis was placed on action such as going to the site rather than creating documents. In response, we plan to strengthen the courses to improve the communication ability. For writing, in ALPS, the students experience writing a report in English as a team, and experience writing in Japanese for the master's thesis individually.

We feel that all students are capable of learning the basic thinking and method needed to solve the problems of large-scale complex systems to a certain level through required subjects. On the other hand, to be able to utilize the thinking and method in society and industry, it may be necessary to take courses other than the required ones at the Graduate School of SDM as well as at other universities and graduate schools, and the students themselves must apply them in their research and work. The effectiveness of the education depends largely on the students' strength of the consciousness for the problem, breadth of vision, and their ability to take

Fig. 13 Comparison of consciousness of SDM students (upper bar graph) and engineering students (lower bar graph)

action. Although it is difficult to solve all these issues through graduate school education only, we feel many issues can be solved by the close collaboration between the Graduate School of SDM and society and industry, the individual guidance to students by the instructors, and the further promotion of various exchanges among students composed of diverse human resources.

Since the education for enhancing deep knowledge and advanced specialty is also important, we are considering the curriculum where such abilities can be improved along with the other abilities. Another issue is the large gap in the abilities and knowledge level of the students depending on the courses since the specialties differ by students. Currently, the lectures are given for the students with higher abilities and knowledge level, and supplementary lectures are given separately.

4.6 External evaluation

As of the end of AY 2008, the external evaluation after one year of the Graduate School of SDM was conducted by the five members of the external evaluation committee. As a result, high evaluation was obtained for the new education, while the following points of improvements were indicated. These included the further collaboration with industries on the results of one year at the Graduate School of SDM, the mechanism for giving independence to students such as employing the students who have completed the program as the course mentor, and the thorough infusion of education and research concept of SDM where “both the trees and the forest are seen” or seeing the individual essence as well as maintaining a wide vision.

We are working to improve the education based on these indications. For the further collaboration with industry, we are considering and adjusting the ALPS where proposals of the team can be realized through collaboration with industry. Also, we are considering the mechanism where the issues taken up in the courses are matched with the issues in industry, and where the proposals generated in the courses are fed back to the companies that provided the topic.

5 Summary

The Graduate School of SDM was established to train people who are capable of leading the construction and operation of the diverse large-scale complex systems from technological to social systems, and the first students graduated in March 2010. From the evaluation of the students and members of the external evaluation committee, we believe the students have acquired the abilities and knowledge that they must have to handle the large-scale complex systems, as set at the inception of the graduate school. The results of the master’s researches conducted by the students confirm that the students have acquired the method and thinking to clarify the social demands systematically, to create the ideas, and to realize them through the curriculum that emphasizes group learning and group discussions by diverse human resources. On the other hand, future issues include the reinforcement of the educational curriculum to improve the advanced specialties of each student, and measures to fill the gap in ability and knowledge levels of the students for each course due to the wide-ranging student background. We believe further revisions in the curriculum and further strengthening of the collaboration with society and industry, related education and research institutions, and universities and graduate schools are effective. Also, we believe this unique graduate school education can be improved by investigating and evaluating the results and issues of the graduate level education of SDM science by conducting follow-up surveys of the graduates in society and industry.

6 Acknowledgements

This study was partially supported by the Global COE Program “Center for Education and Research of Symbiotic, Safe and Secure System Design” of the Ministry of Education, Culture, Sports, Science and Technology, and part of the SDM education was used for training the young researchers of the Global COE Program. We are thankful for this support. We also express deep gratitude to Masataka Urago, Tetsuro Ogi, Seiichi Sasaki, Seiko Shirasaka, Kenichi Takano, Ryuichi Tejima, Tetsuya Taima, Masaru Nakano, Shinichiro Haruyama, Taketoshi Hibiya, Toshiyuki Yasui, late Kosuke Ishii, and Olivier de Weck, who have spent effort for the establishment of the Graduate School of SDM from the beginning.

Terminologies

Term 1. Faculty development: Organizational effort by which the faculty members improve and enhance the lessons and the teaching methods

Term 2. Spiral-up style: The method where a goal is achieved in a spiral form rather than in a linear form
The movement toward the goal is made by turning the PCDA (plan-do-check-action) cycle, including making a plan, executing it, verifying it, and then incorporating the improvements in the next plan.

Term 3. V-model: The framework to describe the lifecycle of system development from demand analysis, operation, to disposal
The left side of the V-shaped conceptual diagram shows that the demand drops to lower level as the demand is segmented by design, and the right side shows that the system is integrated by testing and assembly.

Term 4. Architecting: The act of realizing a concept, allotting the function to the elements, and then clarifying the relationship (interface) between the elements

Term 5. Free seating style: The style where students are assigned no specific seating
The seats and the rooms are used on first-come first-serve basis or by preliminary reservation.

Term 6. Concurrent design: The design method in system development where the people in charge of all phases of the system lifecycle from planning, operation, to disposal gather, discuss various issues, and cooperate to work simultaneously.

Term 7. Call triage: The mechanism to determine the necessity of dispatch in emergency calls, where the urgency and seriousness of the sick are determined based on the information given by the caller
The City of Yokohama started this system on October 1, 2008.

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Completed the course at the Graduate School of Science and Technology, Keio University in 1998. Doctor (Policy and Media). Joined the National Space Development Agency of Japan (NASDA) in 1998. Engaged in the R&D for devices onboard the H-IIA rocket. After working as the Visiting Researcher of the European Space Agency, returned to the Japan Aerospace Exploration Agency (JAXA) as a senior developer to work on the independency verification and efficacy check of the software onboard spacecraft. Currently, Associate Professor, Keio University. Studies systems engineering and intelligent system using aerospace technology. Member of INCOSE, IEEE, Information Processing Society of Japan, and others. Promotes international collaboration and interactive courses at the Graduate School of SDM. For this paper, was in charge of the overall structure, and the analysis and discussion of the results to present.

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Discussions with Reviewers

1 Overall

Comments and Questions (Naoto Kobayashi, Center for Research Strategy, Waseda University)

This paper presents the curriculum and the basic concept and mechanism for the establishment of the Graduate School of System Design and Management (SDM) that newly opened at the Keio University in 2008. The school has unique characteristics unseen elsewhere. In this effort, multiple disciplines are integrated transcending the conventional disciplines to solve the social issues, and it is a new and attractive attempt in the practical education. The article is an extremely useful report in terms of social and education consequences.

However, looking at the first draft as a research paper, there are certain points lacking. First, I can understand the historical developments that led to the establishment of the Graduate School of SDM, but I cannot see what exactly the authors of the paper did in that process. I understand that the university itself took action to create this new school (or some preparatory organization), but I would like to know what the authors specifically did, such as designing and building the SDM as a whole, or some practical activities such as "5.2 Evaluation by the students" or "5.3.3 Collaboration with business world and overseas institutions". I also think the points that are stated in this paper should be organized and discussed.

To convert this into a *Synthesiology* research paper, (1) first clarify what the authors did in establishing the Graduate School of SDM, and (2) complete the paper by describing the research objective of this study; the scenario; the selection, synthesis, and integration of the elements; and the evaluation of results and future developments (as written in the "Instruction").

To be considered as a research paper, the following development may be taken.

[Example 1] Thinking with emphasis on the synthesis method of the new Graduate School of SDM where multiple disciplines are integrated (in this case, the authors must play central roles in the establishment of the graduate school).

1. Research objective: "To develop the synthesis method for the newly established Graduate School of SDM" etc.
2. Scenario: By discussing the synthetic method for the conventional graduate school of SDM and SDM science, describe the scenario for the construction of true SDM science and education through future curriculum revisions.
3. Selection of the elements and their synthesis and integration: Describe why the multiple disciplines (elements) needed for SDM science in establishing the Graduate School of SDM were selected, and how they were integrated as a whole.
4. Evaluation of the result and future development: Based on the above decisions, investigate whether the concept of education and research of the Graduate School of SDM for "looking at both the trees and the forest" was thoroughly achieved. If the initial goal was not achieved, suggest improvements to achieve the goals. If the goal was achieved, consider the points that will lead to further advancement.

[Example 2] Thinking with emphasis on the verification of the principles and practice of the Graduate School of SDM (In this case, the authors must play central roles in the verification and evaluation.)

Comments and Questions (Motoyuki Akamatsu, Human Technology Research Institute, AIST)

The draft gives an impression that it is an article introducing the graduate school, and the point as a thesis is not clear. Please clarify the points that you wish to communicate in terms of synthesiology, delete the parts that are unrelated to enable the readers to get to the point.

As a *Synthesiology* paper, please describe the overall effort as a scenario rather than merely listing the facts. You should describe how the whole process of curriculum creation, actual education, the effect of the education at the Graduate School of SDM was conducted with what kind of objectives or intentions, and how it was realized. Moreover, what did you think the students acquired upon seeing the actual results produced by the students? I think you can provide useful information to the readers if you state such objectives, facts, and your interpretations.

Answer (Naohiko Kohtake)

Ohkami is the proponent of the Graduate School of SDM, and had engaged in international surveys and preparations for about 10 years prior to the establishment of the School. Maeno and Nishimura are faculty members since its establishment. Maeno is in charge of the overall concept of the Graduate School of SDM and the education and research curriculum for the social skill courses, while Nishimura plays a central role in building the education and research curriculum for the technological courses. Finally, Kohtake was involved before its opening from the standpoint of industry, and became a faculty member one year after its opening. In this study, he works on the interactive courses, the international collaboration, the analysis and verification of the education results, and the discussions for the Graduate School of SDM.

To write this article as a research paper, we rewrote it according to the guideline shown in [Example 1], and the research objective, scenario, selection of elements and their synthesis and integration, evaluation of the results, and future developments were described. The newly drawn Fig. 1 represents the scenario, and the relationship between our effort and society was explained by clarifying the relationship with the stakeholders. Also, how the scenario was realized, what kind of results has been produced, what are the issues that must be solved in the future, and their interpretations are described. The presentation of the paper was substantially changed.

2 Title and subtitle

Comments and questions (Motoyuki Akamatsu)

The main title of the draft is "Graduate school education for 'system design and management science' transcending the disciplines", but I think it is lacking as a title for a "synthesiology" paper. I think SDM itself is "synthesiology", and creating the education system is "synthesiology". Therefore, please consider a title that clearly expresses that it is a "synthesiology" paper from both perspectives, such as using the title "Graduate school education for…" with the subtitle "Developing leaders who can construct and operate large-scale complex systems".

Answer (Naohiko Kohtake)

Thank you for your suggestion. We changed the title and the subtitle as follows to present the specific content of the paper:

Graduate education for multi-disciplinary system design and management- Developing leaders of large-scale complex systems -

3 Objectives and points of the SDM curriculum

Comment and question (Motoyuki Akamatsu)

You wrote that you set the abilities listed from A) to C) as abilities to be acquired in response to the expectations for universities and graduate schools in Table 1, but please explain these points. Also, there is a matrix of abilities and courses in Table 2, but please state what are the points in having the students effectively acquire SDM science such as in the selection of the curriculum, points emphasized in the courses, and selection of the educational materials.

Answer (Naohiko Kohtake)

There were unclear points and redundancies in the relationships of Table 1, the list described in Items A) to C) of section 4.1, as well as in Table 2, so the relationships were clarified and revisions were made to the relationship of the abilities and knowledge the students should acquire. The abilities and knowledge the students should acquire corresponds to A) to F) of chapter 3 of the revised paper. These were determined based on the findings obtained from the interviews to more than 100 companies conducted before the opening of the Graduate School of SDM, as well as the data from the Education Issues Committee of the Nippon Keidanren described in Table 1.

We also revised the matrix of the abilities and courses in Table 2 to explain the thinking behind the curriculum setting, and the points and mechanisms of the course. A specific explanation was described in section 3.1, with particular emphasis on required subjects. The recommended subjects and the elective subjects were added in Table 3.

4 Educational method for learning SDM

Comments and questions (Motoyuki Akamatsu)

You mention the lectures, ALPS, and SDM research as ways of learning, but for synthetic research, please organize what can/cannot be learned in lectures, what can/cannot be learned in ALPS, and what can/cannot be learned in SDM research. It will also be beneficial if you address to what extent SDM can be learned through education, and what are the limits of education.

Answer (Naohiko Kohtake)

The basic set-up is to learn the theories in the lectures, to design a system in a team of about five to eight people in a set period in ALPS using the knowledge and methods learned in the lectures, and then each student engages in individual research. However, even in lectures, we emphasize interactivity where the thinking and methods are actually learned through hands-on experience. We encourage the students to attend lectures as needed during the ALPS and the research. Also, the students can invite lecturers to learn more theories, and therefore the courses are mutually supplementary. The students enhance their individual specialties through the process of research.

Since the majority of the students have business experiences, they bring their research topics from their real life experiences to the Graduate School of SDM. Therefore, it is not possible to capture every single aspect of the systems at the Graduate School of SDM. However, the faculty members and the students already have diverse specialties, and are capable of teaching their specialized knowledge to each other in the form of "semi-student semi-teacher (way in which the position of teacher and student are not set, but they learn from and teach each other)". We believe essentially any subject can be handled using this method.

However, since the level of specialty and consciousness differ by student, we do think that what the students learn about SDM depends on the individual student's strength of the consciousness of the problem, breadth of vision, and ability to take action. We are aware that this is an issue. Therefore, we wrote in section 4.5 as follows.

"We feel that all students are capable of learning the basic thinking and method needed to solve the problems of large-scale complex systems to a certain level through required subjects. On the other hand, to be able to utilize the thinking and method in society and industry, it may be necessary to take courses other than the required ones at the Graduate School of SDM as well as at other universities and graduate schools, and the students themselves must apply them in their research and work. The effectiveness of the education depends largely on the students' strength of the consciousness for the problem, breadth of vision, and their ability to take action. Although it is difficult to solve all these issues through graduate school education only, we feel many issues can be solved by the close collaboration between the Graduate School of SDM and society and industry, the individual guidance to students by the instructors, and the further promotion of various exchanges among students composed of diverse human resources."

5 Fusion of humanities and sciences; international collaboration

Comments and questions (Motoyuki Akamatsu)

There are many activities listed as the efforts of the Graduate School of SDM. I think the readers will better understand if you offer specific explanations on, for example, what is learned through human resource exchange transcending the framework of sciences and humanities, or what is the relationship between international collaboration and systems design education.

Answer (Naohiko Kohtake)

○What is learned through human resource exchange transcending the framework of sciences and humanities?

The real society is a place where sciences and humanities are fused. To design the technological or social systems, the knowledge and experience in diverse fields such as economics, political science, and engineering are necessary. Therefore, we believe the significance of the human resource exchange transcending the framework of sciences and humanities at the Graduate School of SDM is that it is possible to learn in a structure similar to the real society.

In fact, in ALPS, which is required by all first-year master's students, we take care that the teams will have diverse people not only of humanities and sciences, but also in nationality, business experience, age, and gender. The students are expected to solve a specific issue utilizing the difference in language, difference in way of thinking, and difference in specialty.

Specifically, the description in section 4.2 was revised and expanded, and specific example was given.

○What is the relationship between international collaboration and systems design education?

Using specific case studies, the descriptions in sections 4.1 to 4.4 were revised and expanded to explain the results of our efforts to present. Particularly, we explained the abilities and knowledge acquired by the students and the idea created, by presenting the activity of a team participating in ALPS.